A Perspective in Interdisciplinary Built Environment Education

Computation for Earthquake Resilience

Edited by
Serdar Aşut and Simona Bianchi

TU Delft | Architecture and the Built Environment

TU Delft OPEN Publishing

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Colophon

A Perspective in Interdisciplinary Built Environment Education:
Computation for Earthquake Resilience

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Keywords:
Built environment education, Interdisciplinary education, Computation, Earthquake resilience, Curriculum development

Published by:
TU Delft OPEN Publishing | Delft University of Technology, The Netherlands

DOI: https://doi.org/10.59490/mg.116

ISBN: 978-94-6518-174-5

Electronic version of this book is available at:
https://books.open.tudelft.nl

Cover design: Zarah Polderdijk

Template design: Anja van der Watt

Graphical design: Daniel Lux, Zarah Polderdijk

Conflict of Interest: No conflict of interest to disclose.

Data Access Statement:

Data availability differs between chapters. For chapters where data is shared, specific details and access information are provided within that chapter. If datasets or supplementary materials are available from external sources, these sources are listed in the chapter's bibliography.

Peer Review:

This book has been peer reviewed. The peer review was single-anonymous. The Editors and the Publisher would like to thank the reviewers for their time and effort. The scientific committee that reviewed the chapters consists of Charalampos Andriotis, Serdar Aşut, Simona Bianchi, Stijn Brancart, Olga Ioannou, Gabriele Mirra, Sevil Sarıyıldız, Aleksandar Staničić, and Michela Turrin.

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The views, findings, and arguments presented in each chapter are solely those of the respective authors. Responsibility for the accuracy and integrity of chapter content rests with the authors, and the editors or publisher do not necessarily endorse or verify all statements therein.

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INTRODUCTION

Interdisciplinary education matters because the most significant questions are too complex to be answered with the knowledge of a single field. This book aims to present a perspective on the pedagogical foundations necessary for interdisciplinary learning, specifically in the built environment education. It is one of the outcomes of the CORE Studio, a course taught in the Building Technology MSc program at the Faculty of Architecture and the Built Environment of TU Delft.

CORE encouraged students to tackle complex problems of the built environment by integrating techniques and tools from various disciplines and utilizing computational methods and technologies. One of the problems addressed in CORE was earthquake resilience and recovery, introduced as the course theme after the devastating 2023 earthquake in Türkiye. The starting point of this endeavor was to reflect on our responsibilities as architects, engineers and building scientists in response to such a profound event. The CORE Studio, as an environment for collaboratively developing ideas, conducting research and educating future architects and engineers, could provide the necessary platform for this. Moreover, its focus on computation could help develop innovative solutions for more resilient built environments. Therefore, in September 2023, the studio was targeted to address this challenge with the title "Computation for Earthquake Resilience and Recovery."

The course was taught by an interdisciplinary team of educators, researchers and practitioners, each offering a unique perspective. Their combined expertise encouraged the examination of the complex subject from multiple angles. 46 MSc students in Building Technology, most of whom had a background in architecture, continued the discussion by developing projects that integrated knowledge from various fields. Both the results and the whole process became inspiring for all participants, which triggered the idea to share them on different platforms.

The first platform was a symposium held in İzmir, Türkiye, in April 2024. It brought together students and educators from CORE, along with colleagues and students from several architecture schools in Türkiye, to share their experiences in integrating earthquake-related subjects into education. The event featured seminars, exhibitions and workshops with representatives from industry, government and non-governmental organizations. It enabled a large and diverse group of participants to exchange experiences and ideas. It provided a valuable opportunity to collaboratively discuss how education in the built environment can effectively address the urgent and complex issue of earthquake resilience management.

The symposium triggered the idea of compiling the work into a book, leaving a lasting imprint for future educators and researchers to draw upon. Several authors who are already active in related themes were invited to add their perspectives and share experiences in the book. Some of the CORE students also prepared concise documentation of their studio projects to be included. This collective effort shaped the content of this edited volume.

This book is organized into three parts. Part 1, Educational Endeavours, presents various experiences that elaborate on the integration of earthquake resilience in the built environment education. It starts with a chapter written by Serdar Aşut, who discusses the role of computation in interdisciplinary built environment education, drawing on the experiences of the CORE Studio. It is followed by Roberto Gentile's chapter, which presents a pedagogical experience that integrates data science into humanitarian engineering education. Following this, Mauricio Morales-Beltran discusses how earthquake-resistant design principles can be taught to architecture students. This chapter is followed by Lale Başarır, Burkay Pasin, and İlker Kahraman, who present their experience in integrating post-disaster dwelling design topics into architectural design studio education. The next chapter, written by Erdem Onan, Aleksandar Staničić, and Serdar Aşut, highlights the transversal or soft skills essential in interdisciplinary education, with a specific emphasis on self-regulated learning. This part concludes with two chapters that present projects that were initiated or conducted by students. The first one is the Urgent Design Studio initiative written by Gizem Nur Aydemir, Bilge Arslan, Damla Turgut, Nusret Atakan Harmanci, and Arda Fidansoy; and the latter is the Ardıç project written by Buse Beste Aydınoğlu, Mauricio Morales-Beltran, Utku Özer, Elizabeth Cunningham, Göktuğ Ünlü, Buse Ecem Gönülalan, and Denizhan Şallı.

Part 2, Research Insights, includes some critical state-of-the-art research subjects concerning earthquake-resilient built environments. It begins with Simona Bianchi's chapter, which explores low-damage low-carbon techniques and their application to a building's main load-bearing structure and envelope systems. The following chapter, written by Birgül Çolakoğlu, elaborates on the integration of circular economy principles into disaster recovery and reconstruction, with a focus on earthquake-prone regions in Türkiye. Then, Oğuz Cem Çelik presents an evaluation of building performances from the two major earthquakes of February 2023. In the following chapter, Uğur Demir and Fehmi Doğan share findings from their inspections conducted on numerous reinforced concrete buildings in areas affected by these earthquakes. This part concludes with a chapter that presents a computational method for integrating seismic simulation into the architectural design of tall buildings, written by Pooyan Kazemi, Michela Turrin, Charalampos Andriotis, Alireza Entezami, Stefano Mariani, and Aldo Ghisi.

Part 3 includes some of the student projects on Computation for Earthquake Resilience and Recovery, which were developed at the CORE Studio during the

Fall 2023-2024 semester. Ten of the studio projects are included in this part, with the students' voluntary additional effort to prepare the materials included in this book.

A complex and challenging educational endeavor like this, as well as the production of this book, could not have been possible without the efforts of many people who contributed in various ways. Therefore, we extend our sincere thanks to all authors and students who provided valuable content that is brought together in this volume. Additionally, we send our gratitude to the members of the scientific committee who provided constructive peer review feedback on the chapters.

We also would like to thank the team who taught the CORE Studio in 2023, namely, Charalampos Andriotis, Juan Carlos Prażmowski Baczyk, Stijn Brancart, Puck Flikweert, Jamal van Kastel, Mauro Overend, Sevil Sarıyıldız, Leandre Sassi, Frank Schnater, and Fred Veer. Also, we appreciate the contributions of guest lecturers who provided invaluable content, namely, Nazlı Aydın, İhsan Engin Bal, Milena Casto, Cemre Çubukçuoğlu, Uğur Demir, Roberto Gentile, Gabriele Granello, İbrahim Emre Gündoğdu, Pooyan Kazemi, Meriç Kessaf, Imke Lánský, Francesco Messali, Giovanni Milan, Kamil Owczarek, Daniele Perrone, Gertjan Peters, Clayton Prest, Sam Price, Tiina Ristmäe, Eleni Smyrou, Sarper Takkeci, Dragos Tomas-Danila, Leyla van der Waarde, Chris de Weijer, and Aleksandra Wróbel. Last but not least, we thank and congratulate all our students who showed great effort throughout the course.

We hope this volume will support the drive for effective interdisciplinary education in the built environment and help advance the creation of more resilient built environments through the use of computational methods and technologies.

Serdar Aşut and Simona Bianchi

Part I

Educational Endeavours

Advancing Interdisciplinary Built Environment Education Through Computation

Serdar Aşut[1]

Computation is both expert knowledge and a transversal competence. This article presents how computation can enhance interdisciplinary learning in the context of built environment education. The need for interdisciplinary education is widely recognized and aligns with industrial and societal transformations. Integrating diverse know-how from various built environment professionals is challenging in an educational context. Computation can help address these challenges as a transversal competence applicable across multiple disciplines by facilitating communication between different fields. This proposition was applied over three academic years in a research and design course within the Building Technology master's program at the Faculty of Architecture and the Built Environment of Delft University of Technology, focusing on a different theme each year. The course was designed following Interdisciplinary Project-based Learning principles and integrated computation through programming as a transversal competence and expert knowledge. This article presents an overview of the objectives and methodology of this course. It specifically focuses on the second year, which explored earthquake resilience and recovery as the course theme. Based on the lessons learned, the article concludes with suggestions for creating effective interdisciplinary environments for built environment education.

Keywords: Built environment education, Computation, Programming, Transversal competences, Interdisciplinary education

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Interdisciplinary Education

Interdisciplinarity refers to the integration of methods, knowledge, and skills, as well as theories, perspectives, and different disciplinary knowledge bodies, to achieve innovative solutions and advancements in uncharted problem areas[1,2,3,4]. It is a process that requires the synthesis of various disciplinary knowledge and methods to provide a more holistic understanding of a given problem[5], tackle complex problems, and stimulate innovation. It is particularly valuable in addressing emerging challenges that do not usually fit within traditional disciplinary boundaries.

It is the process by which information and codes are exchanged across disciplinary boundaries in a search for new or deeper understanding because it is in the overlapping spaces that exist between disciplines where the frontiers of knowledge are located[6]. Yet, it involves challenges because it requires aligning different epistemologies, methodologies, and terminologies, demanding collaboration across fundamentally different ways of thinking and problem-solving. Professionals from different disciplinary backgrounds may struggle to navigate and overcome these challenges, partly because their education did not prepare them for interdisciplinary collaboration. Additionally, education itself presents distinct challenges in this regard.

The need for interdisciplinary education (IE) is widely recognized and aligns with industrial and societal transformations. Chen et al.[7] originate the sense of IE from three arguments provided by Stember[8]. The first one is that ideas in any field are enriched by theories, concepts, and methods from other fields. Secondly, the problems of the world are not organized according to academic disciplines. And finally, learning is hindered by fragmentation. Designing and implementing IE remains a prominent area of research that requires further exploration. The historically discipline-oriented nature of academia often impedes such explorations[9]. Still, it also occurs within even very traditional and monodisciplinary universities, emerging in the interstices of monodisciplinary structures through strategies of ‘managing interstitiality’[10].

Several scholars have emphasized this need and proposed approaches to facilitate IE within built environment education (e.g.[2,11,12,13]). The very nature of built environments presents complex challenges related to their design, planning, production, and use, requiring input from multiple disciplines. Integrating this diverse know-how is not easy, especially in education. A common challenge discussed in the literature is the difficulty of communication between different disciplines. Yocom et al.[14] argue that developing collective understanding is the most challenging theme for IE and that it should focus on sharing disciplinary vocabularies and improving students’ communicative techniques.

Creating a common ground for collaboration in an interdisciplinary environment and overcoming the communication difficulties between disciplines require strategies that bridge differences in methods, terminology, and communication styles. This can be achieved in education through structured frameworks that promote dialogue, mutual understanding, and shared problem-solving approaches. While expert knowledge and disciplinary skills are essential, interdisciplinary collaboration also depends on soft or transversal competencies, such as communication, adaptability, and teamwork. These skills are as critical as technical expertise in ensuring effective cooperation and knowledge integration. While technical competencies are applicable only in the environment for which they were developed, transversal competencies are transferable to different contexts, including leadership, communication, problem-solving, teamwork, and creativity, among others[15]. IE must emphasize the development of transversal competencies as strongly as the disciplinary expertise.

The Role of Computation in Interdisciplinary Education

Computation is both expert knowledge and a transversal competence. It requires students to develop both domain-specific and general problem-solving skills[16]. Broadly, it refers to the use of formal, mathematical systems, theories, and methods, as well as tools and technologies developed on the basis of such systems[17]. It refers to the thought processes involved in formulating problems so their solutions can be represented as computational steps and algorithms[18]. It relates to thinking at multiple levels of abstraction, and it is a universally applicable attitude and skill set everyone, not just computer scientists, would be eager to learn and use[19].

Computation is expert knowledge because it involves specialized skills, methodologies, and theoretical foundations gained through rigorous training and an in-depth understanding of the specific application domains where they are used. It requires knowledge of algorithms, data structures, programming languages, and mathematical principles. It necessitates specialized training in problem-solving techniques, software development, and computational modeling. Moreover, the effective application of these methods often requires expertise in specific fields.

Two factors make computation a transversal competence. The first is that it is applicable across multiple disciplines for diverse problem-solving, data analysis, and modeling applications. The second, which is more related to this article's arguments, is that it facilitates communication between different disciplines.

Computation provides a common language across experts with different backgrounds through data, models, and algorithms. It allows the translation of complex problems into abstract and explainable representations. It makes somewhat subjective concepts and arguments more tangible and comparable. Computational simulations and models provide frameworks for analysis and interpretation through shared and interoperable platforms. It standardizes information processing and representation, enhancing interdisciplinary collaboration and problem-solving. Hence, computation provides a shared language among multiple disciplines. It is a core transversal competence that can facilitate communication between disciplines and address some of the common challenges within an interdisciplinary built environment education, as described earlier.

CORE: Advancing Interdisciplinary Education in Built Environment through Computation

Computation is an essential competence that should be integrated into built environment education. It is both a fundamental area of knowledge necessary in the digital age and a transversal competence crucial for interdisciplinary education and practice. Therefore, effective pedagogies that address both aspects are necessary, considering the rapidly changing landscapes of computational tools and methods. Effective interventions should focus on the development of algorithmic thinking and reinforce the utility of programming as a skill, both generally and specifically within careers[20]. Also, higher education institutions need to consider their agility to respond effectively and anticipate the challenges and opportunities created by the rapidly changing computing environments[21].

CORE Studio was developed at the Faculty of Architecture and the Built Environment (ABE) of Delft University of Technology (TU Delft) as an intervention to enhance interdisciplinary education in the built environment through computation within the Building Technology (BT) MSc program. CORE stands for “COmputational REpertoire for Architectural Design and Engineering.” It is a research and design studio course taught at BT for three years starting in September 2022. It was taught in the fifth quarter (the first quarter of the second year) of the curriculum as a 15-ECTS (European Credit Transfer and Accumulation System) elective. It is a full-time, 10-week course with a total workload of 420 hours (including self-study), and it is the only course that students follow during the same quarter. It was coordinated by the Design Informatics chair and taught in collaboration with the Structural Design and Mechanics chair of the Department of Architectural Engineering and Technology.

CORE aimed to enable and encourage students to develop a repertoire of custom computational skills, methods, and tools to address interdisciplinary challenges related to the built environment by addressing computation as both an expert knowledge and a transversal competence. The course design includes two main components. The first is the introduction of computational skills, tools, and methods, and the second is their application within a design assignment.

Even though computational thinking is rooted in non-digital human approaches to problem-solving, the mainstream approaches focus on programming with digital computers[22], and programming assignments are still the most often used approach to interventions to teach computational thinking[23]. Similarly, CORE introduced computation through programming. The students had prior knowledge of computational design through the Introduction to Computational Design course, a compulsory module in the second quarter of their studies. It introduced them to the main concepts related to algorithmic thinking, parametric modeling, simulations, and digital fabrication. In this course, students also developed skills using Grasshopper (GH), a visual programming interface, and applied these skills in the design assignments. Some students had the opportunity to further develop these skills through the electives they took in the third and fourth quarters. CORE was built on this existing experience, utilizing GH as the central design platform and advancing it with programming in Python. Therefore, it included workshops on Python programming, starting with the basics of programming, covering subjects such as data types, variables, operations, functions, libraries, data analysis, and object-oriented programming. These workshops were held as weekly sessions throughout the first year of the course. In the second and third years, they were organized as an intensive crash course in the first two weeks. Our experiences showed that the latter approach was more effective, as it allowed the students to start programming earlier and enabled better integration in their design assignments. This allowed computational thinking to shape the entire design process from the beginning, including identifying project needs, planning, resource allocation, and pre-rationalization of decisions, thereby guiding the whole process. After the second week, they were guided in their programming work through weekly supervision by tutors.

We think that the focus on computation was one of the factors that attracted students' attention, resulting in high enrollment numbers over the three years of this course. In the first year, 67% of students (38 out of 57) enrolled; in the second year, the enrolment increased to 84% (46 out of 55); and in the third year, 90% (35 out of 39) of BT students chose this elective. This situation supports McCord et al.'s[21] argument regarding the transformation of Architecture, Engineering, and Construction (AEC) education to accommodate computational skills. They argue that students are not a barrier but a driver of change, with student usage of some technologies outpacing curricular coverage.

The course theme changed yearly, addressing an actual societal and industrial challenge. The students were asked to explore the described theme and propose design assignments to tackle specific challenges within it. The first year's theme was "Computation for Mobility," in relation to the Mobility Program 2040 developed by the Municipality of Delft. The second year, which also led to the publication of this book, focused on "Computation for Earthquake Resilience and Recovery" in response to the devastating earthquake that occurred in Türkiye in 2023. And the last year focused on "Computation for Construction Automation," addressing the needs of AEC toward cleaner, more efficient, and safer construction practices.

The formulation of the design assignments within these diverse themes was undertaken by the students, guided by the tutors in accordance with Problem-based Learning (PBL) principles. PBL is an instructional (and curricular) learner-centered approach that empowers learners to conduct research, integrate theory and practice, and apply knowledge and skills to develop a viable solution to a defined problem[24]. In PBL, students work in small collaborative groups and learn what they need to know to solve a problem, which is a well-suited approach to help students become active learners because it situates learning in real-world problems and makes students responsible for their learning[25].

Brassler and Dettmers[26] present the distinctions between Interdisciplinary Problem-based Learning ((i)PBL) and Interdisciplinary Project-based Learning ((i)PjBL) and argue that (i)PBL is far more suited than (i)PjBL to support students' development of interdisciplinary competence. Based on this classification, while CORE incorporates characteristics from both approaches, it is closer to (i)PBL as explained in Table 1 (the characteristics that align more closely are identified with bold text and a coloured cell background).

Characteristics	(i)PBL	(i)PjBL
Duration	Short-term (5–6 problems per semester)	**Long-term (1 project per quarter)**
Problem/Task	**Ill-structured cases, open and narrow**	Real-world, fully authentic tasks
Definition of Problem/Task Making core choices	**(mostly) student**	(mostly) teacher
Process	Following specific steps	**Following general, broad steps of project management**
Problem solving level	**Problem analyses (rather theoretical)**	**Problem solving (rather practical)**
Role of the teacher/tutor	**Process-oriented supervisor/facilitator**	Product-oriented supervisor/ instructor
Outcome/focus/aim	**Presentation of knowledge acquisition**	"tangible" products
Assessment	**(mostly) based on learning**	(mostly) based on product

Table 1. Characteristics of (i)PBL and (i)PjBL (Modified from Brassler and Dettmers [26]).

It is the only course that students follow during the quarter (10 weeks, half a semester), so they focus entirely on one project. The course does not present a fully defined task; instead, it invites and encourages students to work on ill-structured cases around a defined theme, with them taking responsibility for defining the specific task within that theme. The process follows broad project management steps, tailored to the specific needs of each case. The course emphasizes both problem analysis and problem solving equally. The teachers' role is clearly process-oriented rather than product-oriented. The outcomes focus more on knowledge acquisition than on tangible products, and assessment is based primarily on learning rather than on the final deliverables.

The Interdisciplinary Dimension in CORE

An interdisciplinary learning environment can be established in different ways. Perhaps the most ideal approach is enabling collaboration among students from different faculties. However, this was not the case for CORE, as all students were part of the BT program and held bachelor's degrees in architecture (with only a few exceptions). Instead, its interdisciplinary dimension was initially facilitated by addressing real-world problems related to the design, production, and use of built environments, following PBL principles. These challenges inherently require integrating knowledge, skills, and methods from multiple disciplines. For instance, second-year projects within the earthquake resilience and recovery theme spanned a broad range of scientific disciplines (e.g., software, algorithms, control systems, artificial intelligence, expert systems, civil engineering, information systems, databases, urban studies, user interfaces, multimedia, architecture, geotechnics, computer graphics, design sciences, mechanical engineering, materials technology), increasing students' awareness of the need for interdisciplinary collaboration to tackle complex issues. The formulation of the theme further reinforced this need by incorporating all four phases of disaster management: mitigation, preparedness, response, and recovery. This approach drove students to think and act beyond their disciplinary backgrounds, seek expertise and resources from various fields, and integrate them by using computational tools and methods. A detailed analysis of the interdisciplinary content of these projects was presented in another article[27].

Another factor in facilitating interdisciplinarity was the diverse expertise of the teaching team. The involvement of faculty members from various chairs provided a range of perspectives, and the composition of the team could be adapted to fit the course theme each year by inviting different experts to contribute. Additionally, the course reached beyond the department and the university, engaging specialists from multiple fields. Particularly in the second year, a diverse range of experts, including researchers, engineers, architects, and designers from industry, as well as governmental and non-governmental organizations, participated. It was particularly impressive to see the voluntary contributions from professionals dedicated to humanitarian issues, such as disaster.

The interdisciplinary dimension was further strengthened by incorporating computation as a transversal competence. This approach allowed students to comprehend workflows and methods from various disciplines, interpret them, communicate effectively with external experts, and develop innovative solutions. By utilizing computational tools and methods, they were able to bridge gaps between disciplines, integrate diverse sources of knowledge, and apply data-driven methods to tackle complex problems.

One of the outcomes of the course was that students implicitly developed T-shaped expertise in the field of earthquake resilience and recovery. The T-shape refers to a variation of the 'renaissance figure[1]' who can integrate expertise and information technology skills and consider both the technical and social components within the larger system[28]. The horizontal bar of the 'T' represents a breadth of expertise, an ability to engage with other experts across a variety of systems and intellectual and disciplinary cultures; the vertical part of the 'T' represents a depth of expertise in a specific knowledge domain[29].

In the case of CORE, students developed the horizontal bar of the 'T' by gaining awareness of disaster-related challenges and understanding the roles and responsibilities of built environment professionals, including the need for collaboration across various disciplines. This was primarily achieved through a diverse line-up of lectures by experts from various disciplines, some of which were (intentionally) distant from the students' background and, therefore, challenging to grasp. They were complemented by literature research and explored further through discussions with studio tutors. At the same time, they deepened the vertical bar by acquiring specific skills and knowledge in their field of Building Technology, such as structural analysis, performance-based design, and computational modeling, particularly in the context of earthquake resilience and recovery.

They are exposed to broader perspectives and connections beyond their discipline through the horizontal bars of the 'T.' Even if they do not directly apply all these broader insights per se, simply becoming aware of them strengthens the T-shape expertise. As the horizontal bars of different students' T-shapes intersect, the skills necessary for effective collaboration naturally emerge. Computation played a key role in this process by acting as a transversal competence that supported students in interpreting workflows from other disciplines on the horizontal bars of the 'T.' This aspect further strengthens the interdisciplinary dimension of the course and the role of computation as a transversal competence.

1. It is referred to as a 'renaissance man' in the original source [28].

Conclusions and Discussion

The three years of the CORE studio, especially the second year that focused on earthquake resilience and recovery, demonstrate how an interdisciplinary learning experience can be enriched through the use of computation as a transversal competence. This experience offers valuable insights for future research and provides recommendations for developing new initiatives in interdisciplinary built environment education.

One of the main suggestions is to design the assignments based on Interdisciplinary Project-based Learning ((i)PjBL) principles. This can support the development of interdisciplinary skills more fundamentally. These assignments should involve real-world, open-ended problems that require input from multiple disciplines and encourage collaboration with students or practitioners from different backgrounds.

When students with diverse backgrounds or interests work together in the same team, it is important not to expect every member to achieve the same learning goals. One common learning objective for all students must be the development of transversal skills. Besides this, an interdisciplinary learning experience should allow for the customization of learning objectives, enabling students to build on their strengths and interests. This also implies the need for flexible and adaptable assessment methods and customizable learning activities. Managing such complexity requires thoughtful course design and vigorous coordination. The teacher plays a crucial role in maintaining an overarching view of the process in a course design like this.

Computation is essential as expert knowledge and transversal competence in interdisciplinary learning. While it is commonly introduced through programming, the rise of Artificial Intelligence (AI) and Large Language Models (LLM) is reshaping how programming is practiced. Further research is needed to understand how these changes impact computational skills and how they should be reflected in educational settings.

Another suggestion is to incorporate learning activities into the course design to introduce specific transversal competencies more explicitly and raise awareness of their importance among students and the teaching team. These activities can provide students with tools to recognize, reflect on, and intentionally develop competencies needed for interdisciplinary collaboration. Thus, students can become better equipped to navigate interdisciplinary collaborations and apply these skills in academic and professional contexts.

It is also necessary to develop means to measure the impact of interdisciplinary education. Future efforts should develop new evaluation methods that assess immediate learning outcomes and long-term effects. This includes evaluating how graduates apply interdisciplinary thinking in their professional practice and how it influences their work.

Perhaps we should define disciplines more fluidly, allowing experts to grow and evolve within overlapping areas of knowledge. Instead of rigidly assigning authority to specific fields -like the shift from the master builder to specialized engineering disciplines, each operating in its own silo- we might as well acknowledge that this fragmented approach no longer suffices. The complexity of today's challenges calls for interdisciplinary, multidisciplinary, and transdisciplinary approaches. It may be time to let people move more freely across disciplinary boundaries and see what unexpected expertise emerges in those intersections. Educational environments can serve as ideal testing grounds for this approach. They can offer a safe space to explore how fluid disciplinary boundaries can function in practice and assess their outcomes. Thus, we can influence professional practices by experimenting with new ways of working during education.

Funding

This research received no external funding.

Ethical Committee Approval

This work does not require an ethics committee approval.

Acknowledgments

The author acknowledges the invaluable contributions of the teaching team in the 2023-2024 academic year (C. Andriotis, F. Schnater, F. Veer, J.C.P. Baczyk, L. Sassi, J. van Kastel, M. Overend, P. Flikweert, S. Bianchi, S. Brancart, S. Sarıyıldız) and the guest tutors (A. Wróbel, C. Çubukçuoğlu, C. de Weijer, C. Prest, D. Perrone, D. Tomas-Danila, E. Smyrou, F. Messali, G. Granello, G. Milan, G. Peters, I. Lánský, İ.E. Gündoğdu, İ.E. Bal, K. Owczarek, L. van der Waarde, M. Casto, M. Kessaf, M.S. Takkeci, N.Y. Aydin, O. Arslan, P. Kazemi, R. Gentile, S. Price, T. Ristmäe, U. Demir) who made it possible to realize the interdisciplinary learning environment and the outstanding efforts of the students enrolled in the course.

Conflict of Interest

The author declares no conflicts of interest.

References

1. V. Castán Broto, M. Gislason, and M.-H. Ehlers, "Practising interdisciplinarity in the interplay between disciplines: experiences of established researchers," *Environmental Science & Policy*, vol. 12, no. 7, pp. 922-933, 2009, doi: 10.1016/j.envsci.2009.04.005.
2. R. G. Klaassen, "Interdisciplinary education: a case study," *European Journal of Engineering Education*, vol. 43, no. 6, pp. 842-859, 2018, doi: 10.1080/03043797.2018.1442417.
3. J. C. K. Lam, R. M. Walker, and P. Hills, "Interdisciplinarity in sustainability studies: A review," *Sustainable Development*, vol. 22, no. 3, pp. 158-176, 2012, doi: 10.1002/sd.533.
4. S. Menken et al., Eds. *An Introduction to Interdisciplinary Research: Theory and Practice*. Amsterdam University Press, 2016.
5. L. R. Lattuca, D. B. Knight, H. K. Ro, and B. J. Novoselich, "Supporting the development of engineers' interdisciplinary competence," *Journal of Engineering Education*, vol. 106, no. 1, pp. 71-97, 2017, doi: 10.1002/jee.20155.
6. P. Youngman, "21st-century humanities: Art, complexity, and interdisciplinarity," *Human Affairs*, vol. 22, no. 2, pp. 111-121, 2012, doi: 10.2478/s13374-012-0011-6.
7. Y. Chen, T. A. Daamen, E. W. T. M. Heurkens, and W. J. Verheul, "Interdisciplinary and experiential learning in urban development management education," I*nternational Journal of Technology and Design Education*, vol. 30, no. 5, pp. 919-936, 2019, doi: 10.1007/s10798-019-09541-5.
8. M. Stember, "Advancing the social sciences through the interdisciplinary enterprise," *The Social Science Journal*, vol. 28, no. 1, pp. 1-14, 2019, doi: 10.1016/0362-3319(91)90040-b.
9. A. Van den Beemt et al., "Interdisciplinary engineering education: A review of vision, teaching, and support," *Journal of Engineering Education*, vol. 109, no. 3, pp. 508-555, 2020, doi: 10.1002/jee.20347.
10. K. Lindvig, C. Lyall, and L. R. Meagher, "Creating interdisciplinary education within monodisciplinary structures: the art of managing interstitiality," *Studies in Higher Education*, vol. 44, no. 2, pp. 347-360, 2017, doi: 10.1080/03075079.2017.1365358.
11. M. Sibilla and E. Kurul, "Climate change and built environment education: A pedagogical approach to foster interdisciplinary learning," in *University Initiatives on Climate Change Education and Research*, 2024, ch. 81-1, pp. 1-38.
12. N. D. Botchwey et al., "A model curriculum for a course on the built environment and public health," *American Journal of Preventive Medicine*, vol. 36, no. 2, pp. S63-S71, 2009, doi: 10.1016/j.amepre.2008.10.003.

13. A. S. Johnston, "CitySection: A pedagogy for interdisciplinary research and collaboration in planning and environmental design," *Journal of Planning Education and Research,* vol. 35, no. 1, pp. 86-92, 2014, doi: 10.1177/0739456x14557641.
14. K. Yocom, G. Proksch, B. Born, and S. K. Tyman, "The built environments laboratory: An interdisciplinary framework for studio education in the planning and design disciplines," *Journal for Education in the Built Environment*, vol. 7, no. 2, pp. 8-25, 2015, doi: 10.11120/jebe.2012.07020008.
15. M. J. Sá and S. Serpa, "Transversal competences: Their Importance and learning processes by higher education students," *Education Sciences*, vol. 8, no. 3, 2018, doi: 10.3390/educsci8030126.
16. A. Yadav, J. Good, J. Voogt, and P. Fisser, "Computational Thinking as an Emerging Competence Domain," in *Competence-based Vocational and Professional Education*, M. Mulder Ed., (Technical and Vocational Education and Training: Issues, Concerns and Prospects: Springer, Cham, 2017, pp. 1051-1067.
17. T. Knight and T. Vardouli, "Computational making," *Design Studies*, vol. 41, pp. 1-7, 2015, doi: 10.1016/j.destud.2015.09.003.
18. A. V. Aho, "Computation and computational thinking," *The Computer Journal*, vol. 55, no. 7, pp. 832-835, 2012, doi: 10.1093/comjnl/bxs074.
19. J. M. Wing, "Computational thinking," *Communications of the ACM*, vol. 49, no. 3, pp. 33-35, 2006, doi: 10.1145/1118178.1118215.
20. K. Steelman et al., "Work in progress: Student perception of computer programming within engineering education: An investigation of attitudes, beliefs, and behaviors," presented at the 2020 ASEE Virtual Annual Conference Content Access Proceedings, 2020.
21. K. H. McCord et al., "Computing in AEC rducation: Hindsight, insight, and foresight," *Journal of Computing in Civil Engineering*, vol. 38, no. 3, 2024, doi: 10.1061/jccee5.Cpeng-5646.
22. E. N. Caeli and A. Yadav, "Unplugged approaches to computational thinking: A historical perspective," *TechTrends*, vol. 64, no. 1, pp. 29-36, 2019, doi: 10.1007/s11528-019-00410-5.
23. I. de Jong and J. Jeuring, "Computational thinking interventions in higher education," presented at the Koli Calling '20: Proceedings of the 20th Koli Calling International Conference on Computing Education Research, 2020.
24. J. R. Savery, "Overview of problem-based learning: Definitions and distinctions," *Interdisciplinary Journal of Problem-Based Learning*, vol. 1, no. 1, 2006, doi: 10.7771/1541-5015.1002.
25. C. E. Hmelo-Silver, "Problem-based learning: What and how do students learn?," *Educational Psychology Review*, vol. 16, no. 3, pp. 235-266, 2004, doi: 10.1023/B:EDPR.0000034022.16470.f3.

26. M. Brassler and J. Dettmers, "How to enhance interdisciplinary competence—Interdisciplinary problem-based learning versus interdisciplinary project-based learning," *Interdisciplinary Journal of Problem-Based Learning*, vol. 11, no. 2, 2017, doi: 10.7771/1541-5015.1686.
27. S. Aşut, "Computational earthquake management: An educational perspective," *Journal of Design for Resilience in Architecture and Planning*, vol. 5, no. 2, pp. 229-245, 2024, doi: 10.47818/DRArch.2024.v5i2129.
28. D. Guest, "The hunt is on for the Renaissance Man of computing," *The Independent*, vol. 17, no. 9, 1991.
29. S. N. Conley, R. W. Foley, M. E. Gorman, J. Denham, and K. Coleman, "Acquisition of T-shaped expertise: an exploratory study," *Social Epistemology*, vol. 31, no. 2, pp. 165-183, 2017, doi: 10.1080/02691728.2016.1249435.

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Humanitarian Engineering and Data Science: A Teaching Perspective

Roberto Gentile [1]

Humanitarian engineering and data science (HEDS) can be defined as the adoption of engineering and data science to promote human welfare in contexts that lack it, with the active participation of the involved communities. This chapter discusses the proposed teaching delivery of HEDS within an interdisciplinary undergraduate module. This is delivered within the "Global Humanitarian Studies" BSc, in the Department of Risk and Disaster Reduction, University College London. First, this chapter provides an overview of the basic principles of HEDS, and a the set of lecture topics proposed to cover them reasonably cover them. These include: 1) quantitative definitions of poverty and inequality; 2) social justice and sustainability; 3) fundamentals of data science algorithms and prompt engineering; 4) humanitarian data sources; 5) ethics in data science; 6) discussion of real case study applications in research and practice. The discussion describes how basic coding proficiency is paramount for HEDS topics, and how including a coding tutorial series in the module fulfils this need. Finally, this chapter discusses the learning outcomes -and related opportunities- for students, and the challenges involved in the teaching delivery, mainly related to covering a broad field in a short module time and overcoming the inherent skill differences in an interdisciplinary student cohort.

Keywords: Humanitarianism, Engineering, Data Science, Undergraduate Teaching, Engineering Education.

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Introduction and Motivation

The word humanitarian has been defined as "being concerned with or seeking to promote human welfare"[1]. The meaning of human welfare is defined via social justice, here defined as "standards for, and a view on how to promote, human dignity, rights, fulfilment for all of humanity"[2]. The lack of human welfare, or poverty, may be defined in different dimensions including hunger and malnutrition, limited access to education and other basic services, social discrimination, and lack of participation in decision-making. Usually, such metrics correlate with the lack of income. As of 2024, approximately 8.5% of the global population (i.e., nearly 700 million people) live on less than 2.15US$ per day considering purchase power parity[3], which is the internationally defined threshold for extreme poverty[4]. There exists a persistent and growing need to address the problems of this large proportion of humanity, who often lack access to basic needs such as clean water, energy, adequate housing, wastewater treatment, and employment opportunities.

Engineering is "the profession that translates science into technology", which may be regarded as a tool that extends human capabilities[5]. Some of the major problems of technological advancement in developing countries seem to arise from difficulties in the translation of science into technology[5]. Around the world, higher education is characterised by a pedagogical movement focused on providing academic training and skills to address the above pressing problem of such marginalised communities who lack the resources to do so for themselves. This inherently interdisciplinary goal aims at activating the collaboration among actors involved in such efforts (e.g., students, academics, practising engineers and other professionals, community members) to concurrently make a meaningful, sustainable difference in the lives of marginalised people. Among the taught disciplines tackling the above challenge[6], humanitarian engineering refers to the use of science and technology to direct resources with active compassion to meet the basic needs of all, especially the economically poor or otherwise marginalised, while seeking a balance of listening and learning from the members of the community and local stakeholders while humbly sharing appropriate engineering knowledge[7]. This exists in the context of other emergent topics such as: social entrepreneurship – the creation of social impact by developing and implementing a sustainable business model which draws on innovative solutions that benefit the disadvantaged[8]; frugal engineering – the rethinking of the product/process development process to design, develop and deliver innovative solutions to customers in marginalised communities[9]; service learning in engineering – the experiential education[10] in which students combine academic instruction with the participation in an organized service activity that meets identified community needs and reflect on the service activity in such a way as to gain further understanding of course content[11]. The above-mentioned educational programmes have different specific goals, but they share one commonality: they emphasise how projects solutions not only require technical consistency but also an understanding of the social and cultural contexts where they are implemented, the community needs, and a sustainable implementation.

Several humanitarian engineering modules are available around the world, including at the Colorado Schoolschool of Minesmines[12], IRIS Sup[13], University of South Wales[14], and University of Warwick[15], among others. None of those modules explicitly incorporate data science, although this field has essentially touched almost every aspect of society in the last few years. Data science - which can be considered part of engineering since it complements the design of new technologies - is a “field-interdisciplinary concept involving data design, collection, and (statistical) analysis”[16]. In the late 1990s, when data started to become abundant, this field was referred to as an expansion of statistics beyond theory into technical areas[17], and since data science was expected to significantly change the field of statistics, it warranted a new name[16].

This chapter describes a teaching experience at the Departmentdepartment of Risk and Disaster Reduction, University College London, deployed to overcome the above challenge, represented by the taught module Humanitarian Engineering and Data Science (HEDS) delivered within the BSc Global Humanitarian Studies (department of Risk and Disaster Reduction, University College London). HEDS can be defined as the adoption of engineering and data science to promote human welfare in contexts that lack it, with the active participation of the involved communities. HEDS combine technical skills with a profound commitment to addressing global social issues. By using the principles of humanitarian engineering, this field seeks to design solutions that are not only effective but culturally and socially relevant, empowering communities and promoting resilience. Data Science enhances these efforts by providing critical insights into complex humanitarian problems. Through data collection[18], machine learning[19,20], and predictive modelling[21], data science enables a deeper understanding of patterns in issues like food insecurity, disease outbreaks, and natural disaster risks. By merging these fields, professionals can create data-driven solutions that inform resource allocation, optimize aid delivery, and predict future challenges, leading to more efficient and impactful interventions.

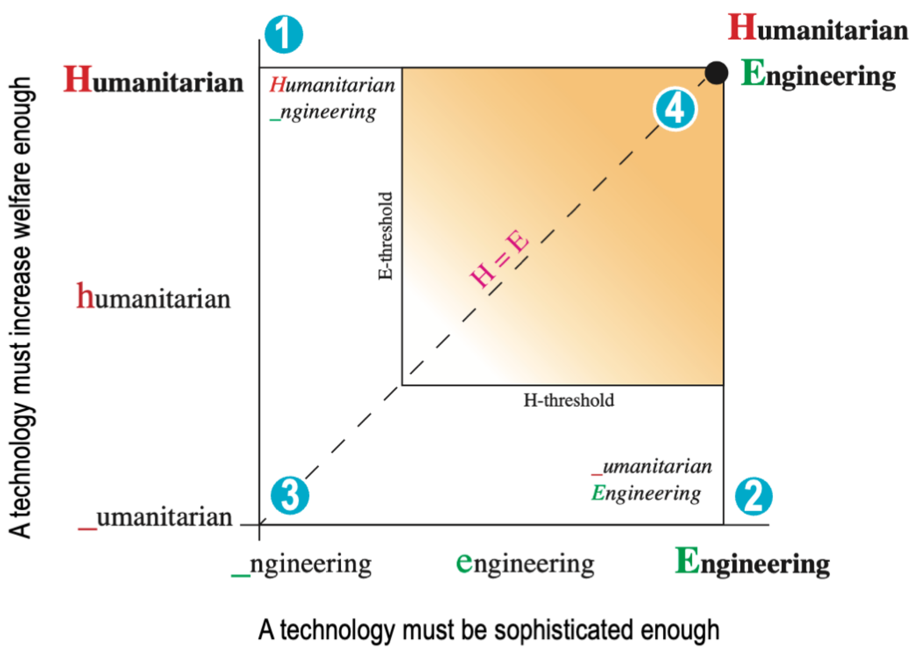
Compared to other modules, HEDS is characterised by three specific points: 1) it includes data science in the learning experience, based on the assumptions that this can be considered part of engineering, and acknowledging the exponential increase in data-driven technologies worldwide; 2) it targets undergraduate students of an interdisciplinary degree, rather than targeting engineering or data science students with specific technical knowledge; 3) it includes a bottom-up learning approach including implicit-to-explicit understanding[22] based on student-specific practical coursework that allows to infer general knowledge from context-specific case studies.

After describing the rationale and the content of the taught module, this contribution analyses the past module deliveries through the provided student feedback, emphasising the above challenges. General final remarks are subsequently provided.

Structure of the Taught Module

Module Rationale and Aim

A HEDS project can be defined considering several factors. Drawing from previous efforts in defining humanitarian engineering projects (e.g., [2], [23], [24]), HEDS projects should aim at increasing welfare, and they can tackle basic human needs, as well as higher-level needs such as education and economic development (i.e., the project should be "humanitarian enough", Figure 1). Since human welfare is connected to the promotion of human dignity and rights, HEDS refers to both short-term disaster relief (e.g., emergency response, humanitarian aid) and long-term human development (e.g., technological projects in developing countries). Among different community needs, an important one involves increasing technological capacity, thus directly benefitting from engineering and data science knowledge and results (the project should be "engineered enough", Figure 1). Moreover, both the identified need and related technological solution



Examples
> 1: pure humanitarianism; e.g., food resource program to a community in need
> 2: pure engineering; e.g., new server farm for an investment bank
> 3: not humanitarian nor engineered: e.g., paint a wall in your house
> 4:humanitarian engineering; e.g., water purification system co-produced with local community

Figure 1. A HEDS solution must be "engineered enough" and "humanitarian enough". Modified after [2].

should originate with the people directly benefitting from any proposed work. Therefore, a deep knowledge of the local context is fundamental, as well as good communication with the beneficiaries.

The taught module aims to train leaders in the development of HEDS solutions/projects, for which Figure 2 provides an oversimplified summary. Many technical and social profiles would benefit from HEDS concepts. Each of those requires different balances of interdisciplinary skills[25,26], (e.g., engineering or data science knowledge, creativity, context analysis, communication, community engagement, ethics, teamwork, leadership) focused on achieving systemic outcomes (i.e., economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability), as opposed to "just" solving a technical problem or "just" engaging with a community to understand their needs and foster their participation. The emphasis of this module is not the training of specialist engineers or data scientists (since this would be more appropriate through an entire university degree) but providing students with the basics of engineering and data science applied to humanitarian contexts and a clear knowledge of the available data sources. The specific goal is to provide HEDS leaders with the required vocabulary to maximise the effectiveness of their interactions with different professional figures and stakeholders (e.g., community members, policymakers, funders), and provide the tools to account for social and cultural interpretations and/or constraints. Such skills are equally important for the success of HEDS projects.

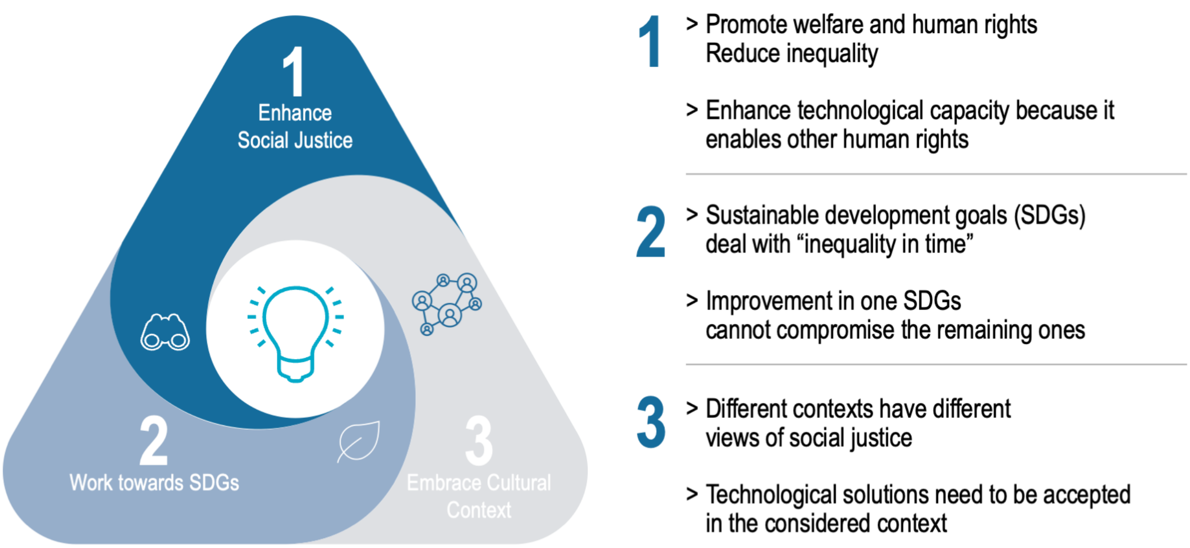


Figure 2. HEDS solutions: a summary.

Module Objectives and Contents

Based on the above definition of HEDS projects, and the aim of the taught module, several objectives are extracted and used as the basis for designing the module contents. Those are summarised in Table 1, referring to a 10-week module with 40 hours of in-person interaction with students. First, introducing data science within the scope of the module generated the need to provide students with basic coding proficiency, which is deemed fundamental to interact in private and public sectors in which data-science applications are now common. Here coding is intended as the process of writing instructions in a particular programming language, and it is a subset of programming, which instead refers to designing, developing, testing, and deploying complex software systems. Given the importance of the topic, half of the lecture time (10, 2-hour sessions) is allocated to coding tutorials. The remaining 10, 2-hour sessions are dedicated to regular lectures.

Type	Topic	Objective
Lecture	Introduction to HEDS	Broadly define HEDS solutions and the factors that influence them
	Poverty and Inequality	Assess poverty in terms of economic, educational, health, and other dimensions. Quantify inequality
	Engineering for Social Justice	Link welfare to human rights, technological capacity, and sustainability. Explore cultural interpretations
	Data Science Fundamentals	Explore data science approaches and establish a solid vocabulary for them
	Prompt Engineering for generative AI	Explore large language models and their vocabulary. Define in detail the structure of effective prompts
	Ethics in Engineering and Data Science	Explore the importance of ethics in engineering and data science. Provide tools to ensure it in HEDS
	Engineering Projects for Community Development	Provide industry-based examples of HEDS projects in different contexts
	Funding of HEDS Projects	Explore the mechanisms to fund HEDS projects with real examples
	Pro-poor, Risk-based Urban Planning	Provide a real example of a research-based HEDS project with a strong impact on communities

Table 1. Module contents.

Type	Topic	Objective
Coding tutorial	Introduction to Python	Provide a gentle introduction to the Python language and the simplest commands
	Data Manipulation and Visualisation	Provide practical tools to enhance the communication of any result
	Scientific Computation	Provide practical tools to perform basic scientific computa-tions on simple data sets
	Prompt Engineering Examples	Explore the effectiveness of different prompting strategies for large language models
	Supervised Learning	Provide practical tools to perform basic data science pro-jects, such as linear regression using a raw dataset
	Coding Drop-in for Class Projects	Provide student-specific feedback and guidance on the code implementation of their coursework
	Virtual Reality for Risk-based Urban Planning	Provide a hands-on experience of how emerging technolo-gies can be used for HEDS projects

Table 1. Module contents.

Since HEDS projects involve welfare, the first objective is to learn how to characterise it, as well as characterise the lack of welfare through poverty and inequality. This is done considering several dimensions of poverty which involve the economic dimension as well as education, health, and social exclusion (e.g., from power or networks). Compound metrics are used (e.g., human development index, World Bank, 2024), also including quantitative definitions of inequality (e.g., Gini Index). A subsequent lecture explores the link between welfare, social justice, human rights, and technological capacity, which allows to interpret such concepts in the context of HEDS. This lecture also explores sustainable development to reduce "inequality over time". The role of cultural values, customs, and interpretations are explicitly considered as part of a successful HEDS project. Context analysis and communication are considered.

The second block of lectures starts with a broad overview of data science, with the specific objective of defining a solid vocabulary that allows future HEDS leaders to effectively communicate with the data scientists in the HEDS team. The lecture involves definitions of algorithms, models, machine learning (supervised and unsupervised), deep learning, big data, and artificial intelligence, providing clear examples for those. TheClearly, the mathematical definitions of those are not covered, except for a simple implementation of supervised learning. The subsequent lecture involves generative AI, with specific reference to large language models and the so-called prompt engineering (i.e., the “art” of asking the right question to get the best output from large language models). The final lecture of this block provides a detailed description of ethics. First, ethics is defined within engineering, considering different codes of practice in different countries (e.g., [28], [29], and their common principles related to honesty and integrity, respect for the public good, accuracy and rigour, effective leadership and communication. Ethics is then defined for data science (e.g., [30], [31], [32], [33], [34], where tentative guidelines of practice are more recent and less established. Their shared principles are described: non-maleficence, responsibility/accountability, transparency and explainability, fairness, and respect for human rights.

The final block of lectures starts referring to practical issues in HEDS, such as project funding and management. This is done involving industrial and/or NGO players, who occasionally participate as guest lecturers. Such interactions promote awareness of current societal issues and their connections to academic areas. The subsequent two lectures involve real case studies. The first draws from the NGO sector, involving a selected guest lecturer different each year. The second draws from the research sector, and it is led by the module leader. This involves a pro-poor, risk-based urban planning methodology[35] developed within the Tomorrow’s Cities research project (tomorrowscities.org, last accessed November 2024) and deployed in 10 Global South contexts. The methodology moves beyond exclusively analytical approaches to disaster risk assessment, embedding such quantitative tools within a broader procedural framework for multi-stakeholder engagement with a participatory approach to risk-informed decision-making (i.e., impact metrics are driven by the needs and aspirations of the considered stakeholders).

Half of the module involves coding tutorials using Python (python.org, last accessed November 2024), a particularly spread, open-access language. Every module week includes one lecture and one tutorial, and the coding tutorials are aligned as much as possible with the contents of the lectures. The tutorials are conducted in a classroom providing every student with a machine equipped with a Python integrated development environment. A lecturer and a teaching assistant constantly pause the activities to provide individual support to students. The tutorials (with contents available at github.com/robgen/HEDSpython, last accessed November 2024) are aimed at students with no previous coding background, and therefore they start with a gentle introduction to coding, together with the most basic concepts and commands involved in it. Subsequently, the tutorials involve data manipulation methodologies (e.g., handling tabular data), and visualisation techniques involving different plots and dashboards. Further tutorials involve tools for basic scientific computations and a full implementation of a simple data science project involving the cleaning of a raw dataset and its analysis through a supervised learning algorithm. A further session involves exploring different techniques of prompt engineering, which aids students in interpreting unknown coding commands and debugging the code they need for their coursework (described in the section “Module Assessment”). To assist students through their coursework development, at least two sessions involve providing them with individual feedback and guidance on the code implementation they chose for their coursework. The final tutorial session looks beyond simple coding and allows students to experience how innovative technologies can be embedded into HEDS projects. This involves a hands-on experience of using virtual reality sets to simulate the pro-poor, risk-based urban planning methodology they learned in their last lecture.

Module Assessment

The assessment for this module is aimed at testing: 1) the ability of students to engage in multi-interdisciplinary teamwork to satisfactorily identify opportunities for HEDS projects and device reasonable conceptual solutions accounting for the specific needs and views of an imagined social context; 2) their ability to analyse a small portion of the larger conceptual solution and their ability to implement a small component of it through a data science method. The first point is assessed through a group presentation. The second portion of the assessment involves an individual report (~1000 words) in which each student selects a specific component of the conceptual project defined in the group work, and provides a

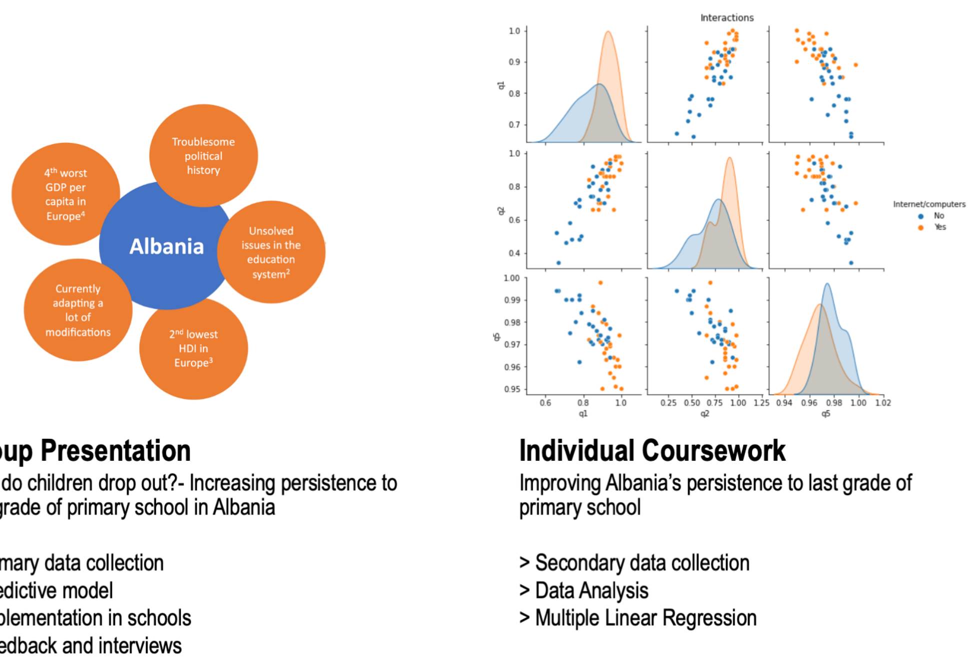


Figure 3. Example of coursework involving a group presentation and individual report (Courtesy of Kaja Adamczyk).

simplified implementation of it, including a code implementation. Figure 3 shows the details of an example of coursework, considering both the group presentation and individual report.

For the first coursework, groups of students will provide a short oral presentation related to a conceptual application of a data science technology to the humanitarian context. The topic is selected by the groups with help and continuous feedback from the module leader. No Python implementation is required at this stage. The presentation normally covers: 1) the motivation for the study; 2) a description of the community to serve (including poverty measures); 3) The motivation for selecting a specific data science technology; 4) the methodology adopted to have the active participation of the community; 5) the ethical implications of the studied application, and the proposed approach to minimise those; 6) the sustainability implications of the studied application, and the proposed approach to minimise those; 7) the key performance metrics of the application; 8) a discussion on similar real projects; 9) the selection of one or more specific parts of the application to be further developed in the subsequent individual coursework. The specific learning outcomes of the first coursework include: subject-specific knowledge - basic principles of data science applied to humanitarian contexts, basics of a selected data science technology studying its existing applications in humanitarian contexts; intellectual, academic and research skills - read, analyse, and reflect critically on the writings and presentations, discuss a humanitarian topic using a common language across disciplines, adopt an multidisciplinary interdisciplinary holistic approach to analysing evidence and forming a point of view, perform basic data analysis; practical and transferable skills - demonstrate an appropriate awareness of an audience in the presentation of research findings, express arguments clearly and fluently, use visual aids to enhance communication, work across traditional disciplinary and sector boundaries, defend an independent point of view in argument, manage time and work to deadlines, appraise and assess the quality of their colleagues' project work and reflect upon their own experiences.

The reports referring to the second coursework usually involve: 1) a background analysis of the selected case study area and community, both qualitatively and quantitatively, using any publicly available dataset; 2) general details of the conceptual implementation discussed in the group presentations; 3) details of the envisioned methodology, required team/expertise, work plan, measurable objectives, ethical issues; 4) a "market" analysis discussing the strength and weaknesses of similar real applications (if existing), e.g., applying similar methodologies to other case-study areas/communities; 5) identification of one component of the conceptual methodology to implement using data science techniques. This can be the data gathering/analysis of a specific dataset or the application of a simple machine learning algorithm (supervised or unsupervised) to a specific dataset. The specific learning outcomes of the second coursework include: subject-specific knowledge - apply basic principles of data science in relation to humanitarian contexts; adopt data science approaches to analyse and help tackling a humanitarian topic; plan and design a solution to a humanitarian data science problem; assess alternative design strategies in terms of economic, social, and environmental factors and justify design in terms of these factors; explain how to gather, manipulate, and extract information from data; develop basic skills in design including creativity and sketching and apply these skills to a specific design problem; intellectual, academic and research skills - read, analyse, and reflect critically on the writings, presentations, and code implementation of those in the field of humanitarian engineering and data science; discuss and debate the most effective data science means of dealing with a specific humanitarian problem; identify, locate, and select appropriate sources of data and interpret and use these to describe the issues facing a given community; perform basic data science analyses; demonstrate basic proficiency in Python programming; practical and transferable skills - demonstrate awareness of an audience in the presentation of research findings and communicate information, ideas, problems and solutions to both specialist and non-specialist audiences; express arguments clearly and fluently, enhanced by visual aids; work across traditional disciplinary and sector boundaries; use and improve negotiation, professional communication, presentation, planning, design, management, research, and analysis skills.

Lessons from Past Deliveries

This module has been delivered (as an optional, 2nd year undergraduate module) in the academic years 2022/2023 (~15 students) and 2023/24 (~35 students). This allowed collecting student feedback to analyse the strengths of the module, the challenges students face, and accordingly design slight modifications of the module. The feedback from students has been generally positive, with very high satisfaction in terms of the contents and the delivery. This is demonstrated by several requests for additional readings, which in the second year were provided to students every week. Another positive aspect to consider is the strong interest in the practicality of the taught concepts and their connection with real-life applications, especially considering the introduced case studies (both industry-based and applied research-based). Students were highly interested in coding, asking to gain more knowledge about it and more optional coding exercises. Students appreciated the link between lecture contents and the coding tutorials and particularly enjoyed having individual support and feedback for their coursework. This result was reasonably surprising for at least two reasons: 1) almost all students had no previous coding experience and most of them came from social sciences and humanities backgrounds; 2) many students also openly shared that coding was the component of the module representing their biggest challenge.

A particular example of this challenge refers to data science concepts that are so bound to the specific dataset they are applied to that they are hard to explain in abstract form. One such example is data cleaning, which is the process of detecting, correcting, or removing errors and inconsistencies in data to improve its quality, accuracy, and reliability for analysis (e.g., removing rows of a table that contains empty cells, or substituting empty cells with a neutral value, e.g., a zero or a one). In the second year of delivery, this led to removing some of the example problems considered in the tutorials and allocating that time to individual feedback sessions. This allows to provide students concrete rather than abstract feedback, which is communicated more directly. A further challenge involves handling mathematical formulations. Although the module does not include detailed mathematical derivations, one specific example of this challenge involves the formulation to calculate the Gini coefficient. In the second delivery year, in-class, step-by-step exercises were added to improve such delivery, with comparatively fewer students flagging the same issue (although the cohort had more than doubled in size). A final challenge involves the reasonably non-standard nature of the coursework, which involves students defining the specific HEDS solution to analyse. In the second delivery year, a student from the previous cohort was invited to present their coursework to the class, providing a tangible example for students.

Conclusion

This chapter discussed the undergraduate taught module Humanitarian Engineering and Data Science (HEDS), proposed within the interdisciplinary undergraduate degree Global Humanitarian Studies, offered by the Department of Risk and Disaster Reduction (University College London). Compared to other modules worldwide, HEDS is characterised by three specific points: 1) it includes data science in the learning experience, based on the assumptions that this can be considered part of engineering, and acknowledging the exponential increase in data-driven technologies worldwide; 2) it targets undergraduate students of an interdisciplinary degree, rather than targeting engineering or data science students with specific technical knowledge; 3) it includes a bottom-up learning approach including implicit-to-explicit understanding based on student-specific practical coursework that allows general knowledge to be inferred from context-specific case studies.

The module aims to train leaders in the development of HEDS projects. Many technical and social profiles would benefit from HEDS concepts. The emphasis of this module is to provide students with the basics of engineering and data science applied to humanitarian contexts and a clear knowledge of the available data sources. This is done by balancing interdisciplinary skills such as engineering or data science knowledge, creativity, context analysis, communication, community engagement, ethics, teamwork, and leadership. The specific goal is to provide HEDS leaders with the required vocabulary to maximise the effectiveness of their interactions with different professional figures and stakeholders (e.g., community members, policymakers, funders), and provide the tools to account for social and cultural interpretations and/or constraints. Such skills are equally important to the success of HEDS projects.

Through the adopted delivery approach and coursework, the module allows students to satisfactorily achieve the set learning objectives related to subject-specific knowledge, intellectual, academic and research skills, and practical and transferable skills. Students can plan and design a solution to a humanitarian data science problem; assess alternative design strategies in terms of economic, social, and environmental factors and justify their designs in terms of these factors. They develop basic skills in design including creativity and sketching and apply these skills to specific design problems. They can read, analyse, and reflect critically on the writings, presentations, and code implementation as well as discuss and debate their solution and selected sources of data. Finally, students were asked to express arguments clearly and fluently, work across traditional disciplinary boundaries, and use negotiation and professional communication.

The main teaching challenge for this module is related to the need to teach basic coding to an inherently diverse student cohort characterised by different backgrounds and amounts of previous technical knowledge. Although students were highly interested in coding, asking to gain more knowledge about it and more optional coding exercises, many of them also openly shared that coding was the component of the module representing their biggest challenge. According to a limited, 2-year experience in delivery, the most effective solution to this challenge is to introduce sessions where students get individual support and feedback on coding they have developed. Satisfactory students' performance in the coursework, which involves a simple code implementation, indicates that having reasonable expectations (based on the students' starting point), and providing individual support, allow them to overcome the above challenge.

Future research should investigate the above challenge further, both providing more empirical evidence and adopting specific theoretical frameworks for its interpretation. Similarly, the proposed solution involving a more extensive use of individual feedback sessions should be further investigated and tested.

Ethics

The adopted anonymised student feedback data has not been collected within this study, but within a departmental survey compliant with the ethical procedures of University College London. Since such data qualifies as secondary in the context of this study, no further ethical approval was needed.

Conflict of Interest

The author declares no conflicts of interest.

References

1. A. Stevenson and C. A. Lindberg, Eds., *New Oxford American Dictionary*. Oxford University Press, 2010. doi: 10.1093/acref/9780195392883.001.0001.
2. K. Passino, *Humanitarian Engineering: Advancing Technology for Sustainable Development*. Columbus, OH, USA: Bede Publishing, 2016. (CC-BY license)
3. L. Sarno and M. P. Taylor, "Purchasing power parity and the real exchange rate," *IMF Staff Papers*, vol. 49, no. 1, pp. 65–105, 2002, doi: 10.2307/3872492.
4. World Bank, "Understanding Poverty." [Online]. Available: https://www.worldbank.org/en/topic/poverty/overview
5. A. K. Sen, *The Idea of Justice*. Harvard University Press, 2009, doi: 10.4159/9780674054578.
6. T. H. Colledge, "Convergence: Philosophies and pedagogies for developing the next generation of humanitarian engineers and social entrepreneurs," *International Journal for Service Learning in Engineering*, p.24, 2012.
7. C. Mitcham and D. Muñoz, *Humanitarian Engineering*. Cham: Springer International Publishing, 2010, doi: 10.1007/978-3-031-79964-8.
8. J. Mair and I. Martí, "Social entrepreneurship research: A source of explanation, prediction, and delight," *Journal of World Business*, vol. 41, no. 1, pp. 36–44, 2006, doi: 10.1016/j.jwb.2005.09.002.
9. V. Seghal, K. Dehoff, and G. Paneer, "The importance of frugal engineering," *Strategy + Business*, vol. 59, pp. 1-5, 2010.
10. A. Y. Kolb and D. A. Kolb, "Experiential learning theory," in *Encyclopedia of the Sciences of Learning*, Boston, MA: Springer US, 2012, pp. 1215–1219, doi: 10.1007/978-1-4419-1428-6_227.
11. A. R. Bielefeldt, M. M. Dewoolkar, K. M. Caves, B. W. Berdanier, and K. G. Paterson, "Diverse models for incorporating service projects into engineering capstone design courses," *International Journal of Engineering Education*, vol. 27, no. 6, pp. 1206 – 1220, 201.
12. Colorado School of Mines, "Humanitarian Engineering." [Online]. Available: https://humanitarian.mines.edu
13. IRIS Sup, "Humanitarian Manager." [Online]. Available: https://www.iris-sup.org/formation/manager-deprogrammes-internationaux-humanitaire-et-developpement
14. University of New South Wales, "Humanitarian Engineering." [Online]. Available: https://www.unsw.edu.au/engineering/study-with-us/study-areas/humanitarian-engineering
15. University of Warwick, "Humanitarian Engineering." [Online]. Available: https://warwick.ac.uk/fac/sci/eng/postgraduate/humanitarianengineering

16. C. Hayashi, “What is Data Science ? Fundamental Concepts and a Heuristic Example,” in *Data Science, Classification, and Related Methods*, 1998, in Studies in Classification, Data Analysis, and Knowledge Organization, pp. 40-51, doi: 10.1007/978-4-431-65950-1_3.
17. W. S. Cleveland, “Data science: An action plan for expanding the technical areas of the field of statistics,” *International Statistical Review*, vol. 69, no. 1, pp. 21–26, 2001, doi: 10.1111/j.1751-5823.2001.tb00477.x.
18. R. Kohavi, R. Longbotham, D. Sommerfield, and R. M. Henne, “Controlled experiments on the web: survey and practical guide,” *Data Mining and Knowledge Discovery*, vol. 18, no. 1, pp. 140-181, 2008, doi: 10.1007/s10618-008-0114-1.
19. D. Sculley et al., “Machine learning: The high-interest credit card of technical debt,” in *SE4ML: Software Engineering for Machine Learning* (NIPS 2014 Workshop), 2014.
20. Y. LeCun, Y. Bengio, and G. Hinton, “Deep learning,” *Nature*, vol. 521, no. 7553, pp. 436–444, 2015, doi: 10.1038/nature14539.
21. T. Hastie, R. Tibshirani, and J. Friedman, *The Elements of Statistical Learning*. New York, NY: Springer, 2009, doi: 10.1007/978-0-387-84858-7.
22. W. B. Stanley, R. C. Mathews, R. R. Buss, and S. Kotler-Cope, “Insight without awareness: On the interaction of verbalization, instruction and practice in a simulated process control task,” *The Quarterly Journal of Experimental Psychology Section A*, vol. 41, no. 3, pp. 553–577, 1989, doi: 10.1080/14640748908402382.
23. Penn State University, “Humanitarian Engineering and Social Entrepreneurship.” [Online]. Available: https://www.hese.psu.edu
24. Stanford University, “Design for Extreme Affordability.” [Online]. Available: https://extreme.stanford.edu
25. U.S. Department of Labor, “Gartner Top Technology Trends 2023 in K-12 Education,” 2023. [Online]. Available: https://www.gartner.com/en/information-technology/insights/top-technology-trends/top-technology-trends-k12education
26. USA National Academy of Engineering, *Educating the Engineer of 2020*. Washington, D.C.: National Academies Press, 2005, doi: 10.17226/11338.
27. World Bank, “Human Development Index.” [Online]. Available: https://hdr.undp.org/data-center/human-development-index#/indicies/HDI
28. European Council of Engineers Chambers, “Code of Conduct for European Chartered Engineers,” 2008. [Online]. Available: https://www.ecec.net/fileadmin/pdf/ECEC-Code-of-Conduct.pdf
29. UK Royal Academy of Engineering, “Statement of Ethical Principles for the Engineering Profession,” 2005. [Online]. Available: https://www.engc.org.uk/media/2334/ethical-statement-2017.pdf

30. A. Jobin, M. Ienca, and E. Vayena, "The global landscape of AI ethics guidelines," *Nat Mach Intell*, vol. 1, no. 9, pp. 389–399, 2019, doi: 10.1038/s42256-019-0088-2.
31. European Commission, "Ethics Guidelines for Trustworthy AI," 2018.
32. University of Helsinki, "Ethics of AI." [Online]. Available: https://ethics-of-ai.mooc.fi
33. Google, "Responsible AI Practice." [Online]. Available: https://ai.google/responsibility/responsible-aipractices
34. Microsoft, "Microsoft AI Ethics." [Online]. Available: https://www.microsoft.com/en-us/ai/responsible-ai?activetab=pivot1%3aprimaryr6
35. G. Cremen et al., "A state-of-the-art decision-support environment for risk-sensitive and pro-poor urban planning and design in Tomorrow's cities," *International Journal of Disaster Risk Reduction*, vol. 85, 2023, doi: 10.1016/j.ijdrr.2022.103400.

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A Reflection on Earthquake-Resistant Design in Architectural Education: A few Suggestions

Mauricio Morales-Beltran[1]

The premise that schools of architecture located in seismic-prone countries should provide instruction on earthquake-resistant design seems valid. The fact that most are not doing so is not only dangerous but also an inconsistent approach. The disastrous effects of recent earthquakes worldwide serve as proof that more holistic approaches are needed—in which not only engineers, but especially architects, play a fundamental role. But how do we teach architects about principles that have traditionally been taught by and to engineers? This chapter reflects on key points related to educating architectural design students on earthquake-resistant design and offers suggestions for teaching strategies that effectively engage students, in both design studios and lecture-based courses. Ultimately, this chapter aims to identify new avenues for seismic design education and disseminate best teaching practices in architectural education.

Keywords: Seismic design, Architectural education, Seismic resilience, Teaching methods

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Why teaching architects about seismic design?

The major argument for educating architects on seismic design is that architectural decisions significantly impact the seismic performance of buildings[1,2,3,4,5]. Inadequate conceptual design and poor detailing of building elements by architects can hinder structural and construction engineers' ability to incorporate effective earthquake resistance measures[1,3,6]. Failing to ensure seismic resilience could lead to severe building damage and, in the worst cases, loss of life during earthquakes. Consequently, architects have a critical responsibility to ensure the safety of building occupants, particularly in regions prone to seismic activity. Compliance with local seismic codes is not only a safety measure but also a legal requirement in many earthquake-prone countries, such as Türkiye, New Zealand, Japan, USA, and Chile. Professional organizations for architects in these countries—such as the Chamber of Architects and Engineers of Türkiye, the New Zealand Registered Architects Board, the Architectural Institute of Japan, the American Institute of Architects, and the Association of Architects of Chile—publish and regularly update ethical codes that govern architects' professional conduct and responsibilities to society. These ethical guidelines emphasize the importance of seismic resilience in building designs, making it essential for architects to incorporate these standards into their work[7]. Furthermore, architects involved in building inspections need to be equipped not only with the necessary knowledge in the relevant codes and standards to ensure compliance, but also with comprehensive knowledge of how regulations should be interpreted and applied during both the architectural design and construction phases. Building inspections, particularly in seismic regions, serve as a proactive measure to evaluate and improve the structural integrity of buildings, ultimately promoting earthquake resilience. In this context, professional architects play a key role in the creation of earthquake-resistant environments[8].

Architects also play a central role in project conceptualization, planning, and execution, by coordinating professionals from various disciplines[3]. While each construction professional is responsible for their own area of expertise, having a good understanding of how to integrate these fields is crucial for the architectural profession, especially in seismic regions[6]. Architects and civil engineers, in particular, must share design responsibilities, which requires a basic understanding of both disciplines to communicate effectively and collaborate. Although architectural design and structural system design are often considered as the domains of two distinct professions, these processes are inherently interconnected and serve the same goal. Yet, as the primary designer of the building, it is particularly the architect's responsibility to bridge this gap from the initial draft onward[9].

Engineering alone cannot prevent disasters

Successful disaster-prevention strategies require architects. When Takagi and Wada[10] state that "the development of seismic engineering technologies will never eliminate earthquake disasters," they are acknowledging that creating resilient building structures for large earthquakes requires more than just engineering solutions—it must also address societal needs. Architecture, as a discipline, inherently adopts a holistic approach, enabling and demanding architects to account for all aspects of a building's design, including those related to the society they will be part of. This is because architects have a social responsibility to ensure that all communities—particularly vulnerable populations in earthquake-prone areas—have access to safe and affordable housing; Architects are also tasked with effectively communicating seismic-resistant strategies to building owners and community leaders. In post-disaster contexts, architects are vital in rebuilding safer, more resilient communities by applying seismic design principles to prevent future devastation. Even when retrofitting heritage structures, architects must balance seismic safety with the preservation of local cultural traditions[11].

Many advantages emerge from understanding seismic design as part of a holistic strategy, which includes not only societal needs but also cultural expressions. From an architectural point of view, seismic design can be integrated at a social level by increasing community awareness and promoting local identity[12]. In this sense, an architectural design that incorporates seismic principles from the outset not only meets the performance standards specific to a location but also fosters a sense of identity within the community where the building is situated. Bankoff[13] discusses the concept of "seismic architecture" as a cultural adaptation to earthquakes and thus provides a clear example of how culture is inextricably linked to disaster risk management. This is evident not only in the practical measures taken to address hazards but also in the long-term educational transmission of knowledge through heritage. Bankoff's historical review of case studies shows that seismicity is typically one of many factors influencing structural forms and construction techniques over time. Architecture in seismically active regions in the past often blended aesthetics with practical earthquake-resistant measures, creating designs that were, in essence, "inspired" by the threat of disasters. Furthermore, evidence suggests that, in many cases, the entire fabric of the urban environment could be restructured to better mitigate the risk of earthquakes[13,14,15].

Architects are responsible for designing public open spaces, which are considered key elements of seismic resilience at the urban level. In the aftermath of major earthquakes, public open spaces become hubs for both short-term disaster response and long-term recovery efforts[16]. During such events, public spaces play a critical role not only in the emergency phase but also in the reconstruction phase. Streets and squares serve not only as temporary shelters but also as strategic points for food distribution and organizing reconstruction activities[17]. However, few open spaces are specifically designed to support these intermittent yet critical uses[16,18]. Allan and Bryant[19] argue that successful integration of recovery planning and urban design requires a shift in perspective—seeing a city's open spaces as a "second city," a network of spaces designed not only to enhance everyday urban life but also to serve as vital life-support systems and agents of recovery in the event of an earthquake. In a review conducted by French et al.[16], various ways landscape architects and other professionals in related design fields can proactively plan and design open spaces to support seismic resilience are highlighted.

Changes in current seismic engineering philosophy

Another reason to encourage earthquake-resistant design in architectural education stems from the significant changes that seismic design and construction technologies have experienced over the past 50 years. To prevent building collapse during large earthquakes while keeping construction costs manageable, current design and detailing methods allow structures to undergo ductile plastic deformations. This approach means that, although buildings may experience significant damage, they are not expected to collapse[20]. However, it also suggests that entire cities could lose functionality in the aftermath of a major earthquake. Recent large-scale earthquakes have shown that many buildings, despite being well-designed and constructed, were not destroyed but were rendered non-functional (Figure 1), often leading to demolition rather than repair[21,22,23,24]. Given these facts, the seismic design philosophy that emerged in the late 1970s has been gradually reconsidered. The focus of seismic design for buildings and infrastructure is currently shifting from merely saving lives to ensuring business continuity in modern, resilient societies; Structures must be designed to be quickly restored to full operation with minimal disruption and cost following major earthquakes[10]. Beyond ensuring safety, seismic design should also contribute to the sustainability of buildings by reducing the need for costly repairs after disasters and ensuring that critical infrastructure—such as schools, hospitals, and community centres—remains operational during post-earthquake recovery. Well-designed, resilient buildings help mitigate both social and economic disruptions following earthquakes by minimizing the need for extensive reconstruction[10].

This new seismic design philosophy also emphasizes the importance of non-structural components during earthquakes[25]. Non-structural elements include furniture, accessories, and equipment like lighting, elevators, and machinery. However, most of the non-structural components are integral part of the architectural design—for instance, windows, doors, partition walls, suspended ceilings, interior finishes, and stairs—and thus, architects are responsible for their performance during earthquakes. Educational initiatives focused on raising awareness about the hazards posed by non-structural elements are, therefore, highly needed[26]. Furthermore, in order to adopt a minimal disruption approach to seismic design, collaboration between architects and structural engineers is essential.

Figure 1. Buildings in Antakya after Kahramanmaraş Earthquakes in 2023.

Challenges in teaching architecture students

That schools of architecture located in countries with high levels of seismic activity, should provide their students with knowledge and skills to address seismic issues in their projects seems a valid premise. Consequently, one would expect that in countries like Türkiye, which has experienced devastating earthquakes in recent years[21,27,28], teaching seismic design would be widespread. However, by 2020, out of 87 architectural programs in Türkiye, only 30 offered at least one elective course on earthquake-resistant building design, and only four included a compulsory course on the topic[29]. Furthermore, among 13,582 graduate theses completed in 2018, only 74 (0.54%) were related to earthquakes[29]. This low percentage can be attributed to factors such as a lack of awareness among faculty members and an inefficient, centralized decision-making structure. However, there are many challenges in incorporating seismic design principles into architectural education. These challenges can be grouped into practical, conceptual, and methodological. They refer to aspects related to the curriculum, divergent approaches to design in architecture and engineering, and differences in teaching and learning methods between these two disciplines. These obstacles are discussed in the following sections.

Curriculum issues

To introduce the concepts of earthquake behaviour in buildings and integrate them into the architectural design process, changes to the curricula of architecture schools must be addressed first[3]. Given its central place within the architectural curriculum, the design studio offers an effective format for learning how to incorporate seismic design principles into the architectural design process. However, instructors often face challenges in ensuring that seismic design is effectively incorporated into design studios. A well-known obstacle is the perceived reluctance of students and some faculty members to prioritize structural subjects in the curriculum[30]. Often regarded as an "engineering" subject, seismic design remains peripheral to the studio, and is not integrated into the core activity of architectural education: designing[2]. While a fully integrated seismic design and studio course could be the ideal approach[1,2,31], the most common format is using lecture courses to teach earthquake-resistant design to architects. Yet, under pressure to limit the number of credit hours required for an undergraduate degree, instructors who teach earthquake engineering often rely on only a few hours—within one semester—to cover these subjects. This limited time makes it unrealistic to expect students to engage in in-depth lecture activities or undertake extensive studio projects that focus on seismic studies.

Different understanding of "design" in Architecture and in Engineering

Either explicit or implicit, a lack of proper mathematical background is often addressed as one of the major obstacles for architects to embrace the principles of seismic design[1,31]. However, in the author's opinion, this is not the true obstacle but rather an effect of the actual problem: engineers and architects view the act of "designing"—which is central to both disciplines—in fundamentally different ways.

Architecture deals with the production of space. As a design method, architecture pivots on holistic and stochastic approaches, ranging from users' perceptions and functional demands to contextual responsiveness, conceptual narratives to construction details, and innovative uses of technology to environmental and social responsibilities. The overlap with engineering lies in structural engineering, which focuses on the production of building structures. As a design method, structural engineering employs focused and deterministic approaches aimed at delivering safe and functional structures, ideally with optimized use of material and energy resources. While both disciplines converge in the design of buildings, the methods used to reach this convergence seemingly require dissimilar sets of knowledge and skills. Engineers are trained to use methods grounded in scientific principles and technical feasibility. In engineering disciplines, students learn by progressively tackling more complex problem-solving techniques, which rely heavily on mathematical foundations. This is why, for engineers, the manipulation of formulae and equations is indistinguishable from the act of designing structures.

Architecture students, on the other hand, typically have a stronger background in creative design, spatial thinking, and conceptual development rather than in technical subjects as physics, structural mechanics, or material science. Therefore, while architecture students may already struggle to reconcile a gravity-based structural rationale with a spatial-functional-contextual-aesthetic narrative, seismic design imposes an extra layer of complexity on their tasks. Dealing with this additional complexity requires applied knowledge of how earthquake forces impact a building's structural system and how to mitigate those forces through appropriate design and detailing. Understanding these concepts often involves advanced calculations, structural dynamics, and engineering theories, all of which are typically taught in the early years of the engineering curriculum. Consequently, in an attempt to introduce these subjects without overwhelming architecture students, instructors often bypass much of the mathematical and physical abstractions by focusing on software tools and visualization techniques to engage students in structural topics.

From this perspective, it is clear why engineers see that the major obstacle in training architects in seismic design is their limited background in engineering principles, material science, and structural mechanics—and almost none in structural dynamics. However, the underlying issue is that seismic design, as being essentially structural design, is a quantitative process—driven by performance—while architectural design is essentially a qualitative process—driven by creativity. Hence, the reluctance of architecture students to be taught seismic design is not based on a lack of a certain (mathematical) knowledge, but on their perception that introducing seismic design rules into their projects limits creativity and design freedom[2]. Therefore, to create effective learning environments that promote the integration of architecture and structural (seismic) design, both quantitative and qualitative teaching and learning methods are needed[32,33].

Different teaching methods

Given that seismic engineering is taught in engineering schools, it is reasonable to assume that the majority of faculty members teaching seismic design in architecture schools are either seismic engineers or architects with postgraduate studies in earthquake engineering. A consistent assumption is that these faculty members, as instructors, would teach seismic design in a similar way they learned it—this is, through a technical, lecture-based format. However, contrary to this approach, architectural students typically learn best through visual and hands-on teaching methods, commonly based on experimentation, models, visual representation, and reflective practice[4,34,35]. Opposing teaching methods in engineering and architecture can have adverse consequences on student learning and practical preparedness. Thus, instead of remaining separate within architectural curricula, these methods should be integrated into coordinated approaches that align with escalating levels of student expertise, representation, and analysis[36]. This integration should be reflected in teaching strategies that incorporate seismic design within the broader context of architectural design while presenting information at a level of rigor appropriate for architecture students, ideally in a visual format.

In addition to a preferable use of graphic representations, most—if not all—teaching methods supports an early introduction of seismic design principles in the architectural design process. Introducing such principles can be understood as input to the “black box” of the design process, which will eventually produce an outcome—a building. Although this schema may seem obvious and, thus, one could assume that is similarly understood by both architects and engineers, it is actually completely opposite in terms of significance to both process and outcome. Engineers are trained to use heuristic and quasi-deterministic methods for problem-solving. These methods rely heavily on selecting the right inputs to achieve a successful outcome. For a given set of inputs, outcomes will always be the same. In the case of seismic design, the outcome is well-known in advance: a building with adequate seismic resistance capacity. Therefore, the major task for engineers is identifying the correct input parameters for the design, such as the symmetrical distribution of earthquake-resistant elements, avoiding vertical discontinuities, and positioning openings in slabs where they will not jeopardize structural integrity, to name a few. Once these optimal parameters are set, the design process guarantees a successful outcome, because it is based on well-established performance procedures, such as seismic codes.

In contrast, architects think and work differently because they are trained to use stochastic methods for problem-solving. These methods are not aimed at finding optimal outcomes, but rather sub-optimal solutions that satisfy a broad set of requirements in a general way. The advantage—and the main reason these methods are used in architecture—is that they are suitable for dealing with a number of uncertainties in the input data. This perfectly reflects the background scenario of any architectural design project, where the designer must consider a variety of often conflicting inputs, such as social aspects, user preferences, budget, available resources, daylight optimization, legal framework, seismic performance—to name a few. Within this myriad of demands, seismic resistance-related inputs (symmetry, continuity, etc.) remain only part of the overall requirements. As a result, the design process can only guarantee their consideration as part of the solution, which may or may not be optimal in terms of seismic performance. This does not mean that seismic resistance can be compromised by prioritizing other design parameters. Rather, it means that ad-hoc teaching and learning methods are required to successfully introduce seismic design principles into architecture, from the early stages of the design process.

Teaching strategies to introduce earthquake-resistant design into architectural education

Integrating seismic design into studio projects

The most effective way to integrate seismic design techniques into architectural education is through design-based learning, with the design studio providing the ideal setting for students to apply these techniques to real-world architectural projects [2,30,31,33,36]. However, the studio must be supported with complementary strategies to help students overcome the inherent complexity of placing seismic design principles into practice. These strategies include the following:

- Cover basic seismic design principles in prior or parallel courses. While a sequential approach to learning suggests that students should acquire foundational knowledge before engaging in design-based experiences, research shows that running a course on seismic design in parallel with the studio project is often more effective[2]. Either strategy, however, would minimize the impact on design studio time, allowing students to select seismic design strategies that enhance their creativity rather than restrict their design freedom[5,31]. Charleson[31] suggests an alternative approach: the course in which seismic design is taught should base its class projects and assessments on studio projects run prior to or in parallel with it.
- Select studio projects with clear distinction between structural and seismic elements. It is important to choose studio projects where the structural elements used for seismic resistance are distinguishable from those for gravity loading. Takagi and Wada[10] suggest that structural components should play distinct roles, with the primary structure supporting gravity loads and seismic elements primarily designed to resist earthquake forces. Choosing relatively larger projects (~6,000 m^2) is recommended[2], as smaller projects often integrate seismic-resistant systems seamlessly with the vertical structure, making it difficult for students to understand the implications for design. Larger projects also provide an opportunity to address the role of non-structural components in the overall seismic performance.
- Encourage interdisciplinary collaboration. In the studio, students are used to working in a collaborative environment, where feedback and design critiques (or “crits”) from instructors help refine ideas and foster growth. Introducing joint critiques, workshops, or courses with structural engineers can teach architecture students how to integrate seismic constraints without compromising the quality of their designs[37]. This interdisciplinary approach can also be extended to postgraduate courses, where more advanced collaboration on seismic design issues can take place[38].
- Rely on case studies. The examination of case studies and learning from precedents is a standard practice in architectural education. Incorporating case studies that specifically address the integration of seismic design

into architectural projects can effectively raise students' awareness of seismic principles and demonstrate how these principles can be inserted into broader design contexts. Emphasis should be placed on case studies that are recognized for their architectural excellence. For example, Rihal[39] presented a study analysing Nervi's projects, particularly those located in seismic zones, and developed conceptual models to better understand their design processes. This study emphasizes the importance of integrating lessons from the history of structural engineering into the teaching of creative structural design in architecture.

Physical models and prototyping

Along with sketching and drawing, model-making is considered a hands-on, learning-by-doing approach that helps students understand spatial relationships, materials, and proportions. For this reason, physical models are widely used in architectural education. Additionally, structural concepts and principles can be more observable and tangible through the use of physical models, with the advantage that students may pay more attention and show better understanding[40,41]. Moreover, students often prefer learning about structures through model-making experiences rather than through lectures focused on mathematical abstractions[4,5].

Using physical models in combination with shaking tables can help students visualize how seismic forces impact buildings and how design strategies can mitigate these effects. For this reason, shaking tables have been extensively used in the context of engineering education[42]. In architectural education, even a simple handmade shaking table can enhance the overall learning experience, helping students understand earthquake-resistant structural systems, with the added benefit of learning not to repeat design errors that have caused extensive damage to buildings in past earthquakes (Figure 2). While models can be built

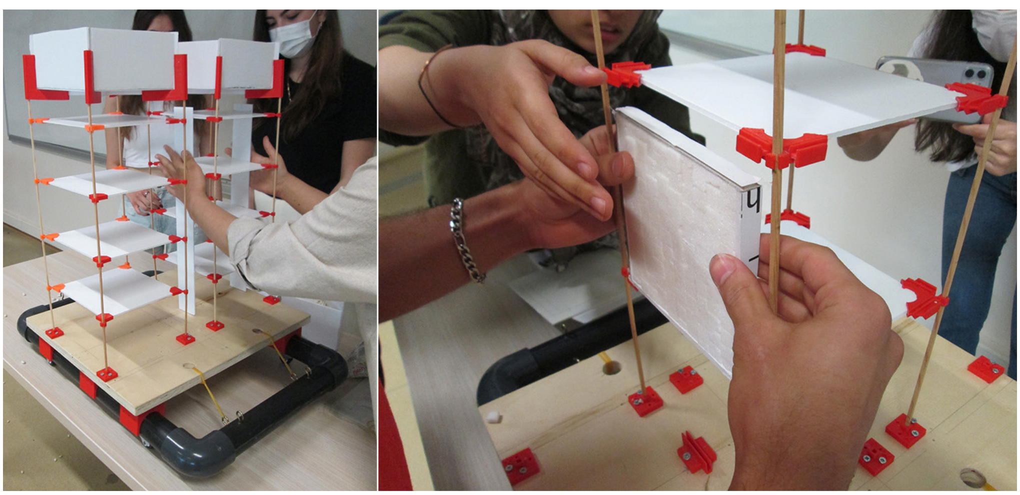

Figure 2. Testing of physical models using a homemade shake table.

using common materials—timber sticks, cardboard, and glue—homemade shaking tables require a more systematic approach, although they can still use fairly inexpensive materials (see [4, 35] for references).

Shaking tables and physical models can also be used during workshops to test preliminary designs and to evaluate successful design strategies for further development. For example, in the workshop described in[43], after testing a few scale models of a tower, students realized that successful designs were those with a wider base area—providing more stability—and with radial symmetry—reducing torsional effects. The use of models in conjunction with shaking tables has also been used as an educational tool to raise seismic risk awareness among the general public, as well as to iteratively demonstrate the physical phenomena that occur during an earthquake and their effects on buildings[35,44].

Although much more complex in terms of implementation and logistics, architecture students can collaborate with engineers to build full-scale prototypes or mock-ups of structural systems (e.g., sections of a braced frame or shear wall). These prototypes allow students to physically interact with the materials and structural details of earthquake-resistant components. An equally challenging yet rewarding approach is the construction of full-scale prototypes in post-earthquake scenarios[45]. Aside from the educational value of prototyping within architectural education[46], the major advantage of these initiatives is not only that the gap between design ideas and real-world implementation is reduced, but that students actively engage in earthquake resilience and risk reduction activities.

Digital tools

While there is plenty of educational software available for teaching engineering students the fundamental concepts of structural dynamics[47,48,49], educational software developed to support the teaching of similar concepts to architects is far scarcer. One plausible reason is that introducing simulation software and structural analysis tools into the architectural curriculum would require a dedicated (structural or technical) course, as modelling even simple systems still requires specific skills and knowledge. Nonetheless, a dedicated software for architects should essentially show how seismic forces affect buildings. Students could then model buildings, apply seismic loads, and visualize how different design decisions influence building performance during an earthquake. This is what Charleson[31] seems to have had in mind when developing RESIST, a software that assists architecture students when designing their studio projects, based on rule-of-thumb guidelines. For a brief overview of web-based educational tools for complementing the teaching of structural dynamics, the reader is referred to[48].

The use of digital tools, such as virtual and augmented reality, can enhance the teaching of architecture students. In recent years, Virtual Reality (VR) has been steadily used in construction engineering training and education[50,51]. VR allows students to immerse themselves in a virtual environment where they can visualize the impact of seismic forces on buildings. Students can use VR to simulate different earthquake magnitudes in their studio design, and understand how varying intensities affect buildings. They can also "walk" through buildings post-earthquake to observe the damage patterns and assess how specific design features mitigate or exacerbate the damage. The implementation of immersive VR-based serious games has been investigated in the context of building evacuation training and research and has been applied to various indoor emergencies such as fires and earthquakes[52]. Augmented Reality tools can superimpose structural data on physical models, helping students see how seismic loads affect their designs in real time[53]. These immersive experiences offer students a tangible way to understand abstract seismic concepts, while also allowing them to modify designs before physical prototyping.

Virtual field trips (VFTs) offer a valuable alternative to traditional field trips, addressing several common challenges such as time constraints, large class sizes, short site visit durations, and difficulties in seeing or hearing in crowded or noisy environments[54]. VFTs can be further enhanced with higher-bandwidth mobile networks and real-time verbal communication between remote participants and in-field livestreaming hosts. Most importantly, compared to traditional media such as photos and videos, virtual field trips provide a richer and more dynamic experience. This enriches each student's understanding of the study area, offering insights into both its biophysical and socio-cultural dimensions[55]. Currently, VFTs are utilized in teaching across various disciplines, including construction[54], STEM disciplines[56], landscape architecture[55], and architecture, engineering, and construction education[57]. Virtual field trips to earthquake-prone regions allow students to observe the performance of real structures and gain insights into the practical application of seismic principles. Visiting areas affected by past earthquakes can also help students understand the social impact of poor or inadequate design. Additionally, virtual field trips to seismically retrofitted buildings can inspire students to apply these strategies in their studio projects, particularly when designing for earthquake-prone areas.

The application of artificial intelligence (AI) techniques, such as deep learning and image processing, can significantly improve decision-making early in the design process, particularly in fields requiring expert knowledge. In architectural projects, for instance, AI's ability to assist in decisions regarding the structural system during the initial phases can greatly enhance the design process[9]. Er Akan et al.[9] proposed an image-classification assistant that mimics how architects learn. This tool could help predict torsional irregularities early in the design by analysing the structural asymmetry in floor plans with deep learning and image classification, allowing potential issues to be identified and addressed. Additionally, AI can be applied to evaluate earthquake risks and identify earthquake-induced damage in buildings by analysing images to detect damage patterns[58].

Educational media

Educational media encompass the use of audio-visual tools for teaching purposes. These technologies are of interest to students because they are familiar with these tools, which easily grab their attention[59]. Among these tools, video has been used for many years to support students' learning in various settings, benefiting from visual materials. These videos can take the form of tutorials on topics such as the behaviour of materials under seismic loads, the use of base isolators, or the analysis of seismic data. Videos can supplement lectures and offer self-paced learning opportunities. Instructional videos can also help introduce complex seismic design principles to non-specialized audiences using customized media and models [35]. Additionally, videos can show how different regions, especially those frequently hit by earthquakes, design for seismic safety. Documentaries about major earthquakes (e.g., Kobe and Haiti), engineering breakthroughs in seismic design, or seismic retrofitting techniques can help students understand the real-world challenges.

While video-based learning strategies can be very effective educational tools, a few key strategies can increase their benefit: signalling with keywords or colour changes to highlight important information[60], and dividing the information into subcategories to make it easier for students to process smaller pieces of information instead of one large topic[61]. Finally, it has been suggested that videos should be kept short to maximize students' interest. Videos of no longer than six minutes are more successful in attracting students' attention[62].

Community engagement

Integrating community-based projects into the curriculum where students collaborate with local stakeholders in earthquake-prone areas, emphasizes designing for social resilience in addition to structural safety. Students can work directly with communities affected by earthquakes to design and implement resilient structures. This might involve participating in post-earthquake rebuilding efforts, designing affordable housing that incorporates seismic safety features, collaborative design activities with communities, or retrofitting existing buildings[63,64,65]. These service-oriented projects allow students to apply their skills in real-world contexts while benefiting communities in need. It fosters empathy, real-world problem-solving, and an understanding of social, economic, and cultural considerations in seismic design[45].

Collaborative workshops with architecture and structural engineers allow architecture students to gain hands-on experience with seismic design tools, materials, and techniques[37]. These workshops can simulate real-world collaboration between architects and engineers. One example, described in[66], takes place annually in India and mimics a typical architectural design studio. In the first one and a half days, students attend lectures, followed by intense hands-on studio sessions where architecture and structural engineering faculty guide students in preparing their design projects. By 2020, more than 700 students from around 55 colleges in India and Nepal had been trained, in addition to around 34 faculty members and professionals who volunteered as resource faculty. Another workshop, Example[43], focused on post-disaster mitigation, challenged architecture students to design a water tower using paper tubes to be deployed in a post-earthquake scenario.

Teaching contents focusing on the effects of seismic forces on structures

From an engineering perspective, the teaching of earthquake-resistant design is inherently linked to the understanding of the phenomena that cause earthquakes. For architects, in contrast, teaching content does not need to explain the causes but should focus on the effects of earthquake forces on structures. An exceptional example is the design of the Imperial Hotel by Frank Lloyd Wright, completed in Tokyo in 1921. According to Kelly[67], Wright was possibly the first person to apply the concept of seismic isolation in a building. The famous architect's intuitive idea of floating the building "as a battleship floats on the ocean" appears to have worked. Kelly states that the completed project was:

> **"[...] in complete contrast to accepted practice at the time and was extremely controversial. Under the site was [a 2,4 m] layer of fairly good soil and below that a layer of soft mud. This layer appeared to Wright as 'a good cushion to relieve the terrible shocks. Why not float the building on it?' [Wright 1977][1]. He tied the building to the upper layer of good soil by closely spaced short piles that penetrated only as far as the top of the soft mud. The building performed extremely well in the devastating 1923 Tokyo earthquake. It was a very highly decorated building with appendages of many kinds, and buildings of this sort generally are badly damaged in earthquakes. The only damage was to statuary in the courtyard of the hotel." [67]**

1. Wright, F. L. (1977). Frank Lloyd Wright: An Autobiography. Horizon Press, New York

The point here is not the cleverness of Wright's intuitive approach, but the fact that, to reach this solution, he did not need inputs from soil mechanics—which became an engineering discipline around the 1920s[68], by the time the hotel was being built—or from the theory of tectonic plates, which was only formulated in the 1960s[69]. It can be argued, though, that Wright was an exceptional architect, and thus this case cannot be generalized to all architects, much less to students of architecture. However, it is a fact that in terms of conceptualization and methodology, architectural design as taught in schools of architecture is closer to Wright's design approach than to any approach used in teaching earthquake engineering.

Lecture contents

Whether a lecture course is run in conjunction with a design studio or as a standalone class, a course on earthquake-resistant design for architects should cover a range of topics that provide both theoretical knowledge and practical application. The key components that must be taught to architects include:

- Earthquake-resistant design incorporates vertical structures designed to provide stiffness and resistance to lateral forces, while preventing excessive deformations and collapse. The most common systems include shear walls, braced frames, and moment-resisting frames (Figure 3).
- Avoiding torsional movement and irregular geometries: Symmetric building designs generally perform better during earthquakes. An asymmetric design can cause torsional effects, where the building twists as it moves, thereby increasing the likelihood of damage.
- Continuous load path: It is essential to ensure that the seismic forces are transferred from the building's roof to the walls and foundation. This means that every structural element should be connected and designed to work together to safely transfer forces.
- Redundancy: A building should have multiple paths for distributing seismic forces. If one part of the structure fails, the other parts should still be able to carry the loads and prevent total collapse.
- The role of non-structural components: Furniture, accessories, equipment and architectural components—such as partition walls, ceiling, and finishing—must be designed to prevent users' injuries and mitigate the risk of interrupting building's serviceability.

Depending on specific cases, architects may need to understand more advanced aspects of earthquake-resistant design. Additional topics include:

- The role of the foundation: The foundation of an earthquake-resistant building anchors the structure and transfers seismic forces into the ground without failure or settlement.

- Base isolation: This technique separates the building from its foundation using flexible bearings or isolators, minimizing the amount of seismic energy transferred to the building.
- Damping systems: These systems help absorb and dissipate the energy generated by seismic forces, thereby reducing the amplitude of the building's vibrations. Types of damping systems include viscous dampers, tuned mass dampers (TMD), and friction dampers.
- Seismic retrofitting: This refers to the process of strengthening existing buildings to enhance their earthquake resistance. Environmental protection demands the retrofit of existing buildings that not only extends their service life but also reduces energy consumption and carbon emissions[70].
- Building codes: Standards such as Eurocode 8 and the Turkish Earthquake Code (TEC) are based on seismic zone mapping and provide guidelines for designing buildings that can withstand earthquakes of various magnitudes.

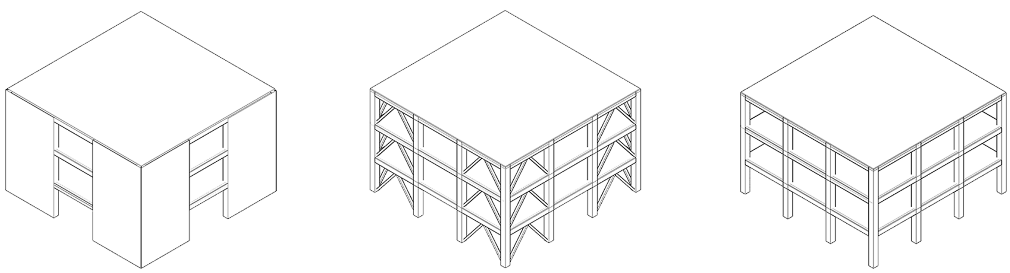

Figure 3. Typical seismic resistant systems, symmetrically placed on the corners of the building example.

Table 1 outlines suggested topics for a course intended to equip architects with the skills to integrate seismic design principles into their projects while maintaining architectural integrity. Further descriptions are provided in Appendix.

Lecture topics	Minimal	Ideal	Full
Nature of earthquakes and ground motions	—	x	x
How buildings resist earthquakes	x	x	x
Earthquake-resistant structural systems (shear walls, braced frames, moment frames; role of diaphragms)	x	x	x
Building configuration (torsion, soft stories and other issues)	x	x	x
Non-structural elements (that affect structure and others)	x	x	x
Advanced technologies (base isolation and energy dissipation)	—	x	x
Urban planning and regulations	—	x	x
Seismic retrofitting	—	—	x
Foundations and geotechnical issues	—	—	x
Total	4	7	9

Table 1. Suggested seismic design course contents for minimal, ideal, and full input (based on [31]).

Configuration principles

In the 1980s, Arnold and Reitherman, among others, highlighted the importance of early architectural decisions on building performance during earthquakes, introducing the concept of "configuration" [71]. Initially, the term referred to a building's "form," which, in Arnold's view[72] encompassed not only the structure—whose logic was often absent in the architecture he discussed—but also non-structural components and any other elements resulting from architectural design choices. As this concept began to influence seismic guidelines for architects, the meaning of "configuration" evolved. It came to refer more specifically to the organization of volumes and their translation into structural systems. Consequently, later studies and guidelines began using "configuration" to describe a building's form in relation to its structural elements, while separate guidelines were created to address non-structural components in a seismic context[73,74].

This shift was not a deliberate decision but rather a reflection of the architectural design process. In many architectural projects, the initial design is conceived as a series of volumes—three-dimensional geometries organized by a particular pattern (or lack thereof)—and placed in a specific location. The reasons behind the specific volumes are not central to this argument, but this top-down approach is a fundamental part of architectural design. In architectural education, the term "volumetric model" is often used in studio settings to describe an early design proposal, which will be refined and detailed through an iterative process. As such, the idea of "configuration" aligns well with the concept of early volumetric proposals in architecture.

By manipulating the geometry and formal composition of a building, architects use configurations to create spatial relationships in a qualitative manner, without necessarily determining the precise dimensions of each element. This distinction between structural and architectural configuration suggests that, in teaching architecture, seismic design should be introduced as a set of principles that govern the geometric properties of a building's form to provide it with basic earthquake resistance. The advantage of this approach is that the use of seismic design principles—rather than rigid seismic design criteria—aligns with the qualitative and holistic nature of early-stage architectural design. While still generic, these early building configurations incorporate seismic design principles while allowing for further manipulation of the form. As the design progresses, architects refine the configuration, and seismic engineers can then provide the necessary sizes and specifications for seismic-resistant elements.

In architectural terms, the core design principle for seismic-resisting buildings is that their configurations must ensure symmetry and continuity in the distribution of seismic-resistant elements. Specifically, the building configuration should feature:

- a symmetrical building configuration. Buildings with irregular shapes—such as those with re-entrant corners or significant offsets—are more prone to uneven seismic load distribution. These irregularities can cause stress concentrations, which make certain parts of the building more vulnerable to damage. Seismic joints (gaps) can be used to separate irregular building forms (Figure 4).

- a symmetrical distribution of seismic-resistant elements. Torsional

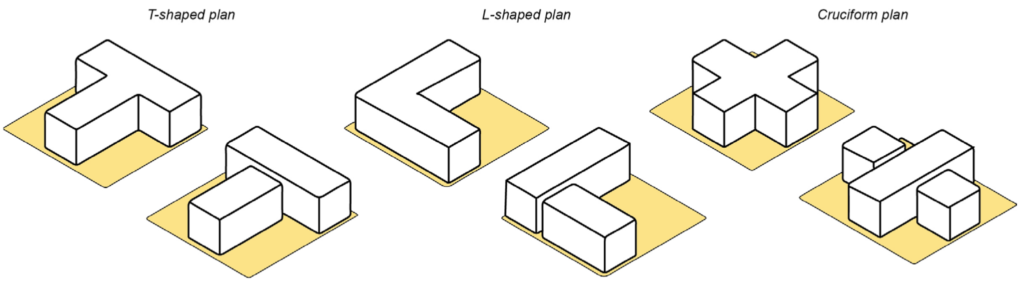

Figure 4. Common irregular configurations (re-entrant corners) and possible solutions using seismic gaps.

irregularities, where the centre of mass (CoM) and centre of rigidity (CoR) are not aligned, can severely reduce a building's seismic performance[75]. This misalignment causes uneven stress distribution, leading to potential damage during an earthquake. Extreme plan eccentricities, as shown in Figure 5, result in pronounced torsional effects, which should be addressed in the early stages of the design. Torsional resistance can be improved by strategically placing seismic-resistant elements at the perimeter of the building (Figure 6). Although minor eccentricities are inevitable, undesirable torsional effects can be minimized by carefully planning the distribution of seismic-resistant elements in the architectural layout[12,76].

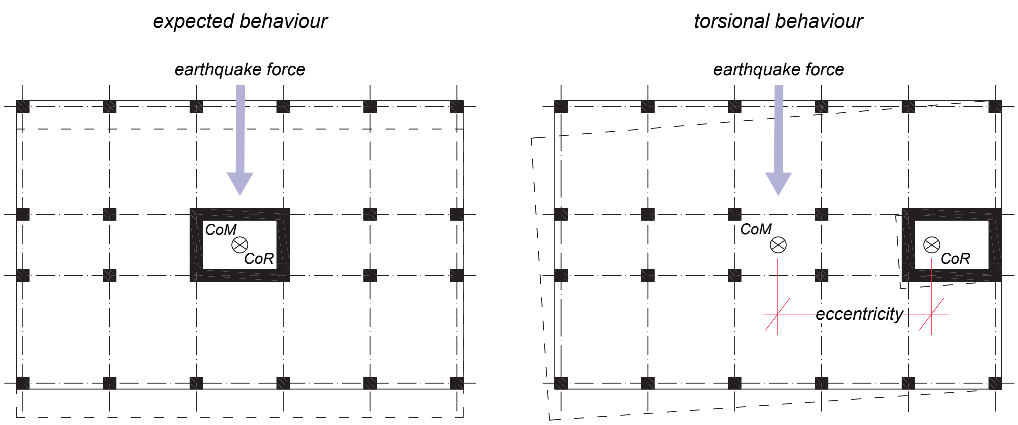

Figure 5. Different expected and torsional behaviour of a building based on its plan eccentricity (distance between CoM and CoR).

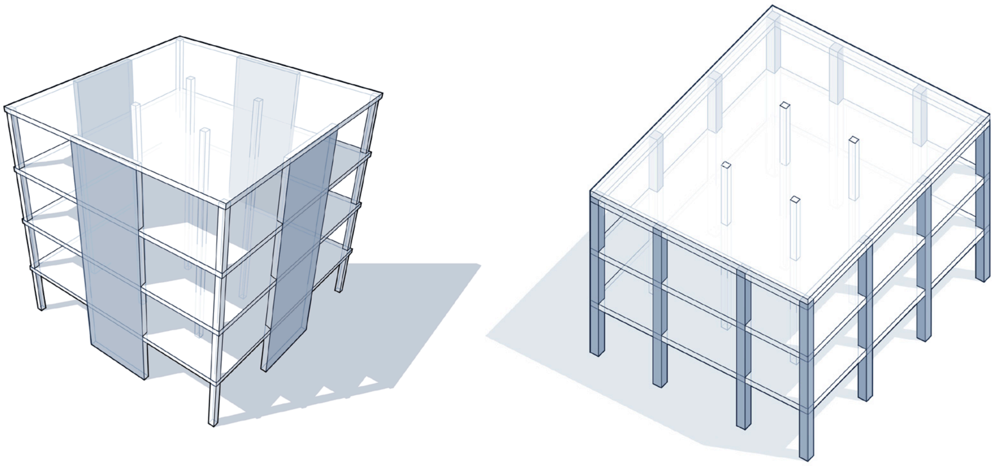

Figure 6. Examples of regular and symmetrical configurations.

- horizontal continuity of diaphragms (floor and roof structures). Ensuring a continuous load path is crucial for the seismic performance. A continuous diaphragm allows seismic forces to travel seamlessly from the roof and floors to the vertical systems, and then down to the foundation. Discontinuities in beams or floor openings can disrupt this load path, weakening the diaphragm's capacity to transfer seismic forces. When beams are discontinuous, lateral forces must be transmitted through thinner floor slabs, increasing the risk of excessive torsion (Figure 7). Therefore, these configurations should be avoided[77].

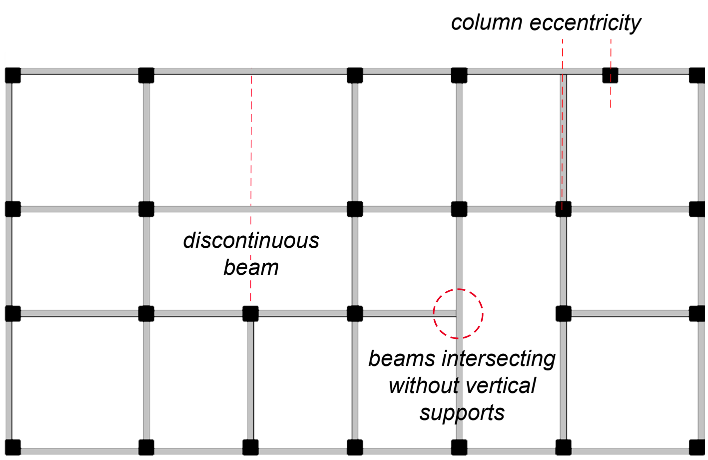

Figure 7. Horizontal discontinuity in seismic-resistant elements.

- vertical continuity of the seismic-resistant elements. Post-earthquake surveys have consistently shown that buildings with vertical irregularities are more vulnerable to seismic damage. Vertical irregularities often lead to concentrated stress in certain structural elements, which can trigger early damage and potentially cause progressive collapse[78]. Abrupt changes in the mass or stiffness between floors, such as large floor openings, setbacks, or cantilevers, create weak points, leading to uneven load transfer during an earthquake. Common design mistakes include short (or captive) columns—columns with increased lateral stiffness due to partial restrictions on bending[21]—and soft storeys— storeys that are significantly more flexible than the adjacent ones[79], as depicted in Figure 8 and Figure 9, respectively.

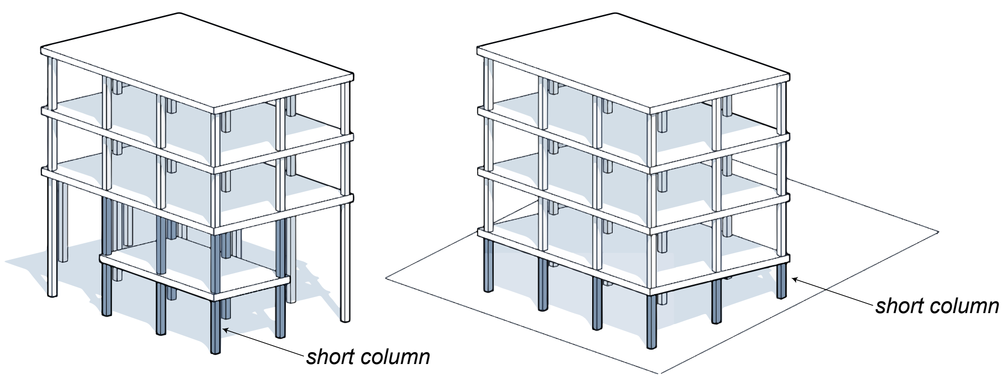

Figure 8. Examples of short columns.

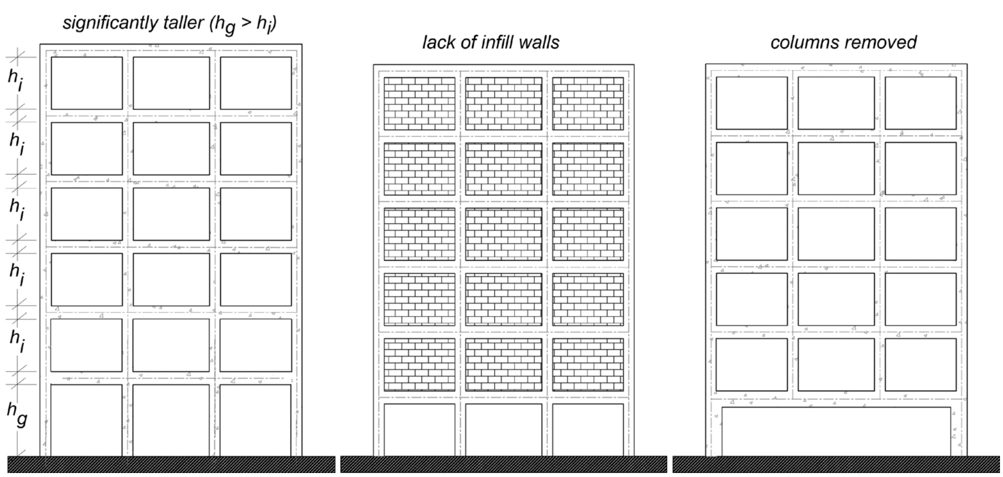

Figure 9. Common causes of soft story mechanisms at ground floor levels.

Final remarks

This chapter explored key aspects of educating architectural design students in earthquake-resistant design and presented strategies for effectively engaging them in both design studios and lecture-based courses. The following points summarize the core principles of best teaching practices and innovative approaches for integrating seismic design into architectural education:

- Studio is the key. The success of teaching strategies for introducing seismic design in architectural education largely depends on their integration with design studios. A design-based learning approach—the foundation of the studio model—remains the most effective method for teaching students how to apply earthquake-resistant principles in practice.
- Sensorial experiences over mathematical abstractions. Successful teaching practices in architecture emphasize learning through sensory experiences rather than abstract mathematical concepts. Techniques such as hands-on model-making, shaking tables, and digital tools like virtual and augmented reality help students engage directly in seismic design. While some mathematical understanding is necessary, instructors should avoid overloading students with formulas and equations, focusing instead on experiential learning.
- Non-structural components must be included. New seismic design approaches emphasize the importance of maintaining a building's functionality after a large earthquake. This aligns with goals such as energy savings, carbon reduction, and avoiding resource depletion. Non-structural detailing is a key component in achieving this, and architects must be trained in this area. Collaboration with engineers should also be encouraged to ensure that both structural and non-structural elements are effectively addressed.
- Architecture-tailored seismic design software is lacking. Aside from the notable exception of RESIST[31], there is a lack of software specifically designed to help architecture students apply seismic principles to their design projects. While many seismic design tools exist for engineers, they are not tailored to the mindset and skills of architecture students.
- Digital tools for improving visualization techniques. As architecture students are often predominantly visual learners, teaching methods that leverage virtual environments and advanced visualization techniques can significantly enhance their understanding. Consequently, there is a need for improved design concept visualization tools, including image visualization/animation, image manipulation, interactive flowchart-based analysis, design animation, and walk-through virtual navigation.

Funding

This research received no external funding.

Ethics Committee Approval

This work does not require an ethics committee approval.

Acknowledgments

The author thanks Hazal Sarı, Beril Yılmaz, Özge Özkonak, and Buse Beste Aydınoğlu for their kind assistance in preparing some of the drawings presented in this study.

Conflict of Interest

The author declare no conflicts of interest.

References

1. K. Mitra, S. Ailawadi, and D. C. Rai, “Initiatives in educating future architects in earthquake resistant design practices,” *Seismological Research Letters*, vol. 84, no. 5, pp. 820–828, 2013, doi: 10.1785/0220120173.
2. M. Morales-Beltran, A. Charleson, and E. E. Aydin, “Sawtooth method for teaching seismic design principles to architecture students,” *Journal of Architectural Engineering*, vol. 26, no. 1, p. 04019031, 2020, doi: 10.1061/(ASCE)AE.1943-5568.0000387.
3. S. K. Jain, “Earthquake safety in India: Achievements, challenges and opportunities,” *Bulletin of Earthquake Engineering*, vol. 14, no. 5, pp. 1337–1436, 2016, doi: 10.1007/s10518-016-9870-2.
4. O. Karadag and N. G. Canakcioglu, “Teaching earthquake-resistant structural systems in architecture department: A hands-on learning experience,” *Architectural Science Review*, vol. 67, no. 4, pp. 332–344, 2024, doi: 10.1080/00038628.2023.2288967.
5. M. Morales-Beltran and B. Yildiz, “Integrating configuration-based seismic design principles into architectural education: Teaching strategies for lecture courses,” *Architectural Engineering and Design Management*, vol. 16, no. 4, pp. 310–328, 2020, doi: 10.1080/17452007.2020.1738995.
6. D. E. T. Viteri, M. A. Guerra, and F. Yepez, “Board 2B: WIP: What architects should learn according to the industry in seismic countries,” presented at the 2023 ASEE Annual Conference & Exposition, 2023.
7. M. Dallı and A. Soyluk, “Ethical analysis of architecture on structural irregularities in major earthquakes in Turkey,” *International Journal of Disaster Resilience in the Built Environment*, vol. 15, no. 2, pp. 259–273, 2024, doi: 10.1108/IJDRBE-01-2022-0012.
8. A. T. Özden and M. Erkılıç, “Regulatory role of architecture in building code appliance: Continuing Education system and building inspection relation,” in *New Frontiers in Architecture, Planning and Design*, İzmir, 2023, pp. 135–164.
9. A. Er Akan, K. Bingol, H. T. Örmecioğlu, A. Er, and T. O. Örmecioğlu, “Towards an earthquake-resistant architectural design with the image classification method,” *Journal of Asian Architecture and Building Engineering*, vol. 23, no. 1, pp. 157–170, 2024, doi: 10.1080/13467581.2023.2213299.
10. J. Takagi and A. Wada, “Recent earthquakes and the need for a new philosophy for earthquake-resistant design,” *Soil Dynamics and Earthquake Engineering*, vol. 119, pp. 499–507, 2019, doi: 10.1016/j.soildyn.2017.11.024.
11. Architectural Institute of Japan, “Code of ethics (AIJ),” Architectural Institute of Japan. Accessed: 18, 2024. [Online]. Available: https://www.aij.or.jp/eng/about/ethics.html

12. M. Morales-Beltran, “Effective architecture-seismic design integration in teaching practice: Elementary school design-case study,” presented at the 16th World Conference on Earthquake Engineering, 2017, pp. 1–10. [Online]. Available: https://www.wcee.nicee.org/wcee/article/16WCEE/WCEE2017-3117.pdf
13. G. Bankoff, “Design by disasters: Seismic architecture and cultural adaptation to earthquakes,” in *Cultures and Disasters*, Routledge, 2015, pp. 53–71.
14. M. Bostenaru Dan and I. Armas, “Earthquake impact on settlements: the role of urban and structural morphology,” *Nat. Hazards Earth Syst. Sci.*, vol. 15, no. 10, pp. 2283–2297, 2015, doi: 10.5194/nhess-15-2283-2015.
15. E. Angell, “Assembling disaster: Earthquakes and urban politics in Istanbul,” *City*, vol. 18, no. 6, pp. 667–678, 2014, doi: 10.1080/13604813.2014.962881.
16. E. L. French, S. J. Birchall, K. Landman, and R. D. Brown, “Designing public open space to support seismic resilience: A systematic review,” *International Journal of Disaster Risk Reduction*, vol. 34, pp. 1–10, 2019, doi: 10.1016/j.ijdrr.2018.11.001.
17. M. Montejano-Castillo and M. Moreno-Villanueva, “The adaptability of public space in Mexico City after an earthquake: A Preliminary classification,” *International Journal of Safety and Security Engineering*, vol. 6, no. 2, pp. 104–113, 2016.
18. D. Koren and K. Rus, “The potential of open space for enhancing urban seismic resilience: A literature review,” *Sustainability*, vol. 11, no. 21, 2019, doi: 10.3390/su11215942.
19. P. Allan and M. Bryant, “The critical role of open space in earthquake recovery: A case study,” presented at the EN: proceedings of the 2010 NZSEE conference (2010, Nueva Zelandia), 2010, pp. 1–10.
20. B. Binici et al., “Performance of RC buildings after Kahramanmaraş earthquakes: lessons toward performance based design,” *Earthquake Engineering and Engineering Vibration*, vol. 22, no. 4, pp. 883–894, 2023, doi: 10.1007/s11803-023-2206-8.
21. O. C. Celik et al., “Multidisciplinary reconnaissance investigation covering structural, geotechnical, and architectural based damage to mid-rise residential buildings following the February 6th, 2023 Kahramanmaraş, Türkiye earthquake doublets (Mw 7.8, Mw 7.6),” *Soil Dynamics and Earthquake Engineering*, vol. 182, p. 108738, 2024, doi: 10.1016/j.soildyn.2024.108738.
22. B. Westenenk et al., “Analysis and interpretation of the seismic response of RC buildings in Concepción during the February 27, 2010, Chile earthquake,” *Bulletin of Earthquake Engineering*, vol. 11, no. 1, pp. 69–91, 2013, doi: 10.1007/s10518-012-9404-5.

23. J. M. Jara, E. J. Hernández, B. A. Olmos, and G. Martínez, “Building damages during the September 19, 2017 earthquake in Mexico City and seismic retrofitting of existing first soft-story buildings,” *Engineering Structures*, vol. 209, p. 109977, 2020, doi: 10.1016/j.engstruct.2019.109977.
24. M. Motosaka, “Lessons of the 2011 great east Japan earthquake focused on characteristics of ground motions and building damage,” presented at the Proceedings of the international symposium on engineering lessons learned from the, 2011, pp. 1–4.
25. A. Filiatrault and T. Sullivan, “Performance-based seismic design of nonstructural building components: The next frontier of earthquake engineering,” *Earthquake Engineering and Engineering Vibration*, vol. 13, no. 1, pp. 17–46, 2014, doi: 10.1007/s11803-014-0238-9.
26. S. Ertas Besır et al., “Evaluation of professional awareness levels of interior architecture students with practice assignment,” *MBUD*, vol. 8, no. Special Issue, pp. 378–393, 2023, doi: 10.30785/mbud.1346412.
27. G. Dogan, A. S. Ecemis, S. Z. Korkmaz, M. H. Arslan, and H. H. Korkmaz, “Buildings damages after Elazığ, Turkey earthquake on January 24, 2020,” *Natural Hazards*, vol. 109, no. 1, pp. 161–200, 2021, doi: 10.1007/s11069-021-04831-5.
28. A. Nuhoğlu et al., “A reconnaissance study in İzmir (Bornova Plain) affected by October 30, 2020 Samos earthquake,” *International Journal of Disaster Risk Reduction*, vol. 63, p. 102465, 2021, doi: 10.1016/j.ijdrr.2021.102465.
29. A. Ayyıldız Potur and H. Metin, “The place of earthquake in architectural education and the educational dimension of the earthquake: An evaluation of the global agenda and Turkey context,” *Megaron*, vol. 16, no. 2, pp. 223–254, 2021, doi: 10.14744/megaron.2020.94210.
30. A. Bartosh, B. Krietemeyer, and S. C. Mac Namara, “Student pre-perceptions of integrated design and the role of technical courses in the architectural studio,” presented at the 2016 ASEE Annual Conference & Exposition, New Orleans, Louisiana, 2016. doi: 10.18260/p.25920.
31. A. Charleson, “Earthquake engineering education in schools of architecture: Developments during the last ten years including rule-of-thumb software,” *Journal of Architectural Engineering*, vol. 24, no. 3, p. 04018020, 2018, doi: 10.1061/(ASCE)AE.1943-5568.0000324.
32. K. E. Hedges, “Introduction to architectural structures: Lessons learned from parti pris pedagogy,” presented at the 2014 ASEE Annual Conference & Exposition, Indianapolis, Indiana, 2014, pp. 1–15. doi: 10.18260/1-2--20707.
33. S. C. Mac Namara, “Bringing engineering into the studio: Design assignments for teaching structures to architects,” presented at the 2012 ASEE Annual Conference & Exposition, 2012, pp. 25–270.

34. E. J. G. C. van Dooren, J. van Merriënboer, H. P. A. Boshuizen, M. van Dorst, and M. F. Asselbergs, “Architectural design education: In varietate unitas,” *International Journal of Technology and Design Education*, vol. 28, no. 2, pp. 431–449, 2018, doi: 10.1007/s10798-017-9396-1.
35. M. Morales-Beltran, E. Kızılörenli, and C. Duyal, “Educating non-specialized audiences about seismic design principles using videos and physical models,” *Int. J. Assess. Tools Educ.*, vol. 11, no. 3, pp. 537–566, 2024, doi: 10.21449/ijate.1441197.
36. Whitehead Robert, “Rebuilding a framework for learning: rethinking structural design instruction in an architectural curriculum,” in *Structures Congress 2015,* in Proceedings. , 2015, pp. 2600–2612. doi: 10.1061/9780784479117.225.
37. G. Marriage and J. Gamman, “Advancing collaboration between students of architecture and engineering,” presented at the Proceedings of the 2017 Architectural Science Association (ASA) conference, ASA Wellington, 2017.
38. S. Aşut, “Computational earthquake management: An educational perspective,” *DRArch*, vol. 5, no. 2, pp. 229–245, 2024, doi: 10.47818/DRArch.2024.v5i2129.
39. S. Rihal, “Pier Luigi Nervi”s Palazzetto dello sport–lessons and perspectives on conceptual seismic behavior,” presented at the Proceedings of IASS Annual Symposia, International Association for Shell and Spatial Structures (IASS), 2014, pp. 1–8.
40. S. Gunasagaran, M. T. Mari, S. Kuppusamy, S. Srirangam, and M. R. Mohamed, “Learning construction through model making and its application in architecture design studio,” *International Transaction Journal of Engineering, Management, & Applied Sciences & Technologies*, vol. 12, no. 11, pp. 1–10, 2021.
41. D. L. López, M. D. Rodríguez, and S. G. Costas, “Intuition and experimentation as teaching tools: Physical and interactive computational models,” presented at the INTED2022 Proceedings, IATED, 2022, pp. 9727–9734.
42. Cimellaro Gian Paolo and Domaneschi Marco, “Development of dynamic laboratory platform for earthquake engineering courses,” *Journal of Professional Issues in Engineering Education and Practice*, vol. 144, no. 4, p. 05018015, 2018, doi: 10.1061/(ASCE)EI.1943-5541.0000393.
43. M. Morales-Beltran, P. Eigenraam, and J. Latka, “Paper-based water tower for post-disaster emergency scenarios,” in *Advances in Engineering Materials, Structures and Systems: Innovations, Mechanics and Applications*, 1st ed., London, UK: CRC Press, 2019, pp. 952–956.
44. A. Vanciu-Rău, A. Ţigănescu, D. Tătaru, and D. Rău, “The seismic simulator as a didactic tool for seismic education,” *AIP Conference Proceedings*, vol. 2218, no. 1, p. 060004, 2020, doi: 10.1063/5.0001037.

45. B. B. Aydınoğlu et al., “The Ardıç project: post-disaster social architecture for a small community in Antakya,” in *A Perspective in Interdisciplinary Built Environment Education: Computation for Earthquake Resilience*, Delft, the Netherlands: TU Delft OPEN Publishing, 2025.
46. M. Morales-Beltran, “Teaching with prototypes: Learning architecture through making,” *UOU*, no. 06, pp. 146–153, 2023.
47. E. I. Katsanos, O. N. Taskari, and A. G. Sextos, “A matlab-based educational tool for the seismic design of flexibly supported RC buildings,” *Computer Applications in Engineering Education*, vol. 22, no. 3, pp. 442–451, 2014, doi: 10.1002/cae.20568.
48. C. G. Panagiotopoulos and G. D. Manolis, “A web-based educational software for structural dynamics,” *Computer Applications in Engineering Education*, vol. 24, no. 4, pp. 599–614, 2016, doi: 10.1002/cae.21735.
49. S. François et al., “Stabil: An educational Matlab toolbox for static and dynamic structural analysis,” *Computer Applications in Engineering Education*, vol. 29, no. 5, pp. 1372–1389, 2021, doi: 10.1002/cae.22391.
50. P. Wang, P. Wu, J. Wang, H.-L. Chi, and X. Wang, “A critical review of the use of virtual reality in construction engineering education and training,” *International Journal of Environmental Research and Public Health*, vol. 15, no. 6, 2018, doi: 10.3390/ijerph15061204.
51. T. Kuncoro, M. A. Ichwanto, and D. F. Muhammad, “VR-based learning media of earthquake-resistant construction for civil engineering students,” *Sustainability*, vol. 15, no. 5, 2023, doi: 10.3390/su15054282.
52. Z. Feng, V. A. González, R. Amor, R. Lovreglio, and G. Cabrera-Guerrero, “Immersive virtual reality serious games for evacuation training and research: A systematic literature review,” *Computers & Education*, vol. 127, pp. 252–266, 2018, doi: 10.1016/j.compedu.2018.09.002.
53. Y. Turkan, R. Radkowski, A. Karabulut-Ilgu, A. H. Behzadan, and A. Chen, “Mobile augmented reality for teaching structural analysis,” *Advanced Engineering Informatics*, vol. 34, pp. 90–100, 2017, doi: 10.1016/j.aei.2017.09.005.
54. J. Wen and M. Gheisari, “A review of virtual field trip applications in construction education,” in *Construction Research Congress 2020*, 2020, pp. 782-790, doi: 10.1061/9780784482872.085.
55. C. Chen, L. Wang, T. Murtha, and D. Hulse, “Lessons from livestreaming fieldtrips: Evaluating an alternative fieldtrip approach in teaching landscape architectural studios,” *Journal of Digital Landscape Architecture*, vol. 7, pp. 616–623, 2022.

56. J. Zhao, P. LaFemina, J. Carr, P. Sajjadi, J. O. Wallgrün, and A. Klippel, "Learning in the field: Comparison of desktop, immersive virtual reality, and actual field trips for place-based stem education," in *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 2020, pp. 893–902. doi: 10.1109/VR46266.2020.00012.

57. R. Fruchter, "Developing an empathic design mindset through virtual field trips in buildings," in *Computing in Civil Engineering 2023*, 2024, pp. 295-303, doi: 10.1061/9780784485248.036.

58. H. Salehi and R. Burgueño, "Emerging artificial intelligence methods in structural engineering," *Engineering Structures*, vol. 171, pp. 170–189, 2018, doi: 10.1016/j.engstruct.2018.05.084.

59. E. Bravo, B. Amante, P. Simo, M. Enache, and V. Fernandez, "Video as a new teaching tool to increase student motivation," in *2011 IEEE Global Engineering Education Conference (EDUCON)*, 2011, pp. 638–642. doi: 10.1109/EDUCON.2011.5773205.

60. M. Ibrahim, P. D. Antonenko, C. M. Greenwood, and D. Wheeler, "Effects of segmenting, signalling, and weeding on learning from educational video," *Learning, Media and Technology*, vol. 37, no. 3, pp. 220–235, 2012, doi: 10.1080/17439884.2011.585993.

61. C. J. Brame, "Effective educational videos: Principles and guidelines for maximizing student learning from video content," *CBE—Life Sciences Education*, vol. 15, no. 4, 2016, doi: 10.1187/cbe.16-03-0125.

62. B. Ahn and D. D. Bir, "Student interactions with online videos in a large hybrid mechanics of materials course," *Advances in Engineering Education*, vol. 6, no. 3, 2018.

63. Sutley Elaina J., van de Lindt John W., and Peek Lori, "Community-level framework for seismic resilience. I: Coupling socioeconomic characteristics and engineering building systems," *Natural Hazards Review*, vol. 18, no. 3, p. 04016014, 2017, doi: 10.1061/(ASCE)NH.1527-6996.0000239.

64. F. Galeazzi, P. D. G. Di Franco, R. Toulson, C. Camporesi, and S. Patel, "Earthquakes, communities and heritage: Telling stories of resilience through co-designed immersive media," *Visual Studies*, vol. 38, no. 1, pp. 101–118, 2023, doi: 10.1080/1472586X.2022.2102539.

65. D. C. Greene, "Increasing resilience to earthquakes through educating community builders: Teaching earthquake-resistant building techniques in Guatemala," *Geoscience for the Public Good and Global Development: Toward a Sustainable Future*, vol. 520, p. 295, 2016.

66. S. K. Jain, K. Mitra, S. Brzev, and D. C. Rai, “Educational initiatives in promoting confined masonry for improving earthquake resilience in India,” in *Proceedings of the 17th World Conference on Earthquake Engineering*, Sendai, Japan, 2020. [Online]. Available: https://wcee.nicee.org/wcee/article/17WCEE/7g-0001.pdf

67. J. M. Kelly, “Aseismic base isolation: Review and bibliography,” *Soil Dynamics and Earthquake Engineering*, vol. 5, no. 4, pp. 202–216, 1986, doi: 10.1016/0267-7261(86)90006-0.

68. A. Verruijt, *An Introduction to Soil Mechanics*. Springer Cham, 2018, doi: 10.1007/978-3-319-61185-3.

69. J. Korenaga, “Initiation and evolution of plate tectonics on earth: Theories and observations,” *Annual Review of Earth and Planetary Sciences*, vol. 41, no. 1, pp. 117-151, 2013, doi: 10.1146/annurev-earth-050212-124208.

70. A. Wada, “Strength, functionality and beauty of university buildings in earthquake-prone countries,” *Proceedings of the Japan Academy*, Series B, vol. 94, no. 2, pp. 129–138, 2018, doi: 10.2183/pjab.94.009.

71. C. Arnold and R. Reitherman, “Building configuration and seismic design: The architecture of earthquake resistance,” National Science Foundation, Washington, D.C., NSF/CEE-81604, 1981.

72. C. Arnold, “Seismic design,” *JAE*, vol. 33, no. 4, pp. 19–22, 1980, doi: 10.2307/1424685.

73. A. Charleson, *Seismic Design for Architects*. London: Routledge, 2012, doi: 10.4324/9780080888255.

74. FEMA, *Designing for Earthquakes—A Manual for Architects*. FEMA 454. Washington, DC, 2006.

75. H. Gokdemir, H. Ozbasaran, M. Dogan, E. Unluoglu, and U. Albayrak, “Effects of torsional irregularity to structures during earthquakes,” *Engineering Failure Analysis*, vol. 35, pp. 713–717, 2013, doi: 10.1016/j.engfailanal.2013.06.028.

76. A. Noorifard, M. R. Tabeshpour, and F. M. Saradj, “Preventing irregularity effects of infills through modifying architectural drawings,” *Architecture, Civil Engineering, Environment*, vol. 9, no. 2, pp. 77–92, 2016, doi: 10.21307/acee-2016-024.

77. C. Özmen and A. İ. Ünay, “Commonly encountered seismic design faults due to the architectural design of residential buildings in Turkey,” *Building and Environment*, vol. 42, no. 3, pp. 1406–1416, 2007, doi: 10.1016/j.buildenv.2005.09.029.

78. S. C. Dutta, P. K. Das, and P. Sengupta, “Seismic behaviour of irregular structures,” *Structural Engineering International*, vol. 27, no. 4, pp. 526–545, 2017, doi: 10.2749/222137917X14881938989765.

79. M. Morales-Beltran, F. Durmuşlar, and E. Kızılörenli, “User-oriented architectural design of separated infill walls to prevent soft ground story in reinforced concrete low-rise buildings,” *Journal of Architectural Engineering*, vol. 27, no. 3, p. 04021018, 2021, doi: 10.1061/(ASCE)AE.1943-5568.0000478

Appendix. Full proposed course contents

Table 2. Basic course contents.

Topics	Sub-topics	Contents
Nature of earthquakes and ground motions	Basic Seismology	Earthquake causes and mechanics (plate tectonics, fault lines, ground shaking).
		Seismic waves: P-waves, S-waves, and surface waves.
		Measuring earthquakes: Magnitude, intensity, and frequency.
	Seismic Hazard and Risk	Seismic hazard maps and zones. Understanding seismic activity and the global distribution of earthquake zones.
		The impact of earthquakes on buildings and communities.
		Case studies of major earthquakes and their effects on urban environments.
How buildings resist earthquakes	Seismic Loads and Ground Motion	How seismic forces (lateral and vertical) affect buildings.
		Dynamic characteristics of buildings: Mass, stiffness, damping, and natural frequency.
		Concepts of resonance and how it affects building performance.
		The influence of soil conditions and site response.
	Building Dynamics and Behaviour During Earthquakes	Sway, vibration, and deformation modes.
		Importance of damping and energy dissipation.
		Concepts of base shear and building drift.
Earthquake-resistant Structural Systems	Vertical Structure	Shear walls: Function, design considerations, and materials.
		Braced frames: Types (concentric, eccentric), and their applications.
		Moment-resisting frames: Design, behaviour under seismic loads, and flexibility.
		Combined systems and hybrid approaches.
	Horizontal Structure	Rigid diaphragms: Function, design considerations, and materials.
		Transfer diaphragms and bond beams
Building Configuration	Horizontal Configuration	Torsion and the importance of building symmetry and regularity in plan and elevation.
		Horizontal irregularities and their impact on seismic performance.
		Design strategies for reducing torsional effects.
		Openings and voids in diaphragms.
	Vertical Configuration	Vertical irregularities and their impact on seismic performance.
		The role of building height and aspect ratio.
		Avoiding soft story and short column failure mechanisms.

Topics	Sub-topics	Contents
Non-structural components	Infill and Partition Walls	Infill Walls; Problems associated with infill walls
		Solutions to problems caused by infill walls
		Partition Walls
	Claddings	Cladding or exterior components, such as masonry cladding and veneer (adhered and anchored)
		Prefabricated panels
		Glazing and glass blocks
	Ceilings and Canopies	Suspended modular ceiling systems; ceilings directly applied to the structure
		Suspended heavy ceilings
		Canopies
Advanced technologies	Base Isolation	Principles and advantages of base isolation systems.
		Types of base isolators: Elastomeric bearings, sliding bearings, and hybrid systems.
	Energy Dissipation	Tuned mass dampers, viscous dampers, friction dampers, and their role in reducing building motion.
Urban Planning and Regulations	Urban Planning	Impact of earthquake hazards on urban areas.
		Disaster management and risk reduction planning.
		Urban settlements and site selection strategies.
	Regulatory Frameworks and Compliance	Overview of relevant building codes: International Building Code (IBC), Eurocode 8, FEMA guidelines, and local codes.
		Liability and legal implications for architects in seismic design.
Seismic Retrofitting	Assessment of Existing Buildings	Techniques for evaluating the seismic vulnerability of older buildings.
		Tools and technologies for seismic performance assessment (e.g., non-destructive testing).
	Retrofit Strategies for Earthquake Resistance	Adding shear walls, bracing, and moment-resisting frames to existing buildings.
		Strengthening connections and joints to improve load path continuity.
		Base isolation retrofits in existing structures.
Foundations and geotechnical issues	Soil-Structure Interaction	Understanding how soil conditions (rock, clay, sand) affect building response during an earthquake.
		Site-specific seismic hazard assessment.
	Types of Foundations in Seismic Design	Shallow foundations: Spread footings and mat foundations.
		Deep foundations: Piles and caissons for liquefaction-prone areas.
		Techniques for improving foundation performance (e.g., soil compaction, grouting, deep foundations).

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Designing for Resilience: Integrating Disaster Management and Post-Disaster Dwelling in a Third-Year Second-Semester Architectural Design Studio

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This chapter investigates the integration of disaster management and post-disaster dwelling design within architectural education. It analyses the curriculum of an undergraduate course; a third-year second-semester architectural design studio (ARCH 302) that has adopted this integrative approach since 2020. The chapter advocates an educational framework that goes beyond conventional mitigation strategies to enhance disaster management's preparedness, response, and recovery phases.

The curriculum encourages the design of resilience to earthquakes and other disasters. Students engage in site-specific research addressing critical factors such as water supply, drainage, and waste management, promoting the design of dual-purpose green zones for daily use, and emergency response with a land use option for a temporary dwelling organization, communal facilities, and open spaces.

Over the past five years, the integration of disaster concepts into the course aimed to create awareness, with a focus on post-disaster usage scenarios in the last two years. In these scenarios, students were encouraged to use the Rhino/Grasshopper (RH/GH) definitions as tools. However, this disaster awareness effort is not a fundamental computational study.

This chapter emphasizes pre-designing for post-disaster needs, including temporary shelters that consider user comfort, functionality, and environmental impact. An analysis of Türkiye's disaster responses reveals shortcomings in temporary housing planning, design, and management. This raises the question of whether mandating safe zones within large plots (over 2000 m^2) alongside designated neighbourhood gathering areas can contribute to improved disaster preparedness. Assignments and designs from the third-year second-semester architectural studio reflect

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students' sensitivity to disaster-related challenges, indicating the potential of architectural design studio courses to equip future architects with resilience-focused design skills.

Keywords: Designing for resilience, Preparedness, Post-disaster assembly, Pre-disaster planning

Introduction

On February 6, 2023, Türkiye experienced two major earthquakes that struck the same day, significantly affecting the southeastern region. The first earthquake, with a magnitude of 7.7, occurred at 04:17 a.m., centered in Kahramanmaraş. This was followed by a second quake of 7.6 magnitude at 1:24 p.m., intensifying destruction across the affected areas.

A presidential report[1] indicated that a total of 2,618,697 buildings across 11 provinces were exposed to the impact of earthquakes. Of these, damage assessments were conducted on 1,712,182 structures, which revealed extensive destruction. The findings identified 35,355 buildings as destroyed, while 17,491 were marked for urgent demolition owing to severe structural risks. In addition, 179,786 buildings were classified as heavily damaged, 40,228 as moderately damaged, and 431,421 as lightly damaged. The scope of the damage extended beyond residential properties to include historical and cultural landmarks, educational institutions, administrative buildings, hospitals, and hotels, reflecting the widespread nature of the devastation. The earthquakes resulted in a tragic loss of life, with official figures reporting at least 53,537 fatalities in Türkiye and 8,476 fatalities in Syria. More than 122,000 people have sustained injuries across the region. The seismic activity continued in the aftermath, with over 45,000 recorded aftershocks, magnifying the challenges faced during recovery efforts.

The increasing frequency and intensity of natural disasters worldwide highlight the urgent need for effective disaster preparedness across all sectors, including architecture. The role of architecture in disaster preparedness needs to be defined and addressed in the design education phase. Incorporating disaster management principles into architectural curricula represents a shift from traditional design education. Historically, disaster mitigation has been treated as a separate discipline, often related to engineering and urban planning. However, the increasing interdependence between architecture and emergency preparedness has highlighted the need for an interdisciplinary approach. Architectural professionals in Türkiye are often not adequately educated or proficient in addressing structural design problems[2,3], pointing to a broader issue with the current architectural education system's approach to structural design. Nevertheless, structural expertise and seismic design capabilities are addressed within the curriculum from a fragmented perspective and distributed across various courses. While the studio course itself is not designed to develop in-depth knowledge and skills in this area, it draws support from supplementary courses. Additionally, the studio process explores methods to raise awareness of the architect's responsibility to mitigate the impacts of disasters, fostering a holistic understanding of resilience in design.

Concentrating on the content, process, and outcomes of the spring semester of the third-year design studio (ARCH 302) in the Department of Architecture at

İzmir University of Economics (IUE), this chapter argues for a comprehensive framework for architectural design education that not only addresses disaster mitigation but also emphasizes the preparedness, response, and recovery phases.

The studio is structured around iterative design tasks, site surveys and analyses, and collaborative studio work using both conventional and computational methods. Accordingly, the studio was organized into two sections. The students in section 1 follow computational approaches to architectural design, such as parametric design, complex geometries with generative AI, additive construction methods, etc. The students in section 2 follow a hybrid approach integrating conventional methods with computational tools, such as physical and digital model-making, sketching, conceptual diagrams, plan schemes, collage studies, etc.

This chapter highlights the importance of embedding disaster preparedness into the architectural design process, with a focus on natural disasters that sites are most prone to, including earthquakes. Students were tasked with site-specific research, analyzing factors such as water supply, drainage, and waste management–elements critical to ensuring functionality and resilience in post-disaster scenarios, regardless of the type of disaster. Therefore, the majority of students tend to focus on earthquakes, considering them the most significant and devastating risks. The curriculum encourages students to design dual-purpose green zones that serve both everyday communal needs and emergency functions. This approach reflects a broader objective: pre-emptively designing post-disaster scenarios by considering both the technical and social dimensions of temporary shelter solutions. In doing so, this chapter situates architectural education as a key contributor to creating resilient, sustainable communities that are better equipped to withstand and recover from future disasters.

Pre-Designing for Post-Disaster

The Oxford Dictionary defines a disaster as “an unexpected event, such as a very bad accident, a flood, or a fire, that kills a lot of people or causes a lot of damage”[25]. This definition underscores the unpredictable nature of disasters, making it difficult for humankind to predict their outcomes. However, proactive measures can be taken through science and design techniques to prepare for a post-disaster period. Effective planning can mitigate the impact on affected communities. Preparing for post-disaster needs involves anticipating requirements for shelter and support. According to Bashawri et al.[4], disaster relief shelters can be categorized as emergency shelters, temporary shelters, temporary housing, transitional shelters, progressive shelters, core shelters/one-room shelters, and permanent housing.

Analysis of Türkiye’s Disaster Responses

Disasters are undesirable events that pose a significant risk to life and property. However, their impact can often be mitigated by the proper planning and implementation of sound architectural design principles and construction practices. In the case of earthquakes, it is not the seismic activity itself that leads to losses, but poorly designed and constructed buildings. The preparation for such events is essential to ensure the continuity of life and to build earthquake-proof cities, in which past disaster responses reveal a persistent challenge: the lack of coordination. Effective disaster management requires matching the right expertise with specific needs. Without proper guidance, even well-intentioned efforts can lead to counterproductive decision-making. For example, during earthquakes, large-scale tremors generate significant rotational forces, particularly in buildings where the center of mass and center of rigidity are misaligned. Family members, in their urgency to assist trapped relatives, may direct excavators to locations where rooms have shifted because of these forces, complicating rescue efforts. In such scenarios, architects are crucial in guiding rescue teams based on building layouts. Rescue teams arriving at disaster sites are affected by conditions and require immediate access to shelter and nourishment. Their needs must be anticipated and met before arriving at a scene. Additionally, the Turkish Disaster and Emergency Management Authority (AFAD) should regularly inspect and maintain regional warehouses to ensure that supplies such as tents and food remain in good condition.

Architectural design education addressing natural disasters requires a learning environment that is resilient, adaptable, and comprehensive. This environment should encompass more than just imparting design knowledge but entail learning how to deal with emergencies, find solutions, and promote long-term well-being through design. Referring to the Minimum Standards for Education specified by the Inter-agency Network for Education in Emergencies (INEE), we assert that such an environment could be created by integrating four phases: preparation, response, and recovery, following the additional concept of mitigation.

Methodology

Section 2 describes the resilience-focused design method for the course and presents how this method was utilized for the tasks expected from the students. Section 3 explains the integration and introduction of computational skills. Section 4 introduces the findings of ongoing research on the integration of disaster-related responsibilities into the studio curriculum.

Education Method

Studio Setup and Projects

As part of the ARCH 302 studio at IUE, we have covered three phases of disaster management through the following housing projects for the last five years: EcoLodgy (2020), Sustainable and Disaster-Resistant Housing (2021), Social Housing (2022), Aerospace Research Hub with Housing (2023), and CoHousing/CoLiving (2024). Significantly, these projects do not merely address the effects of natural disasters on the built environment, but also the ecological factors in a cross-disciplinary, comprehensive, and critical manner. In other words, they aim to create a nature-oriented mindset in which disaster responsiveness is inseparable from ecological awareness.

Even though the outcomes of the relevant program and the learning outcomes of the specific design studio courses do not address natural disasters, the objectives of these projects have been revised to find effective and sustainable solutions for disaster risks after the İzmir and Kahramanmaraş Earthquakes. Students were assigned several tasks to raise awareness for disaster management across all four phases: mitigation, preparation, response, and recovery. Table 1 presents the design guidelines for each project concerning the specific requirements of each phase. Creating an awareness of building robust and safe environments, as well as a critical consideration of building codes, has been commonly addressed in the mitigation phase of each project. However, the issues covered in the preparation and response phases vary according to the content, scale, and requirements of each project. In both phases, they made site surveys and analyses, as well as research and annotation of the site for disaster preparedness. They designed zones and routes such as assembly areas, training areas, evacuation routes, afforested areas, residential areas, etc. In addition, they were asked to design a multipurpose green zone as part of the landscaping, that serves as an emergency area.

The methodology for coordinating architectural design studio courses centers on a multi-scalar approach to disaster-responsive design, encouraging students to consider the broader context as well as detailed site-specific solutions. The process involves framing the design problem through high-level questions that prompt students to analyze and respond to the complexities of disaster scenarios, in addition to the focal architectural design program. These questions might address topics such as the environmental, social, and infrastructural impacts of a disaster on the built environment, the anticipated needs of displaced populations, and the role of urban planning in mitigating secondary hazards.

By guiding students to critically evaluate various scales, from the regional landscape to individual site conditions, the methodology facilitates a holistic understanding of post-disaster planning within the studio. This initial stage is critical, as students must determine the most appropriate portions of the site to allocate to the post-disaster assembly areas. These decisions involve analyzing factors, such as site accessibility, topography, potential hazards, and proximity to essential services. Students must also consider how the chosen locations for temporary shelters can be integrated with the existing urban fabric, ensuring that the spatial layout supports efficient evacuation routes, safe zones, and access to emergency vehicles.

The students are not merely designing abstract solutions, but are actively engaging in context-aware planning, where they must navigate real-world challenges such as resource limitations, land-use constraints, and the logistics of accommodating diverse population groups. By simulating these complex scenarios, students developed practical skills in disaster risk assessment, site evaluation, and adaptive design strategies, equipping them to make informed decisions in the face of real disaster situations.

Phases of Resilience-focused Design	EcoLodgy	Sustainable and Disaster-Resistant Housing	Social Housing	Aerospace Research Hub with Housing	CoHousing/ CoLiving
Mitigation	Awareness of building robust and safe environ-ments	Awareness of building robust and safe environ-ments	Awareness of building robust and safe environ-ments	Consideration of Building codes	Consideration of Building codes
Preparation	Site Selection, Site Analyses	Site Selection, Site Analyses	Site Selection, Site Analyses	Assembly Area, Training Area, Evacuation Routes	Assembly Area, Training Area, Evacuation Routes
Response	Considering en-vironmental and social parameters of sustainability	Self-Sustaining, Deployable, Modular,	Accessibility, Self-Sustaining,	Temporary Water Supply and Drainage, Waste Removal	Temporary Water Supply and Drainage, Waste Removal
Recovery	Post-disaster Assembly and Living Area	Renewable Ener-gy, Open Space	Renewable Ener-gy, Open Space	Renewable energy, Quality spaces for recovery	Renewable energy, Quality spaces for recovery

Table 1. The design guidelines followed in each project.

Urban Planning and Safe Zones

Selecting suitable locations for temporary shelters after a disaster is critical because poor site choices can lead to secondary hazards. For instance, following an earthquake, some shelter areas experience flooding, resulting in additional casualties. Therefore, thorough assessments must be conducted to ensure that the chosen sites do not pose the risk of further disasters. These evaluations should involve experts from multiple fields to address potential environmental, geological, and safety concerns. Comprehensive measures must be implemented to enhance the security of designated shelter areas. Displaced individuals facing extreme stress and loss may react strongly to even minor provocations, thereby increasing the risk of violence. Strategically placed law enforcement can help to maintain order and support a sense of safety.

Logistics must also be considered to accommodate the regular movement of aid vehicles, ambulances, and potential helicopters. The site layout should ensure that sleeping units are appropriately distanced from communal areas, such as social and dining spaces while maintaining convenient access to toilets and shower facilities. Sanitation infrastructure, especially between sleeping units, should prioritize access to clean water and hygiene.

Storage of Aid: Türkiye's greatest strength in disaster response is its strong spirit of charity and solidarity among its citizens. While aid materials are delivered swiftly, effective storage and distribution are essential to prevent unnecessary hoarding by distressed survivors. Aid should be coordinated by a central source, with priority given to the most urgent needs. This approach helps prevent incidents in which individuals, driven by anxiety, accumulate excessive supplies, as seen in cases of hoarding food items.

Selection of Disaster Response Teams: In large-scale disasters, it is crucial to recognize that local rescue teams are victims as they may have lost their families and friends. Therefore, a system of disaster-sister-city matching—pairing affected regions with distant provinces—can ensure that rescue efforts are conducted effectively. This strategy prevents local responders from being overwhelmed by personal losses, thus allowing them to focus on assisting others.

Children Affected by Disaster: Children require special attention to avoid long-term psychological harm from disasters. Since children may not fully comprehend the situation, providing specialist care and social activities can help them stay connected to their normal lives. Beyond survival, efforts should aim to heal psychological wounds, with designated areas for activities designed specifically to support children's needs.

Hygiene Problem: Disasters often disrupt infrastructure, making hygiene a pressing concern because of limited access to clean water and damaged sanitation systems. Quick infrastructure improvements and clean water provisions are vital, particularly in temporary shelters. Publicly accessible facilities designed for basic needs, such as toilets and showers, should be prioritized to maintain hygiene standards and support ongoing recovery efforts.

Particular attention should be paid to the needs of vulnerable groups, including children, the elderly, and people with disabilities. Planning must account for dedicated areas that support their specific requirements, ensuring that the settlement layout fosters inclusivity and comfort.

Beyond Traditional Mitigation

The mitigation or prevention phase aims to reduce or eliminate the likelihood or consequences of hazards and disasters and make them less severe and cost-effective. This phase includes pre-disaster tasks and issues such as the construction of engineering structures, arrangement/development of building codes, disaster insurance, land use planning, public education, and safety codes[5]. The goal of the preparation phase is to provide educators and learners with the instruments and resources they need to cope with emergencies. It strongly emphasizes capacity building and proactive planning to lessen the effects of unanticipated events such as pandemics, natural disasters, and social upheavals. In this phase, in addition to the curricular requirements, students learn group work, communication, and problem-solving skills. Critical thinking and digital literacy are the important components of this phase.

The response phase begins when disruptions occur. To maintain educational continuity, schools need to take quick and flexible actions such as switching to remote learning, offering psychological support, and ensuring that more vulnerable students get the help they need. Communication and flexibility are essential components of this phase[6]. Moreover, in times of crisis, educators should have the necessary tools and training to avoid inequality and uphold a peaceful and encouraging learning environment.

The recovery phase involves making improvements and restoring the learning environment to avoid returning to pre-crisis levels. This phase incorporates rebuilding infrastructure, addressing the emotional and psychological effects of the disaster on educators and learners, and evaluating the efficiency of the response. Personalized support, such as tutoring or counseling, is also part of this phase to address any learning gaps that might have developed during the response phase.

Resilience-focused Design

Today, the field of architecture education is under increasing pressure to address problems caused by both natural forces and human activity. The escalating incidence of earthquakes, floods, and other calamities attributed to climate change emphasizes the importance of building climate-responsive and climate-resilient structures and spaces. There is a need for architectural schools of thought to teach disaster management in design studios with practical hands-on methods and tools, rather than theoretical aspects. Educators and learners traverse spatial and curricular boundaries, transfer theoretical knowledge into practice, and meet with the community to experience problems on-site. Such a curriculum prepares architects for the real world, encourages disaster risk reduction in communities, and makes architects active members in moving communities to prevent and recover from the consequences of such events.

However, the adaptation of the above-mentioned phases to the learning environment may be challenging, depending on the availability of sources, infrastructure, skills, and knowledge. As Aşut[7] specifies, initiatives around the integration of earthquakes as a design problem in education are mainly focused on seismic design[8,9], seismic design principles[10], earthquake resistance[11,12], and post-disaster emergency shelter design[13].

In cases where real-time and immediate solutions are not possible, the learning outcomes of the design studio and specific project contents and objectives may be improved to address these phases and follow a resilience-focused design process at both the building and urban scales. In this regard, Charleson[14] argues that disaster risk reduction must be integrated into architectural education design thinking, going beyond purely functional and aesthetic considerations. This methodology facilitates the development of a readiness mindset among students, empowering them to make knowledgeable choices when planning for areas vulnerable to natural disasters. He proposed that to prepare students for the challenges of disasters, architectural curricula must include topics such as structural integrity, material durability, and climate-responsive design.

After the three most recent severe earthquakes in Türkiye, the Aegean Sea Earthquake dated October 30, 2020, and the two Kahramanmaraş Earthquakes with a 9-hour interval dated February 6, 2023, the schools of architecture started to integrate disaster risk and management into their curricular structure in a more condensed and effective manner. As formal education temporarily switched to online teaching after these disasters, various solidarity networks were established to provide financial, psychological, and vital support to vulnerable and disadvantaged people, including students. Furthermore, at some architecture schools, staff members and students were involved in extracurricular activities and utilized their professional knowledge and skills for post-disaster spatial needs. The most recent example is Emergency Design Studio, established by students, graduates, and academicians of the METU Faculty of Architecture to meet the primary needs in earthquake zones[15]. They designed and constructed emergency spaces such as shelters, tents, separators) integrated design Studio toilets, and showers, as well as a temporary housing unit, called ‘Paperlog House’ in collaboration with Shigeru Ban Architects and Voluntary Architects’ Network[16].

Another example is the design and prototype production of a life unit by a group of academic staff from the Faculty of Architecture at Dokuz Eylül University[17]. These studies can be considered short-term but quick and effective solutions for emergent problems at disaster sites as part of the response and recovery phases.

Long-term attempts to integrate disaster-responsive principles into architectural education will enable future architects to be equipped with the knowledge and skills needed to create resilient structures. This can be achieved through a curricular structure that integrates theory with practice, encourages cross-disciplinary collaboration, and emphasizes sustainability. Due to increasing awareness after the Aegean Sea and Kahramanmaraş Earthquakes, there have been such attempts, yet few, to revise and improve the curricula of the schools of architecture in Türkiye towards a disaster-responsive approach. In his research on the role of disaster management in architectural education in Türkiye, Bodur provides an overview of these schools. He found that only three nationally accredited bachelor's programs have redefined their program outcomes following natural disaster-oriented architectural education[18]. We question not only the insufficiency of such programs but more importantly, whether they incorporate content and methods following a resilient and comprehensive approach, in which the four phases of disaster management are addressed.

As stated earlier[4], design considerations for temporary shelters and addressing the key topics of functionality, comfort, environmental sustainability, and storage space are crucial for achieving efficient preparation for disasters.

Functionality of the Temporary Shelters. The primary objective of temporary shelters is to provide secure and provisional living space for individuals affected by disasters. These shelters must adapt to different functions based on situational needs. For example, temporary depots may be established to store essential supplies, such as stoves (particularly crucial during winter), clothing (as survivors often possess only what they were wearing during the disaster), blankets, mattresses, and fuel. Access to basic services, including water and sanitation, is essential for sustaining life.

Temporary infirmaries or hospitals may also be required, as rescue teams typically include medical personnel who require appropriate facilities to provide care. Additionally, common areas for dining and social interactions are vital for the psychological recovery of earthquake survivors and victims, promoting a sense of community during the healing process. Thus, determining functional requirements is a critical step in the shelter design process.

Comfort considerations for temporary shelters are heavily influenced by the climate and geographical location. In regions with a mild climate, survivors may spend more time outdoors, whereas in colder areas, shelters must offer sufficient thermal comfort. The need for shelter is a fundamental human requirement that is evolving alongside advancements in technology and changing comfort standards. The basic needs of ancient inhabitants, such as those in Çatalhöyük 10,000 years ago, differ significantly from the demands of modern society. As Louis Kahn noted, “Desire is the creation of need,” highlighting how our evolving desires shape shelter design requirements. The historical evolution of the “window” illustrates this shift. Originally designed as openings for smoke ventilation and fresh air, windows have now become integral elements that provide light, views, and visual comfort. While early shelters primarily aimed to protect against wild animals, today’s requirements extend to safeguarding against diseases, such as COVID-19. Moreover, people from diverse regions may have varying preferences for shelter types, based on local temperature norms and climatic conditions. In hot climates, the potential for temperature drop, particularly at night or in high-altitude and desert regions, presents a significant comfort challenge[19]. Ensuring that shelters can accommodate these variations is crucial for occupant well-being.

Environmental Sustainability: The affordability and sustainability of temporary shelters depend on the choice of materials and construction methods. Designers should prioritize materials that are environmentally friendly and support circularity principles, allowing components to be reused or recycled after the shelter has served their purpose. Material selection must balance durability and cost-effectiveness to ensure resilience while minimizing production expenses, thereby making mass production feasible. Temporary shelters are often designed with mobility and adaptability in mind, allowing them to be upgraded, relocated, or dismantled for material reuse in future applications[20]. The designer’s role is to optimize these factors, ensuring that temporary shelters contribute to both immediate relief and long-term sustainability.

Storage Space: Effective storage is crucial for temporary shelters to ensure access to essential supplies, such as food, clothing, and medical equipment. Storage solutions should be flexible, addressing both shared and individual needs while considering the climate and security to protect items from environmental damage. Accessible, secure, and adaptable storage not only supports functionality and comfort, but also aligns with sustainability by enabling the reuse and recycling of materials. Design considerations must also consider climatic conditions and security concerns. For instance, in hot or humid climates, storage solutions should protect food and medical supplies from heat and moisture damage, whereas in cold regions, provision for weatherproof storage is necessary to prevent items from freezing. The design should also ensure that storage areas are easily accessible, yet secure, protecting valuable supplies from theft or mismanagement. Furthermore, adaptable storage spaces can contribute to the sustainability of temporary shelters by facilitating material reuse and recycling. Modular storage units that can be reconfigured or repurposed for different functions enhance the long-term utility of the shelter, aligning with the principles of circularity and resource efficiency. By prioritizing well-thought-out storage solutions, designers can significantly improve the resilience and liveability of temporary shelters in post-disaster scenarios.

Resilience and efficiency criteria are also interpreted based on previous work by analyzing several design solutions[21]. These criteria include flexibility, modularity, construction without external help, digital fabrication, a small carbon footprint, and upgrade potential.

This methodology acknowledges the limitations of resources and skills, making flexible curricular adaptations essential. Integrating resilience and efficiency criteria into design projects encourages students to prioritize modularity, adaptability, sustainable materials, and construction methods with low carbon footprints.

As discussed in the previous sections, disaster management is significant to conduct design-based formal experimentation. Considering particular knowledge of disaster management, students may apply urban design analysis methods to the given project area and they can develop urban design proposals at a neighborhood scale. Such knowledge and experimentation address the particular learning outcomes of the design studio: being able to conduct design-based formal experimentation, being able to apply urban design analysis techniques to the given project area, and being able to develop urban design proposals at the neighborhood scale.

Design Tasks

The ARCH 302 studio is structured around iterative design tasks, research-based site analyses, and collaborative studio work with an emphasis on integrating computational tools. The students were assigned several tasks to raise awareness of disaster management across all four phases. The mitigation perspective requires collaboration among multiple stakeholders to create structurally robust, safe, and secure built environments. Consequently, this objective is beyond the scope of traditional design studios. However, a holistic framework was established through a series of inquiries that students were expected to undertake. While studying "disasters," they were tasked with developing a timeline (Figure 1) that addressed the challenges posed by various disasters. Through this assignment, they recognized that, in the context of earthquakes, the construction of earthquake-resistant structures falls within the mitigation phase. The subsequent assignment requires students to analyze the site of their semester project concerning the types of disasters to which the land is vulnerable. They prepared a preparedness scenario tailored to their site (Figure 2). The response phase was studied in terms of research and annotation of the site for disaster preparedness. At this stage,

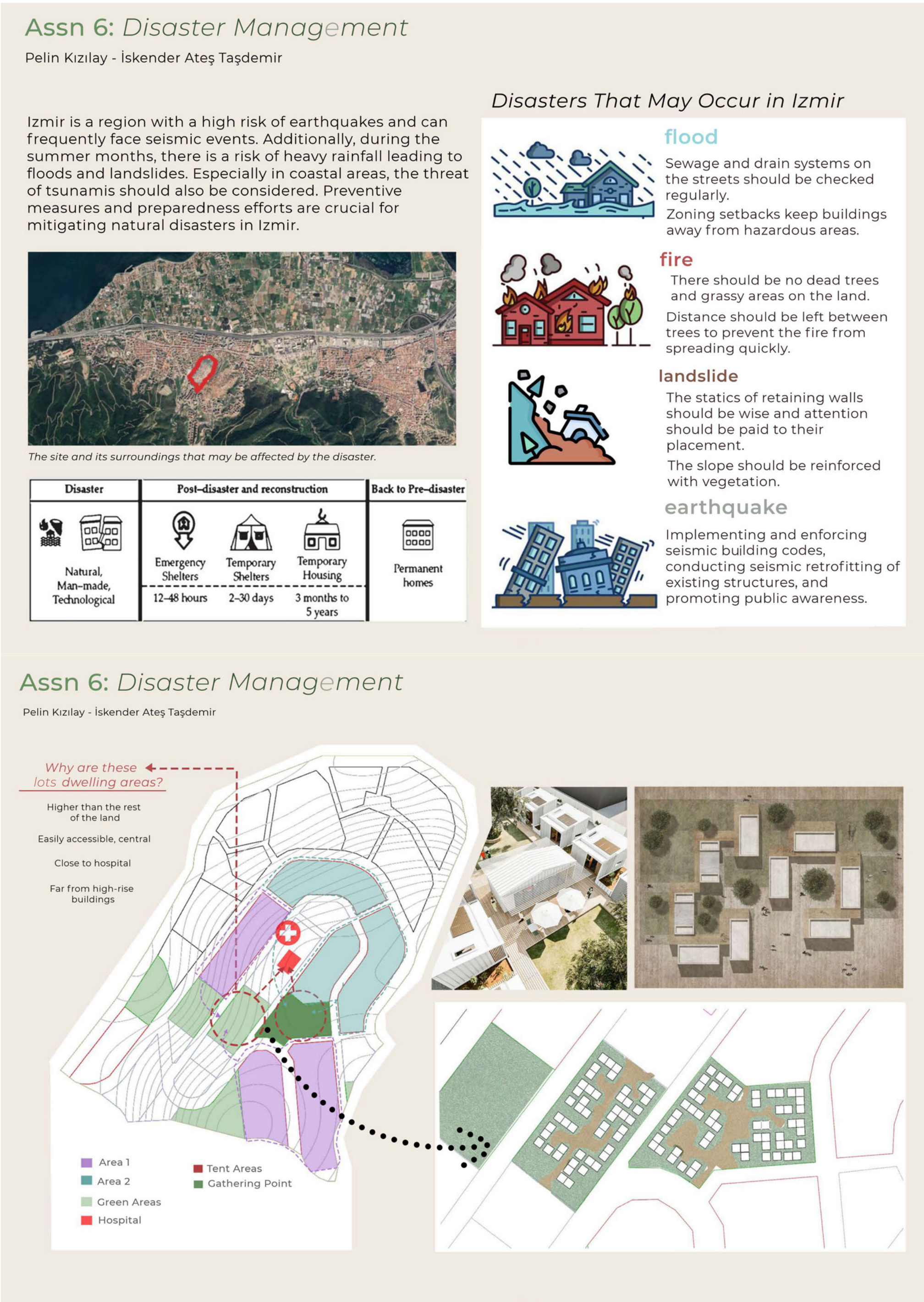

Figure 1. The task to understand Assignment 6 Disaster Management concept by Pelin Kızılay and İskender Ateş.

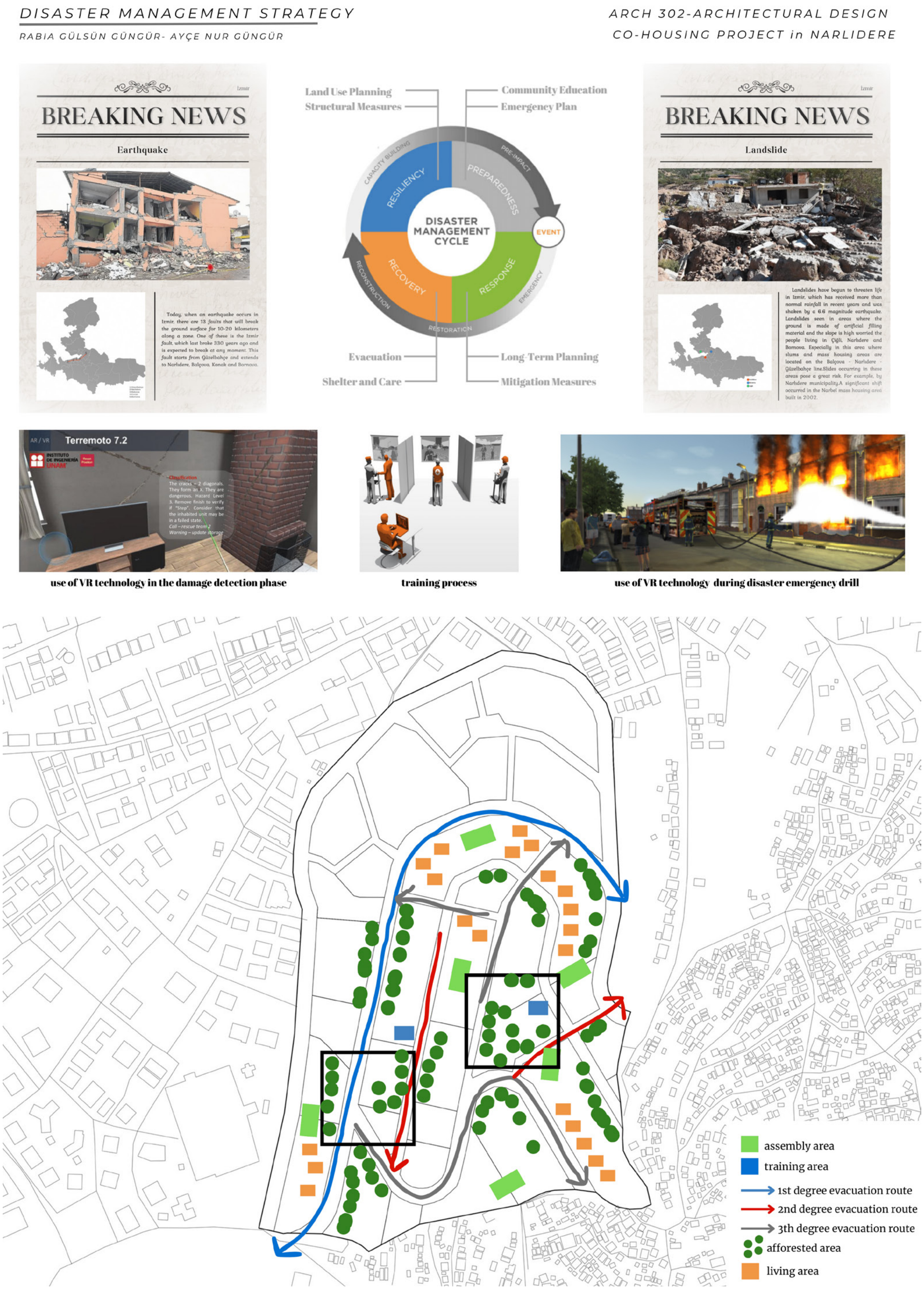

Figure 2. Task to analyze the site based on Disaster Management strategies. (2024). By Rabia Gülsün Güngür and Ayçe Nur Güngür

the students are asked to designate zones and routes such as assembly areas, training areas, 1st, 2nd, and 3rd evacuation routes, afforested areas, residential areas, etc.

The students were tasked with designing a multipurpose green zone as part of a landscaping project aimed at serving as an emergency area. The requirements specified the inclusion of 300 small disaster tents, each with a minimum area of 16.5 m^2, to provide shelter for 1,200 survivors. Additionally, the designs featured a medium-sized general-purpose tent of 63 m^2 intended for educational or social activities as well as a larger tent of 105 m^2 designated for dining facilities. Essential infrastructure considerations, including water supply, drainage, and waste removal, formed a key aspect of this assignment. The submissions were expected to indicate temporary water and sewage lines with distinct colors to differentiate clean water from wastewater, along with the strategic placement of waste bins throughout the site. Figure 3 shows a sample of students who designed a post-disaster assembly area in response to these requirements. The students were further tasked with designing units that adhered to specific criteria: they needed to be self-sustaining in the event of disruptions to energy, water, and sewage grids; deployable and modular for storage and transportation; and capable of being constructed as one- or two-story assemblies. Additionally, the units incorporated renewable energy sources such as solar and wind power and created open and semi-open quality spaces between them.

In addition to these tasks, students were introduced to a set of problems commonly encountered during the assembly process. These challenges include the high cost of production, which often conflicts with the limited economic resources available in the affected country and poses significant constraints on economic efficiency. Another issue highlighted was the lack of involvement of disaster victims in configuring and appropriating the space, which could hinder the development of environments that meet the actual needs and preferences of the community. Furthermore, there was inadequate adaptability to climatic variations and existing social configurations, resulting in designs that may not be suitable for diverse conditions. The assembly process also frequently requires specialized knowledge, which can complicate implementation if local teams lack the necessary skills or training. Lastly, students need to be aware of the unfamiliarity with the norms and principles set by specialized humanitarian and local agencies, which can create inconsistencies and delays in meeting established standards for disaster response[22]. These issues were presented to encourage students to think critically and propose design solutions to address these multi-layered challenges.

The importance of designing both outdoor and indoor spaces with equal attention was emphasized, as these spaces play a vital role in restoring a sense of normalcy and community interaction after a disaster. Outdoor areas can provide gathering

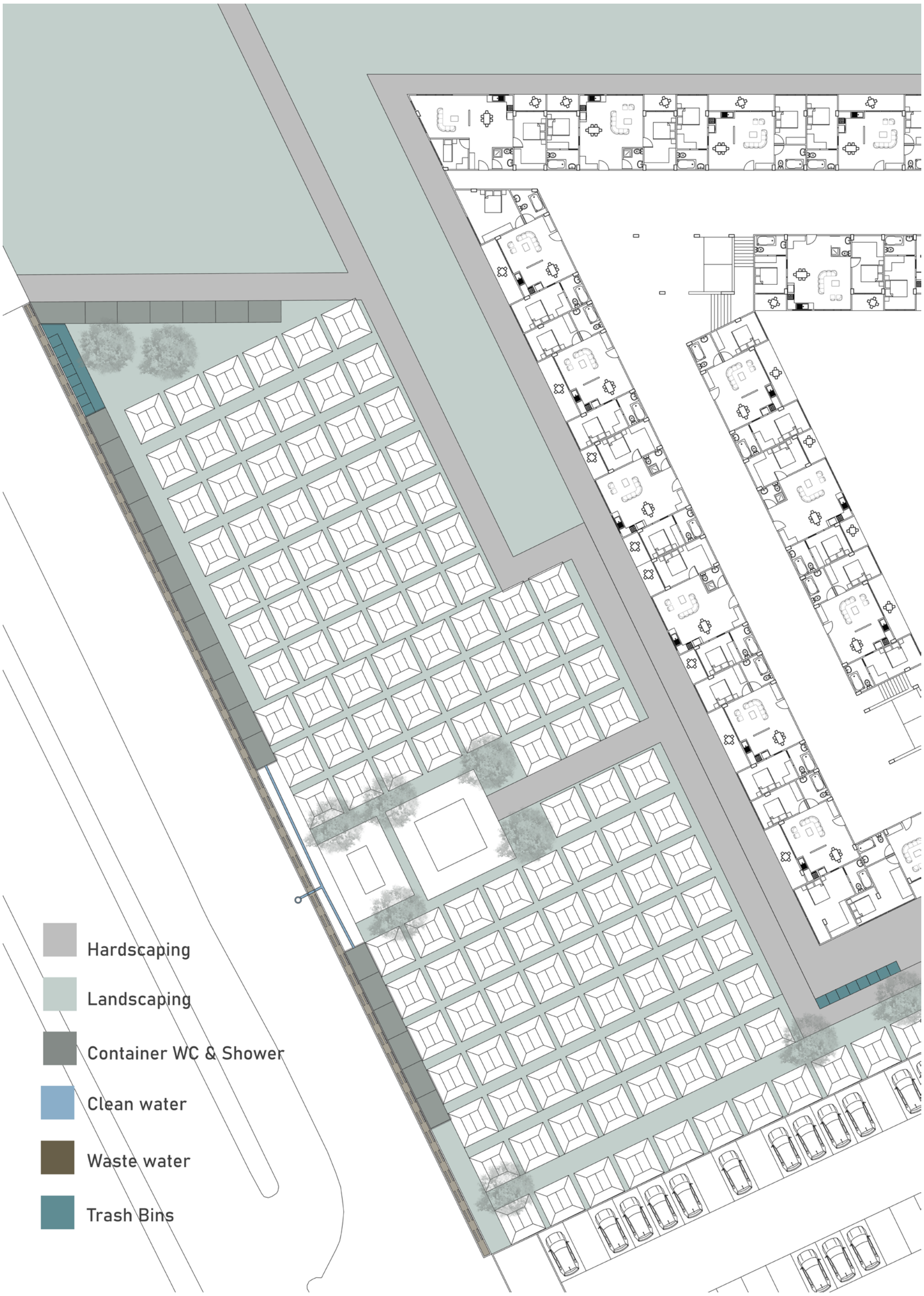

Figure 3. Post-disaster assembly area (2021) by Ciran Arslan.

spaces, promote social engagement, and support communal activities, whereas well-designed indoor spaces offer shelter and a sense of safety. By creating thoughtful transitions between indoor and outdoor environments, this design can foster social cohesion and encourage residents to reconnect, aid in the healing process, and rebuild a resilient community. While the students were guided to develop self-sustaining units for post-disaster scenarios, the primary focus was on assembling the units in a manner that aligned with item 5, which emphasized strategies for creating open and semi-open quality spaces. The students were encouraged to explore various geometric configurations in their designs (Figures 4 and 5).

The design problem, framed as a dual-purpose post-disaster assembly area, serves not only as an emergency solution but also as a conceptual model (Figure 6) for site planning during semester-long architectural design studios. This dual-function approach allows students to explore the complexities of creating adaptable and resilient spaces that can transition from emergency use to long-term community integration. It offers a microcosm of broader challenges in site planning, where considerations such as functionality, sustainability, and social interaction must be balanced within the constraints of temporary and permanent usage. Previously, deficiencies in building physics, such as inadequate thermal resistance, insufficient noise reduction, and poor waterproofing, have been observed in shelters. The in-situ slab foundations of these shelters resulted in “fields of concrete” after the systems were deconstructed, causing unacceptable environmental impacts. Analyzing Türkiye’s post-disaster experiences revealed that some shelters were never used or were only utilized after significant modifications by users. This situation can be attributed to a lack of preparedness in terms of planning, design, and management, which ultimately leads to the construction of low-quality temporary shelters erected under challenging conditions following a disaster[23]. By addressing these issues within the studio, students gain hands-on experience in designing versatile spaces that are prepared for unforeseen events, while contributing to the ongoing development of the built environment.

The course structure combines lectures and hands-on pop-up workshops for skill development in design and modeling alongside studio critiques. The assessment criteria for disaster awareness emphasize the effective application of disaster management concepts, creativity, and contribution to the concept of resilience. In the coming semesters, the proper and effective use of computational means will be part of the criteria as the level of computational skills of students rises.

Figure 4. Allocation of dual-purpose, post-disaster assembly area (2023) by Nilsu Ay and Elif Naz Uluca.

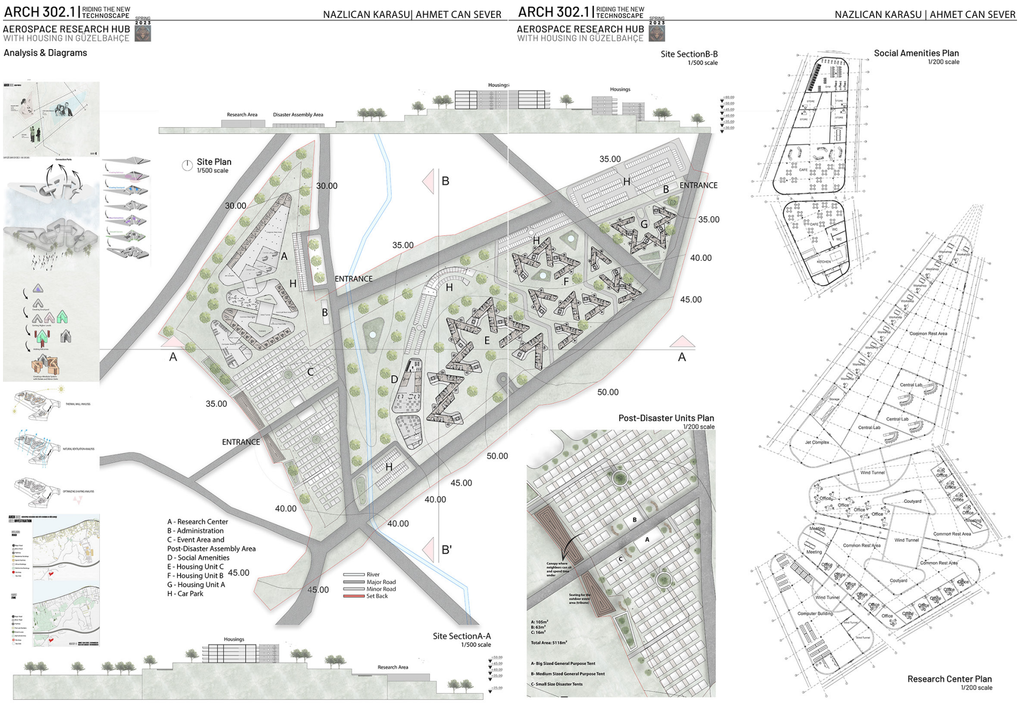

Figure 5. Third-year second-semester architectural studio Spring 2023. Post-disaster Assembly area design by Nazlıcan Karasu and Ahmet Can Sever.

Figure 6. Third-year second-semester architectural studio Spring 2024. Post-disaster Assembly area design by Aylin Akay and Selin Arslan.

Integration and Introduction of Computational Skills

As indicated earlier, the studio course is mostly integrated with computational concepts to encourage students to gain computational skills in parallel with their design processes. RH/GH definitions provide students with a vision to help them design parametric solutions. Therefore, they are encouraged to design growth scenarios that they would otherwise not be able to compute easily, and hence, have many more organizational possibilities. The integration of computational tools into architectural education, particularly in the context of post-disaster housing design, represents a significant advancement in the promotion of resilience in the built environment. In the context of earthquake-resistant architectural practices, the application of computational methods, including deep learning and image classification, offers innovative approaches for the early detection of structural irregularities[24]. This allows the identification of potential design flaws before reaching a critical point. The effectiveness of these techniques in assessing the compliance of structural systems has been demonstrated through the analysis of floor plan data, thereby facilitating prompt identification of torsional irregularities and other structural concerns. The integration of these computational capabilities into the curriculum enables students to develop data-driven strategies for the spatial organization of provisional dwellings, thereby optimizing the utilization of land, accessibility, and safety in the context of post-disaster scenarios. This methodology not only serves to bridge the traditional divide between the design and engineering disciplines but also equips prospective architects with the capacity to utilize digital tools in the construction of adaptable, disaster-resilient communities, examples for computational studies on earthquake mitigation prediction, etc.

As discussed in Section 2, significant emphasis was placed on how the units coalesced to create high-quality outdoor spaces. The students were tasked with proposing rules for the assembly generation process (Figure 7). To facilitate their exploration of growth scenarios, they were provided with GH definitions for utilization within the Rhino environment (Figure 8). Therefore, a customized Polar Fractal Definition was introduced to enhance design explorations.

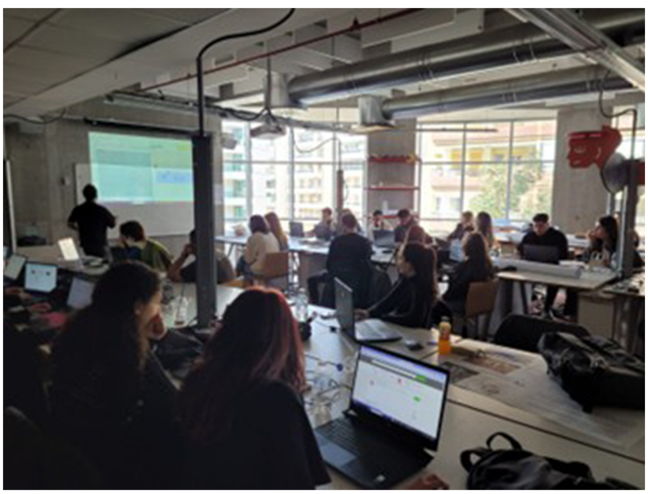

Figure 8. Studio Setting

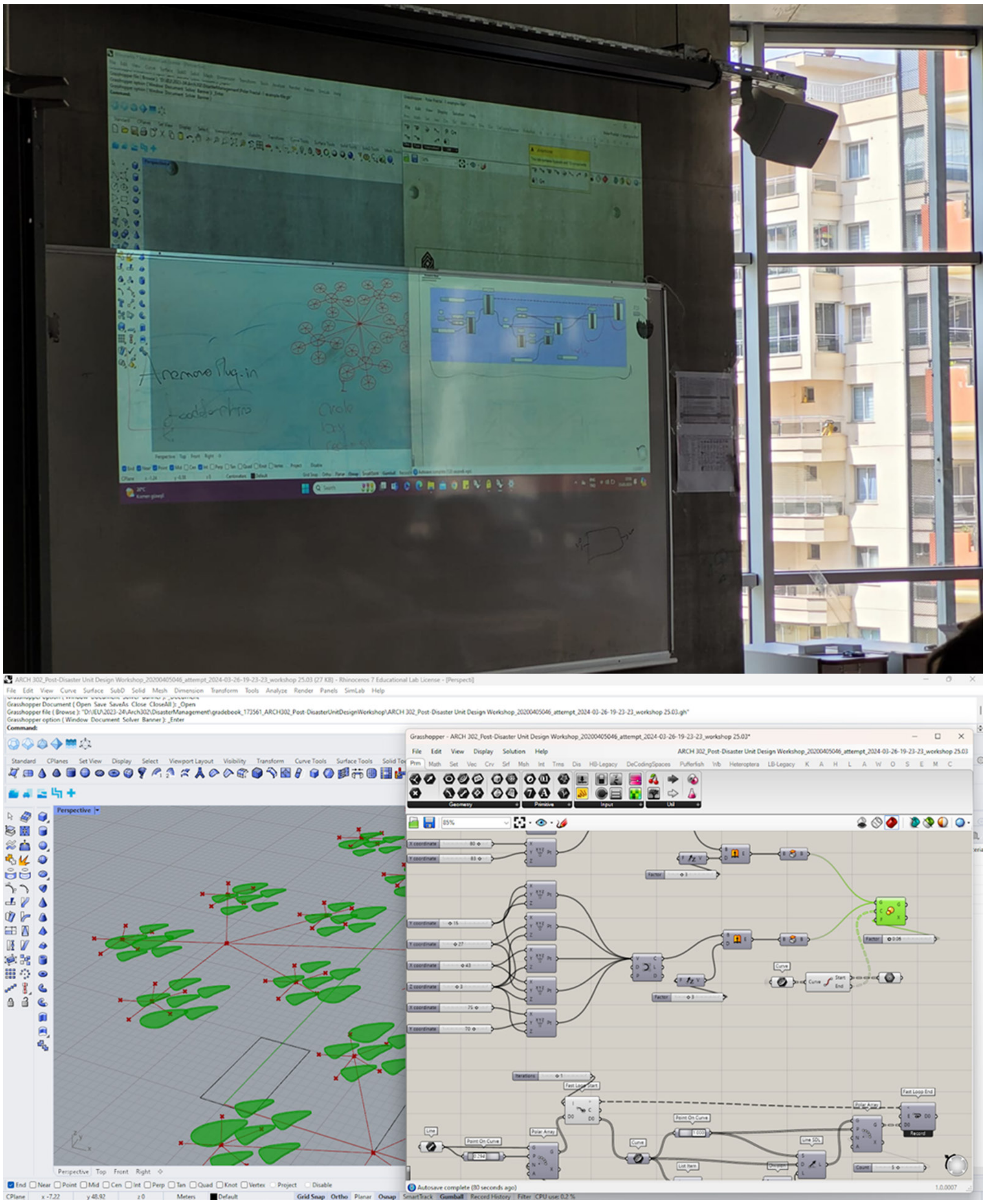

Figure 7. Workshop for computational rule generation of growth scenarios.

Through the application of computational methods such as parametric design and simulation tools, students can explore a variety of design possibilities, enabling them to assess the impact of various configurations on community dynamics and resource allocation. For instance, clustering strategies can facilitate more effective land use, ensuring that essential services, such as water supply, sanitation, and communal spaces, are easily accessible to residents (Figures 3 and 5).

The integration of computational skills fosters a data-driven approach to architectural design. Students are trained to analyze and interpret data related to disaster risks, demographics, and environmental conditions, allowing them to make informed design decisions that are responsive to real-world challenges. This analytical framework not only enhances the resilience of their designs, but also equips students with the capabilities necessary for collaboration with engineers, urban planners, and other stakeholders involved in disaster management.

Findings and Discussion

The ARCH 302 studio at IUE demonstrates a successful model for integrating disaster management principles, equipping students with the skills to design resilient communities in the educational framework. Through computational tools such as RH/GH, students tried clustering ideas, although the primary focus remained on site-specific research and disaster preparedness. The content addressed all phases of disaster management- mitigation, preparation, response, and recovery–by emphasizing the importance of dual-purpose space planning. While students engaged in practical challenges, such as affordability and sustainability, the integration of computational tools revealed a need for earlier exposure to digital methods in architectural education. This approach demonstrated the potential for architectural education to contribute to real-world disaster resilience, while also displaying areas for further curriculum development. As future architects, these students may promote not only safety but also social cohesion and environmental sustainability.

The educational framework employed within the studio has proven instrumental in conveying a comprehensive understanding of disaster preparedness and resilience. Notably, as an example, the approach of the students working on the “Co-living in Narlıdere project” (Figure 6) evolved significantly throughout the project development process. Initially, they allocated the post-disaster area into two zones, one of which was not thoroughly considered. However, after engaging more deeply with disaster-related concepts, they recognized that the proposed zone, located on a steep slope, was unsuitable and needed to be relocated to a flat plot, which was subsequently redesigned. Similar adjustments, stemming from the heightened awareness developed throughout the project, were observed across the studio outcomes as a whole. Concepts emphasized such as dual-purpose areas, clustering, and growth scenarios encouraged the students to rethink and introduce notions of dynamism and flexibility in architectural design decisions (Figures 4 and 5).

Two key proposals have emerged from this framework: the integration of mandatory safe zones within large plots, and the introduction of computational skills to enhance design strategies.

One of the most significant recommendations is the incorporation of mandatory safe zones within large plots of land, specifically defined as post-disaster assembly areas in project briefs, complemented by designated neighborhood gathering areas. This approach emphasizes the necessity for proactive disaster preparedness measures that prioritize the safety and well-being of communities in the event of a disaster. By strategically positioning safe zones throughout urban environments, these areas can serve as designated locations for immediate refuge during emergencies, reducing chaos and ensuring that community members have access to a secure environment.

From the planning of new areas to the revision of existing plans, earthquake risks should be considered at every stage. In this reconsideration, we suggest leaving post-disaster assembly places in areas over 2000 m^2. In this way, defining areas where we can intervene when a disaster occurs will be valuable for post-disaster studies.

Within the studio, incorporating gathering areas within the framework of safe zones fostered a sense of community resilience. These spaces can function as focal points for local interactions, enabling residents to come together for support, information-sharing, and coordination during disasters. This social cohesion is vital for effective disaster response, as well-connected communities are better equipped to assist one another in times of crisis. Furthermore, the design of these areas can be informed by local knowledge and cultural practices, thereby enhancing their relevance and usability.

In addition, the integration of safe zones into larger urban designs allows for a multifunctional approach to land use. These zones can be designed to serve various purposes beyond emergency response, such as recreational spaces or community gardens, thereby maximizing their utility and fostering a preparedness culture. This dual functionality not only enhances the value of the land but also promotes ongoing community engagement and awareness of disaster risks. The introduction of computational skills to the design curriculum has also been an aspect of preparing students for contemporary challenges in architectural practice. By encouraging the use of computational tools, students are empowered to develop efficient clustering strategies for post-disaster dwellings and optimize the spatial arrangement of shelters and facilities. This approach not only streamlines the design process but also enhances the overall functionality of temporary housing solutions.

Conclusion

This chapter has presented the case of ARCH 302 studio with proposals for mandatory safe zones and the integration of computational skills, reflecting a forward-thinking educational approach that prepares students to address the complexities of disaster management. Through the narrative of the studio course and the inclusion of disaster-related problems introduced into the course, the chapter discusses the urgency and necessity of such integration. By implementing a culture of preparedness and resilience, future architects can be encouraged to create designs that not only respond to immediate needs but also contribute to the long-term sustainability and well-being of communities facing the challenges of natural disasters.

The assignments, the problem of dual-purpose safe zones on-site, and the workshop on the use of RH/GH for clustering possibilities helped integrate disaster management principles with architectural site planning and an educational framework. This comprehensive and interdisciplinary approach is expected to provide future architects with the skills and knowledge needed to design resilient communities that can withstand and effectively recover from natural disasters. Beyond a deeper understanding of architectural design knowledge particular to natural disasters, the four-phase approach helps raise awareness of the social, cultural, political, and legal factors to be considered as part of disaster management.

Assigning students to clearly defined tasks to solve individually enhanced their focus on those specific tasks, enabling them to identify and understand the problem spaces associated with each one. This approach allowed them to practice the iterative process across various scales of architectural projects.

For ages, the gap between architectural design education and practice has been a significant problem peculiar to the discipline. Introducing real-life problems like natural disasters into the design studio may help bridge this gap. This strategy not only enables the students to address actual needs and situations by involving community members and other stakeholders in the design process but also gives them practical experience with the complex social and environmental elements found in real-world projects. Furthermore, young designers can easily adapt themselves to solutions to huge problems by taking new approaches without being influenced by old solutions.

We propose that the studio education model covered in this study prepares future architects to design resilient communities capable of withstanding and recovering from disasters by equipping them with the knowledge and skills to anticipate challenges, mitigate risks, and promote the long-term resilience of both urban and rural communities. In other architecture schools, further implementations of this model can be utilized to reach numerous design solutions to real-world environmental problems.

Funding

This research received no external funding.

Ethical Committee Approval

The authors provided consent from all the students whose work was included in this chapter. This work was approved by the Ethics Committee of İzmir University of Economics with file number E-97429853-050.04- 87839, on 10.12.2024

The data that support the findings of this study are available from the corresponding author, [L. Başarır, B. Pasin, İ.Kahraman], upon reasonable request.

Acknowledgments

The authors thank CORE symposium organizers, and studio instructors, specifically to A. Çağlar Şendikici, and the students who contributed to post-disaster design workshops of architectural design studio Third-year second-semester architectural design studio since 2020

Conflict of Interest

The authors declare no conflicts of interest.

References

1. Republic of Türkiye, “2023 Kahramanmaraş and Hatay Earthquakes Report.” [Online]. Available: https://www.sbb.gov.tr/wpcontent/uploads/2023/03/2023-Kahramanmaras-and-Hatay-Earthquakes-Report.pdf. Accessed: Sep. 18, 2024.
2. A. İ. Ünay and C. Özmen, “Building structure design as an integral part of architecture: A teaching model for students of architecture,” I*nternational Journal of Technology and Design Education*, vol. 16, no. 3, pp. 253-271, 2006, doi: 10.1007/s10798-005-5241-z.
3. A. I. Unay and E. Atimtay, “Developing earthquake consciousness in the architect,” *Architecture and Engineering: The Teaching of Architecture for Multidisciplinary Practice*, pp. 267–270, 1999.
4. A. Bashawri, S. Garrity, and K. Moodley, “An overview of the design of disaster relief shelters,” *Procedia Economics and Finance*, vol. 18, pp. 924-931, 2014, doi: 10.1016/s2212-5671(14)01019-3.
5. E. Acar and F. Yalçınkaya, “Integrating disaster management perspective into architectural design education at undergraduate level - A case example from Turkey,” in *Proceedings of the 5th World Construction Symposium*, Jul. 2016, pp. 284–293.
6. J. Duarte, “Inserting new technologies in undergraduate architectural curricula,” in *Predicting the Future: 25th eCAADe Conference Proceedings*, 2007, pp. 423–430.
7. S. Aşut, “Computational earthquake management: An educational perspective,” *Journal of Design for Resilience in Architecture and Planning*, vol. 5, no. 2, pp. 229-245, 2024, doi: 10.47818/DRArch.2024.v5i2129.
8. M. Morales-Beltran, “Effective architecture-seismic design integration in teaching practice: Elementary school design – case study,” in 16th World Conference on Earthquake Engineering, Santiago, 2017, pp. 1–10.
9. C. Theodoropoulos, “Seismic design education in schools of architecture,” presented at the 113th Annual ASEE Conference and Exposition, Chicago, IL, 2006.
10. M. Morales-Beltran, A. W. Charleson, and E. E. Aydin, “Sawtooth method for teaching seismic design principles to architecture students,” *Journal of Architectural Engineering*, vol. 26, no. 1, 2020, doi: 10.1061/(ASCE)AE.1943-5568.0000387.
11. O. Karadag and N. G. Canakcioglu, “Teaching earthquake-resistant structural systems in architecture department: A hands-on learning experience,” *Architectural Science Review*, vol. 67, no. 4, pp. 332–344, 2023, doi: 10.1080/00038628.2023.2288967.
12. A. Soyluk and Z. Y. Harmankaya, “Examination of earthquake resistant design in the education of architecture,” *Procedia - Social and Behavioral Sciences*, vol. 51, pp. 1080–1086, 2012, doi: 10.1016/j.sbspro.2012.08.291.
13. Z. A. Mahmoud, Y. Ahmad, and A. Alias, “Relevance to post-disaster recovery in undergraduate architectural education: A case of Southern Turkish universities,” *Pertanika Journal of Social Sciences & Humanities*, vol. 27, no. 1, 2019.

14. A. Charleson, *Seismic Design for Architects: Outwitting the Quake*. Oxford, UK: Architectural Press, 2008.
15. Acil Tasarım Stüdyosu (Emergency Design Studio), [Online]. Available: https://xxi.com.tr/i/odtululerden-acil-tasarim-studyosu. Accessed: Sep. 28, 2024.
16. Shigeru Ban Architects, [Online]. Available: https://shigerubanarchitects.com/works/paper-tubes/paper-log-house-turkey/. Accessed: Sep. 28, 2024.
17. İzmir Mimarlık Merkezi, "Afet Sonrası Hızlı Kurulabilir Yaşam Ünitesi Tasarımı ve Prototip Üretimi," 2024. [Online]. Available: https://www.izmirmimarlikmerkezi.com/projeler/afet-sonrasi-hizli-kurulabilir-yasam-unitesi-tasarimi-ve-prototip-uretimi. Accessed: Sep.28,2024.
18. A. Bodur, "The role of disaster management in architectural education in Türkiye," in *EJER Congress 2023 International Eurasian Educational Research Congress Conference Proceedings*, Ani Publishing, 2023, pp. 292–307.
19. J. Ashmore, *Tents: A Guide to the Use and Logistics of Family Tents in Humanitarian Relief*, OSHA, Ed. United Nations, 2004.
20. G. Saunders, *Transitional Shelters-Eight Designs*, Geneva: International Federation of Red Cross and Red Crescent Societies, 2011.
21. F. C. Karaoğlan and S. Alaçam, "Design of a post-disaster shelter through soft computing," *International Journal of Architectural Computing*, vol. 17, no. 2, pp. 185–205, 2019, doi: 10.1177/1478077119849694.
22. R. Frade, *Arquitectura de Emergência: Projectar para zonas de catastrophe*, Master`s thesis, Universidade da Beira Interior – Engenharia, Covilhã, 2012, p. 137.
23. M. S. Sener and M. C. Altun, "Design of a post-disaster temporary shelter unit," *ITU A|Z*, vol. 6, no. 2, pp. 58–74, 2009, Istanbul, Türkiye.
24. A. Er Akan, K. Bingol, H. T. Örmecioğlu, A. Er, and T. O. Örmecioğlu, "Towards an earthquake-resistant architectural design with the image classification method," *Journal of Asian Architecture and Building Engineering*, vol. 23, no. 1, pp. 157-170, 2023, doi: 10.1080/13467581.2023.2213299.
25. Oxford Learner's Dictionaries, [Online]. Available: https://www.oxfordlearnersdictionaries.com. Accessed: Mar. 23, 2025.

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Supporting Interdisciplinary Education in the Built Environment through Self- and Socially-Shared-Regulated Learning

Erdem Onan[1], Aleksandar Staničić[1], Serdar Aşut[1]

Tackling today's and tomorrow's societal, technological, and environmental challenges demands expertise that extends beyond the boundaries of any single discipline. Architects and engineers, in particular, must integrate knowledge and skills across domains while effectively communicating with professionals from diverse fields. In response, interdisciplinary education has gained momentum in built environment education, aiming to prepare students for this complexity by engaging them in challenges that mirror real-world problems. However, if experienced professionals struggle to navigate such complexities, how can students be expected to thrive in similarly demanding learning environments? This chapter addresses this question through the lens of self- and socially shared regulated learning (S-SRL). We begin by introducing a commonly used S-SRL model to provide a foundation for understanding how students regulate their learning individually and collectively. Building on this model, we explored the typical challenges students may encounter at various stages of interdisciplinary learning tasks. Furthermore, we review instructional tools and highlight their core design principles that help students overcome these challenges, while supporting the development of essential regulatory skills. In doing so, we offer educators practical insights into fostering personal and group responsibility for learning as well as the collaboration needed to achieve successful interdisciplinary education.

Keywords: Interdisciplinary education, self and shared regulated learning, instructional design, architecture education, built environment education

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INTRODUCTION

"Leyla, an architecture graduate student, joins an interdisciplinary team of students with the aim to design emergency housing in a remote area of Türkiye that has recently been struck by a disastrous earthquake. The idea behind the project is not to simply restore buildings as they were, but to 'build back better'. This means redesigning the emergency shelters in a sustainable and structurally resilient way while paying particular attention to climate adaptation, circular economy, recycling of available building materials, and mobilizing the local workforce - including their unique skills and know-how. The newest findings in the field of post-disaster urban renewal tell us that this novel interdisciplinary approach will contribute significantly to the region's long-term urban and social resilience. Leyla is enthusiastic about the prospect of sharing her knowledge with the world – recently she did a first year Master (MSc1) group project on post-disaster emergency design, where she and her fellow students tested some prefabricated modular solutions. The main premise of her project was how to reconcile the somewhat generic appearance of these models with local aesthetics and culture, arguing that beauty is an essential human need, especially in times of great distress. Furthermore, her rich contact with local authorities and stakeholders makes it possible for her to test some ideas with real-life actors, before implementing them in the project.

Despite her enthusiasm, however, Leyla is uncertain about what to expect from this project. In the first team meeting, students who were assigned as the main designers presented a vision emphasizing architecture in context: small open courtyards with a shared garden, ample natural light, a facade made of traditional building materials, and a technologically sophisticated roof with power-generating solar cells. The enthusiasm quickly faded when the student responsible for building technology raised concerns about structural feasibility and cost. Another student, representing the urban planning perspective, pointed out that in real-world cases, zoning laws might limit building height or restrict the garden's public use. Meanwhile, an environmental science student critiqued the design for its extensive use of glass, noting the potential for increased heat gain that could compromise energy efficiency. Although the discussion was lively, the team struggled to make progress. The architecture students defended the design, the engineers stressed feasibility, the planners raised spatial concerns, and the environmentalists emphasized sustainability – yet they seem to be talking past one another. Each discipline brings its own technical language and priorities, and it's left to the group to bridge these knowledge gaps collaboratively. As Leyla leaves the meeting, she feels a growing sense of uncertainty about how the team will move forward and what success will look like in such a complex, interdisciplinary setting.

Leyla's challenges were not unique to the project. Such difficulties are common in built environment education, where students learn to address complex real-world problems (e.g., sustainable urban development). These problems require professionals to collaborate across disciplinary boundaries, integrating knowledge and expertise from fields such as architecture, civil engineering, and urban planning. However, traditional education often leaves students unprepared for this kind of collaboration, offering limited opportunities for interdisciplinary teamwork[1]. Against this background, interdisciplinary education has gained prominence in contemporary built environment curricula and engineering education in general, with learning environments increasingly designed to confront students with problems that transcend a single discipline, reflect the complexity of professional practice, and prepare engineers for problems of an unknown future[2, 3]. These environments emphasize collaboration among students from diverse academic backgrounds, requiring them to integrate multiple perspectives, communicate complex knowledge, and address multifaceted problems[4]. By simulating the realities of professional practice, interdisciplinary education aims to equip students with the independent and empathic thinking needed to solve wicked social and technological problems of the future.

However, adapting to the demands of interdisciplinary education can be challenging for many students[5]. Such environments not only require students to demonstrate expertise across multiple disciplines, but also place greater demands on their ability to monitor and control both their own learning and their team's collective progress[6]. For instance, in a project requiring civil engineering, architecture, and environmental science students to collaboratively design a sustainable urban district, teams may experience content-oriented challenges, such as applying (inter)disciplinary knowledge to address the technical aspects of the design. Simultaneously, they may encounter process-oriented challenges, such as aligning project goals, building shared understanding, coordinating task distribution, and adapting plans in response to feedback and evolving needs. In our view, for interdisciplinary education to achieve its intended outcomes, it is imperative that students receive targeted support that addresses both the content and process-oriented demands of such projects.

In educational science, self-shared-regulated learning (S-SRL) are two frameworks that offers valuable insights into how students can be supported in navigating content- and process-oriented challenges. Self-regulated learning describes an intentional, goal-oriented process in which students direct their own learning by identifying goals, planning activities, monitoring progress, and adjusting strategies to achieve their objectives[7]. Socially shared-regulated learning extends this understanding to group settings, describing how students jointly establish learning goals, coordinate efforts, and respond to emerging challenges[8]. However, in interdisciplinary higher education, particularly in the built environment, S-SRL frameworks are not widely used to inform educational design, which, in turn, leads educators to miss important opportunities to design learning experiences that actively support students in managing the complex demands of interdisciplinary education. Accordingly, this chapter introduces the S-SRL framework in the context of built environment education, particularly for educators interested in designing interdisciplinary learning experiences. First, we define S-SRL and outline its key components. We then examine how interdisciplinary settings create conditions in which students may need support to overcome various challenges. Finally, we discuss practical tools for providing such support, aiming to contribute to a more responsive and well-aligned interdisciplinary education in the built environment.

Self and Socially Shared Regulated Learning

Researchers in educational science and psychology have long sought to understand why some students engage deeply with learning materials, persist through challenges, and adapt their approaches over time, whereas others struggle to sustain effort or rely heavily on external guidance[9,10]. This pursuit has led to the development of various theories and models that emphasize the role of students as active participants in their learning. A particularly influential line of research in this area is self-regulated learning (SRL), which focuses on how students exercise control over their cognitive (thoughts), motivational (beliefs), behavioral (strategies), and emotional (feelings) processes to achieve their learning goals[11]. Several theoretical models have been proposed to better understand how students self-regulate their learning. Although these models emphasize different aspects, they share significant overlaps, particularly in describing self-regulation as a cyclical and dynamic process[12]. Here, we defer Zimmerman's cyclical model of SRL[7] as it is widely recognized and offers a clear framework for understanding how students regulate their learning over time.

According to Zimmerman[7], SRL unfolds across three fundamental phases: forethought, performance, and self-reflection. In the forethought phase, students' task understanding and motivation laid the foundation for their subsequent learning activities. During this phase, students analyzed the task, set learning goals, and formulated plans to achieve those goals. Crucially, students' motivation, such as their interest in the task and the value they attach to learning, strongly influences their approach, including the strategies they employ to execute learning tasks; thereby influencing their performance[13,14]. In the performance phase, students put their plans into action by engaging in a learning task. Central to this phase are (a) the strategies students employ and (b) their ongoing self-monitoring of progress[15]. For instance, when preparing for an exam, students might rely on strategies such as rereading notes, creating flashcards, or summarizing key concepts[16]. Simultaneously, they monitored their progress by checking their understanding, assessing the effectiveness of their strategies, and adjusting their approach as needed. Finally, in the self-reflection phase, students evaluate their performance and make attributions; they interpret their success or failure by linking them to internal or external factors[17]. For example, students might attribute a high grade to their diligent study efforts (internal), or a poor result to what they perceive as an unfair exam (external). Completing the cycle, these reflections shaped students' motivation and planning for future tasks, potentially strengthening or undermining their self-regulatory efforts.

While earlier models of SRL, such as Zimmerman's cyclical model, focused on individuals regulating their own learning, they offer limited insight into the contexts in which multiple students learn together when they influence and are influenced by others (e.g., peers), such as during collaborative learning tasks, where any type of action is a product of negotiation between multiple individuals. Accordingly, the concept of SRL has been expanded to include co-regulation and socially shared regulation of learning, which accounts for how regulation can emerge and develop within social interactions[8,18]. Co-regulation refers to temporary, interactive forms of regulation in which one individual, often a more capable peer, guides or scaffolds another's regulation until the learner gradually internalizes those strategies. For instance, during a group assignment, a student may overlook monitoring whether their understanding of the task is sufficient. At this moment, a peer or tutor can prompt the student to pause and check their comprehension, encouraging them to reflect on what they know and identify any gaps. In contrast, socially shared-regulated learning describes a more reciprocal and collective process in which group members work together to regulate their joint learning. This involves identifying and establishing shared learning goals, creating a plan, monitoring learning at both the individual and group level, and adjusting their approach in response to evolving needs[19]. For instance, at the outset of a group project, team members might work together to clarify the task requirements, ensure that they have a shared understanding of the goals, and develop a joint plan for dividing responsibilities. Although both co-regulation and shared regulation represent forms of social regulation, the key difference lies in the direction and ownership of the regulatory processes: co-regulation involves one individual guiding another's regulation, whereas shared regulation refers to group members collectively managing their joint learning[8].

Notably, while much of the research on S-SRL has focused on how students monitor and control their cognitive processes, students can also regulate their motivation[20] and emotional processes[21]. For instance, students may sustain their motivation by reminding themselves of the personal relevance of a task (e.g., utility value interventions)[22] or manage their frustration when facing difficulties by reframing setbacks as opportunities to learn (e.g., cognitive reappraisals)[23]. These forms of regulation are particularly important in collaborative and interdisciplinary settings where students must navigate complex tasks, coordinate with peers from different backgrounds, and sustain their motivation over time. The following chapter explores how S-SRL unfolds in interdisciplinary education in built environments, highlighting the ways in which students may individually and jointly regulate their cognitive, motivational, and emotional processes to tackle shared challenges.

Interdisciplinary Education: Definitions and Instructional Approaches

Interdisciplinary education engages students in learning conditions that extend beyond the boundaries of a single discipline and exposes them to knowledge, skills, and methodologies from multiple fields. While it shares similarities with other cross-disciplinary approaches such as multidisciplinary education, it is conceptually distinct. In multidisciplinary education, for instance, disciplines are placed side by side, with each contributing its own viewpoint to a shared topic, but typically without integration. By contrast, interdisciplinary education emphasizes the intentional integration of disciplinary insights and methods to create new understandings that bridge boundaries, aiming to develop a synthesized whole that goes beyond the sum of individual disciplines[2,24,25]. Interdisciplinary education also differs from transdisciplinary education, which goes a step further by engaging stakeholders beyond academia, such as community members, professionals, or policymakers, and seeking a fusion of knowledge that breaks down traditional disciplinary structures altogether. Here, our goal is not to suggest that one approach is more advanced than another but to highlight their similarities and distinctive characteristics, which may in turn shape course design and influence students' learning experiences.

How is interdisciplinary education being delivered? In practice, there is no single recipe for designing interdisciplinary education. The approach to interdisciplinarity may depend on various factors, including the learning tasks and the backgrounds of students and course designers[26,27]. In this view, it lies on a spectrum that incorporates diverse elements or approaches toward interdisciplinarity. For instance, a course on earthquake resilience in a built environment can be designed using varying approaches and styles of interdisciplinarity. In terms of student composition, for example, at a minimal level, students might come from the same discipline with limited opportunities for interaction with peers from other fields. However, the course itself could still incorporate highly interdisciplinary learning tasks co-designed by experts in architecture, civil engineering, geosciences, and urban planning. In such a setup, even if students share the same disciplinary background, they engage with complex interdisciplinary problems that require them to integrate knowledge from various domains, such as site analysis, material innovation, seismic risk assessment, and policy regulations. This conceptualization of interdisciplinarity allows flexible education that can be adapted based on course objectives, diversity of student backgrounds, and desired depth of disciplinary integration.

In classrooms, interdisciplinary education is often implemented through active and learner-centered approaches such as problem-based learning (PBL) and project-based learning (PjBL). While a detailed discussion of these approaches is beyond the scope of this chapter, both are problem-driven pedagogies that engage students in complex, authentic, and often ill-structured problems (i.e., unclear problems with many answers)[28]. These approaches also place greater responsibility on students, requiring them to work independently (e.g., identifying what they know, determining what they need to learn) and collectively (e.g., distributing tasks and roles, negotiating perspectives) over an extended period while positioning teachers primarily as facilitators rather than direct transmitters of knowledge.

Although PBL and PjBL are widely used to deliver interdisciplinary education, these instructional approaches may impose significant challenges on students. The demand for navigating unfamiliar disciplinary content, integrating diverse perspectives, and managing collaboration among peers with different disciplinary priorities and interests can be particularly intense in interdisciplinary contexts. In what follows, we examine some of the challenges that students may encounter in PBL and PjBL within the context of interdisciplinary education by a) focusing on how these challenges may manifest across the cyclical phases of S-SRL, and b) exploring instructional support mechanisms that can help students navigate them effectively.

S-SRL in interdisciplinary education: An interdisciplinary approach to earthquake recovery

We based our discussion on a design studio on earthquake recovery in a built environment. It brings students from architecture, civil engineering, urban planning, industrial design, and geoscience programs to collaborate on the PjBL problem. Students were invited to form teams involving at least one member from each discipline. Teaching activities included workshops and lectures led by experts from various fields in the architecture, engineering, and construction industries. The course lasts 10 weeks and includes collaborative, design-based research, and assignments, where teams iteratively develop, test, and refine designs that address earthquake resilience. For example, a team can develop a post-earthquake recovery hub and shelter system in which students design a modular and scalable structure that can function as a temporary housing and community hub after an earthquake. By attending this course, students are expected to develop both content-related knowledge and expertise, as well as professional competencies, such as:

- Analyze the post-disaster context in relation to the different actors that determine the production of architecture in that context.
- Designing a sustainable and resilient architectural project in collaboration with selected experts.
- Evaluate the emerging architecture, instruments, and methods employed in its design and construction in relation to the collaborative process.

The assessment is based on submitted design projects, team and individual presentations, and individual reflection reports.

Supporting students during the forethought phase of S-SRL

One of the first challenges that students may face in our example arises from the process of establishing shared learning goals and building a shared understanding of the task, both of which are central to the forethought phase of S-SRL. Specifically, students from different fields bring diverse perspectives, disciplinary priorities, and professional identities, which can make it difficult to align expectations and agree on a common approach to problem-solving. Consider an example of designing a post-earthquake recovery hub and shelter system. Students must collectively determine not only what they are aiming to achieve, such as prioritizing modularity for rapid deployment, ensuring cultural appropriateness for community acceptance, integrating with urban infrastructure, or optimizing seismic resistance, but also how they interpret the scope, constraints, and success criteria of the task itself. These decisions require negotiation, mutual understanding of disciplinary contributions, clarification of assumptions, and coordination of goals and subgoals. However, these processes often do not come naturally to students with little or no experience in interdisciplinary teamwork, and misunderstandings at this early stage can hinder collaboration throughout the project, if left unaddressed.

In our view, such a diverse group of students, most likely with no interdisciplinary learning experience, can benefit from structured guidance and support. Järvelä et al.[29] proposed three key principles for designing instructional support: awareness, externalization, and prompting. First, a support mechanism should help students gain deeper insight into their thinking and motivational processes (i.e., awareness), both individually and as a group. This can involve reflecting on the personal goals, desired skills, and knowledge they want to develop, and self-assessments of their understanding and readiness for anticipated learning tasks. Second, students should have opportunities to externalize and share these insights with their group members (i.e., externalization), often through tangible outputs such as drawings and 3D models. Finally, an instructional support tool should prompt and activate students to translate their reflections into concrete next steps (i.e., prompting), keeping in mind both their individual learning and the group's collective work.

Radar and Our Planner are two tools commonly used in the literature to support students in group-learning activities. A radar is a visual diagram with multiple axes, which is derived from students' ratings of their individual and group-level cognitive, motivational, and emotional processes[29,30]. For example, students assessed their understanding of task demands (e.g., How well do you know what is expected of you?), and their confidence in their group's ability to complete the task successfully (e.g., Does your group have the necessary knowledge and skills?). These self-assessments are represented through a two-dimensional chart (a form of spider web, Figure 1) and serve as the foundation for reflection and group negotiations. Note that the dimensions of radar can be adapted, expanded, or reduced depending on the learning objectives or interdisciplinary nature of the task. For instance, in our case, an additional dimension could assess interdisciplinary competencies, such as students' appreciation of different disciplinary perspectives[25].

Figure 1. Our Radar adapted from Jarvela et al. 2016 (No further use allowed)

Note. Sample questions per dimension: Clarity of task goals: Do I clearly understand what needs to be accomplished? Clarity of roles: Do I understand what I expect to do? Individual Motivation: How motivated is I to engage in this task? Group Motivation: How committed is our group to doing well? Trust and Safety: Do I feel safe in expressing my questions, concerns, and options?

Similarly, Our Planner[29] is a structured planning tool designed to help students externalize and coordinate their individual and collective learning activities. Although similar tools have been proposed in the literature, such as the Individual Planner and Group Planner by Miller and Hadwin[31], they prompt students to respond to key questions related to various aspects of task understanding, goal setting, and action planning.

- Defining roles within the team (e.g., Who is responsible for which task?)
- Clarifying task demands (e.g., what are the key requirements and constraints of this project?)
- Setting goals (e.g., what do I aim to achieve in this phase?)
- Establishing a timeline (e.g., what are my/our deadlines and how will progress be tracked?)

By making these elements explicit and shared among peers, Our Planner helps students reflect on their own contributions, while also aligning expectations and strategies within the group. Overall, this dual focus on S-SRL may enable students to proactively plan, negotiate responsibilities, and adjust their approach as needed, thereby fostering more effective interdisciplinary collaboration.

Supporting students during the performance phase of S-SRL

The performance phase of S-SRL refers to how students perform learning activities (individually or collectively), while monitoring and adjusting their strategies as needed. In interdisciplinary education, this phase presents challenges owing to the complexity and unfamiliarity of the learning context. Students are often required to engage in cognitively demanding tasks such as conducting independent research, synthesizing knowledge from diverse fields, and learning to use specialized tools or software. In other words, interdisciplinary education, by design, immerses students in multifaceted problems spanning multiple domains of knowledge. To succeed, students must draw on a broad repertoire of learning strategies that support knowledge acquisition, skill development, and transfer of learning. However, research shows that many students struggle with selecting and applying effective strategies during their self-study, which is a major part of PBL and PjBL, thereby limiting their own learning[32,33]. To this end, research in cognitive and educational psychology has identified several evidence-based techniques that enhance learning[16]. These techniques include, but are not limited to, retrieval practice, spaced practice, and interleaved practice, so-called desirably difficult learning conditions–learning processes that impose higher mental effort on students, drop immediate performance, and benefit learning in the long run[34].

An individual study program that incorporates elements of desirably difficult strategies is illustrated in Figure 2. In a nutshell, retrieval practice involves engaging in learning activities that require students to recall information from their long-term memory without referring to learning materials. This can be achieved through various methods such as self-testing with flashcards, explaining concepts to themselves or their peers, or solving problems without immediate access to reference materials. These strategies strengthen memory retention, promote deeper understanding, and facilitate knowledge transfer across situations[35]. For instance, in the context of our interdisciplinary project, a student might use retrieval practice by sketching out a design principle discussed in a lecture, explaining the seismic load distribution to their peers, or mentally rehearsing how different materials respond to stress under earthquake conditions. Although these learning activities may initially impose higher mental effort and feel less productive, they ultimately enhance knowledge retention and support the transfer of learning across situations, key demands in complex interdisciplinary tasks.

Second, spaced practice refers to distributing study sessions over time rather than concentrating on all study efforts in a single session. This contrasts with cramming, where students attempt to complete their learning activities in the last minute, often through intensive and prolonged study sessions. In our example, students might space their efforts by revisiting site data at different project stages, refining structural calculations across multiple meetings, or periodically reviewing team feedback on the design drafts. Note that spaced practice does not require additional study time; rather, it ensures that the same total study time is distributed across timely intervals, allowing students to revisit the material periodically, strengthen their memory traces, and reduce forgetting.

Finally, interleaved practice involves alternating between different, yet related concepts, categories, or skills within a study session. This approach contrasts with blocked practice, in which students repeatedly focus on one topic or skill before moving on to the next. Interleaved practice is particularly beneficial because it encourages students to compare and contrast concepts, helps them recognize key differences, identifies underlying principles, and makes meaningful connections across topics[36,37]. For instance, in our interdisciplinary project, a civil engineering or architecture student might compare and sketch two structural solutions for seismic zones, such as reinforced concrete frames with shear walls versus light timber frames with cross-bracing. This form of practice helps students identify critical differences in material behavior, structural logic, and design implications while also deepening their understanding of how each solution performs under earthquake conditions. However, without instructional support, students may default on blocked practice because it is easier or more efficient, despite being less effective for long-term learning and transfer.

Day	Morning	Afternoon	Evening
Monday		Course session: Expert lecture on Structural Design Considerations in Earth-quake recovery	Prepare flashcards and self-quiz on design constraints in post-earthquake contexts: • Without reading notes, describe at least four structural and contextual constraints introduced during the lecture.
Tuesday	Compare and sketch two structural solutions for seismic zones. • Reinforced concrete frames with Shear walls • Light timber frame with cross bracing	Gym	Sketch site layout ideas based on Monday's session
Wednesday	Course session: Workshop on simulation tools		Team chat: How can we use what we learned in our design?
Thursday	Compare two post-disaster housing design approach-es. • Lightweight, modular housing used in rural Nepal • Reinforced concrete shelters deployed in urban Turkey	Revise initial design sketch	Dinner with friends
Friday	Revisit flashcards on key design constraints in post-earthquake architec-ture. Write a summary describing key similarities and differ-ences between structural solutions for seismic zones.	Plan next week's goals	

Figure 2. A sample weekly study plan using retrieval, spaced, and interleaved practice.

As mentioned, survey studies indicate that effective study techniques, including retrieval, spaced, and interleaved practices, are often underutilized by students[32,33]. Several factors may contribute to this issue, including a lack of knowledge and awareness of the effectiveness of these study techniques, as well as metacognitive illusions that arise from their desirably difficult nature[38]. Specifically, while effortful strategies often lead to better long-term retention, students may misinterpret increased difficulty as a sign of inefficacy, leading them to favor less-demanding but suboptimal study techniques[39,40]. Additionally, motivational barriers may play a role; students may perceive the effort required for these techniques to be unjustified given their low interest, limited time, or uncertainty about the long-term benefits[38,41].

From the instructor's perspective, a pressing question is: How can students be encouraged to engage in these effective study techniques more frequently? To address this challenge, several strategy training programs have been developed, such as Study Smart[42] and interventions based on the Knowledge, Beliefs, Commitment, and Planning (KBCP) framework[43]. While we refer interested readers to these specific studies, what these programs share is their emphasis on direct instruction, which helps students adopt more effective learning strategies.

- Closing knowledge and awareness gaps: Educating students about how learning happens, warning them about metacognitive illusions, providing explicit instruction on what different study techniques entail, when to use them, and why they work.
- Fostering students' confidence in these strategies: Helping students believe that these techniques will actually work for them by creating low-stakes learning opportunities where they can practice effective study strategies with their own learning materials without fear of academic consequences.
- Providing repeated practice and feedback: Encouraging students to engage in these strategies consistently over time, with guided practice, feedback, and reinforcement to help them integrate these techniques into their regular study habits.

At first glance, the design principles underlying effective strategy training appear to differ from those proposed by Järvelä et al.[29]. However, closer examination revealed a substantial overlap between the two approaches. For example, closing students' knowledge gaps and addressing misconceptions through direct instruction align clearly with the awareness principle. By contrast, the principle of externalization may seem less straightforward. Yet, it is effectively supported by training such as Study Smart, in which students are encouraged to engage in peer discussion and share their own experiences with strategy use. Such activities make thinking processes and experiences visible and socially grounded, adhering to the core features of externalization. Finally, creating repeated opportunities for practice directly supports the prompting principle, helping students translate new knowledge into action and experience the benefits of these strategies first. Together, these design principles offer practical guidance for educators aiming to design instructional support and interventions to help students overcome the challenges of S-SRL.

Supporting students during the self-reflection phase of S-SRL

Central to the self-reflection phase are students' assessments of their individual and collective learning efforts and their reactions to these assessments, wherein they make causal attributions about their successes and failures by linking them to internal or external factors[15]. Here, we identify two common challenges encountered by students. First, they may underappreciate or overlook the value of self- and group-related assessments. This process requires students to compare their current state of learning or performance against a benchmark – be it internal (personal goals or prior performance) or external (e.g., grading rubrics). While recognizing discrepancies between the current state and the desired state can create opportunities for improvement, it can also trigger negative emotions, such as anxiety, self-doubt, or frustration[44], particularly in summative and high-stake situations, where self- and group-assessment significantly impact grades. In such cases, students may view assessment as a threat to their competence and self-worth rather than a tool for personal growth, eventually hindering their engagement in self-regulated assessment activities.

Second, even students who recognize the value of assessment may struggle to accurately evaluate their individual and group-learning processes. Interdisciplinary education exposes students to unfamiliar disciplinary content, tools, and ways of thinking outside their academic training. As they work on complex, multifaceted problems, such as those involved in designing a post-earthquake recovery hub, they may find it difficult to judge whether they truly understand key concepts from other fields or whether their learning is progressing adequately. This difficulty is amplified by the limited time available to build foundational knowledge in unfamiliar areas, which can ultimately lead to students misjudging their learning, overestimating their comprehension, or feeling lost without knowing what is next. This metacognitive shortcoming, in turn, may prevent students from making necessary improvements in their learning at both the individual and group levels.

How can we encourage students to assess their learning and equip them to do so accurately? In their attempts to integrate Assessment for Learning and S-SRL research, Panadero et al.[45] highlighted the necessity of incorporating self- and peer-group assessment activities as a formalized component of instructional design rather than optional or informal practices. Additionally, Panadero and colleagues summarized several principles (Table 1), mainly derived from the Assessment for Learning literature, to implement self- and peer-assessment in classrooms.

Self-Assessment	Peer Assessment
Define the criteria by which students assess their work	Clarify the purpose of peer assessment
Teach students how to apply the criteria	Involve students in developing and clarifying assessment criteria
Give students feedback on their self-assessments	Determine the assessment format and mode of student interaction
Give students help in using self-assessment data to improve performance	Provide quality assessment training
Provide sufficient time for revision	Provide sufficient support for assessment
Do not turn self-assessment into evaluation by counting towards grades	Specify assessment activities and timetable
-	Monitor the assessment process and coach students

Table 1. Principles to implement self- and peer assessment trainings in classrooms.

Synthesizing and reflecting on these principles, together with those introduced earlier in this chapter, we agree that students should first be provided with clear instructions regarding the purpose and rationale behind self- and group-assessment activities, emphasizing their role in learning (i.e., assessment for learning rather than assessment of learning), following the awareness-principle. This introductory session can take place in one of the initial sessions, where students are introduced to course objectives as well as teaching and learning activities. During this session, students and instructors can also make agreements regarding the mode and function of these assessments, for example, whether or to the extent that they can be counted towards grades.

Second, it is essential to provide students with clear and valid standards for assessing both their individual and group learning processes. To this end, students can be given scripts or rubrics to structure their assessments and ensure consistent and valid evaluations. Scripts can take the form of structured prompts or step-by-step guidelines that lead students through the assessment process[46]. For example, in the recovery hub project, a self-assessment script might include prompts such as What disciplinary knowledge did I contribute to the team's design decisions on structural safety? To what extent did I engage with or learn from other fields? A group-assessment script might ask, Did we communicate effectively during the site analysis phase? How did we manage differences when selecting structural systems or materials? Unlike scripts, a self-assessment rubric might present specific dimensions of learning (e.g., goal setting, strategy use, and features of a quality product) with explanations that distinguish between different levels of proficiency (e.g., developing, sufficient, and proficient). In our example, a peer-assessment rubric might include dimensions such as collaboration during prototyping, constructive use of feedback, or efforts to bridge disciplinary gaps, each with clear performance descriptors, defining what constitutes weak versus strong performance. Note of caution: Students might come to see rubrics as checklists solely used for grading. It is therefore critical to link rubrics back to awareness principles, emphasizing their role in learning rather than assessment. Additionally, it is equally important to support externalization, encouraging students to make their thinking, assessments, and judgments visible and share them with their team members. Together, scripts and rubrics help students make more objective, accurate, and actionable assessments, reducing bias in their self- and group-assessments[46,47].

Finally, it is unlikely that students will immediately master how to assess themselves or the learning processes of their groups. Ideally, they should receive structured training on how to implement self- and group assessment, aligning with the prompting-principle. One way to facilitate this learning is through video modeling, in which students observe an expert or a more knowledgeable peer demonstrating and verbalizing the assessment process[48]. Research suggests that observational learning can help students develop a clearer understanding of assessment criteria and reflection techniques[48,49]. However, in practice, time and resource constraints often limit the feasibility of direct training methods. An alternative approach is to incorporate regular self- and group-assessment opportunities into coursework, ensuring that students develop these skills progressively through experience and feedback. By engaging in repeated assessment cycles, students can refine and improve their ability to evaluate their own and their peers' work, specifically when supported through scripts and rubrics. Where possible, providing feedback on students' assessments can accelerate this process and help them calibrate their judgments against more reliable standards. Additionally, repeated assessment opportunities are crucial to allow students to see tangible improvements in their work over time. Overall, this iterative process not only reinforces the importance of assessment as a learning tool but also contributes to the long-term development of self-regulatory skills.

Conclusion

Leyla's story and the challenges she encountered in her education highlight an important reality: neither the built environment nor the ways we teach about it through interdisciplinary approaches are shaped by architects or architectural students alone. Accordingly, preparing students for this reality requires more than relaying discipline-specific expertise, which is the focus of the traditional approach to the built environment education. Instead, this reality and the surrounding complexities call for the ability to work across domains, synthesize and integrate knowledge and skills from multiple disciplines, and communicate effectively, the so-called transversal skills that interdisciplinary education may (and aims) foster[24]. However, interdisciplinary education presents its own challenges, specifically for students navigating unfamiliar content, roles, and collaboration demands. In this chapter, we explore the challenges that students may encounter in interdisciplinary learning environments, focusing on them from the lens of self- and socially shared-regulated learning (S-SRL). Additionally, we examined some of the instructional support tools and mechanisms designed to help students overcome these challenges while gradually developing the knowledge and skills needed to address them independently.

We presented some of the common challenges that students may encounter during interdisciplinary learning situated within the forethought, performance, and self-reflection phases[15]. In the forethought phase, we highlight the difficulties that may result from understanding interdisciplinary learning tasks, establishing shared learning goals, and engaging in effective planning. In other words, reaching consensus on a joint roadmap, outlining both individual and collective learning activities, can be particularly challenging when students come from diverse disciplinary backgrounds (or take different roles in teamwork) and hold differing assumptions about the task. In the performance phase, we focused on the study techniques that students could select and use. Students often rely on familiar but suboptimal study techniques (e.g., highlighting or note-taking) that do not support deep understanding. Given the complexity of interdisciplinary tasks, which require rote memorization, as well as the synthesis and transfer of knowledge, it is essential that students use evidence-informed study techniques that enhance knowledge acquisition and transfer. Finally, in the self-reflection phase, we pointed out the challenges that may arise when students fail to evaluate their learning or are unable to do so accurately because of a lack of clear criteria or valid standards. This can hinder their ability to identify strengths and weaknesses, adjust strategies, and learn from experience, which are critical opportunities for their development as self-regulated learners.

Two important points should be acknowledged regarding the aforementioned challenges. First, these challenges are not necessarily unique to interdisciplinary contexts. However, the complexity and demands of interdisciplinary learning environments can intensify their prevalence or make them more visible. For example, establishing a shared understanding may be more straightforward in a mono-disciplinary project than in an interdisciplinary project, in which students must navigate differing assumptions, terminologies, and perspectives. Second, these challenges were neither exhaustive nor mutually exclusive. For example, in the forethought phase, students' task understanding is critical, but so are their motivational beliefs, such as self-efficacy and collective efficacy regarding their individual and group ability to succeed. Likewise, during the performance phase, students may already have difficulties typically associated with the self-reflection phase, such as neglecting to monitor their task understanding or evaluating individual and group performance. In this chapter, we primarily focus on the challenges that are (meta)cognitive and relational in nature, while setting aside a deeper discussion of the motivational and emotional challenges. We encourage future research to further investigate these dimensions and examine how they intersect the cognitive and social aspects of regulation in interdisciplinary learning.

Additionally, to address the challenges that students may encounter during interdisciplinary learning, we reviewed some pedagogical tools (e.g., Our Radar) and instructional approaches (e.g., the use of self-assessments). While each of these support mechanisms has been shown to effectively address specific challenges, such as planning, using effective study techniques, or engaging in self-reflection, our aim is not merely to present them as isolated interventions. Rather, we sought to highlight the common instructional principles that underpin these tools, particularly those that support the development of S-SRL. The first principle, introduced by Järvelä et al.[29], is awareness, which helps students recognize and understand the importance of approaching both the learning task and their individual and collective learning processes (e.g., thinking, motivation, and behaviors). The second principle is externalization, which is critical when students learn and work together. While students may reflect on their individual learning processes, if these reflections remain tacit or are not well communicated to their peers, they may miss out on the benefits of their awareness. The third principle is prompting – inducing students to take concrete action in response to the challenges and plans identified through awareness and explication. While we agree with Järvelä et al. on these principles, we further propose that external prompts (or any other support mechanism) should gradually fade away, enabling students to act independently over time. Crucially, this shift toward self-regulated actions is unlikely to occur through isolated or one-off interventions. Instead, students need repeated and sustained opportunities to engage with new strategies, tools, and ways of thinking while external support is gradually reduced. Accordingly, the fourth principle we propose is continuity: ensuring that support for S-SRL is not limited to a single activity or moment, but is embedded consistently across the learning experience. Together, these four principles provide a foundation for designing instructional support that helps students overcome the challenges commonly observed in interdisciplinary education while also enabling them to develop the essential regulatory skills needed to navigate complex, collaborative learning environments. By embedding these principles into interdisciplinary courses, educators can create conditions that not only support students but also prepare them to become skilled professionals.

In closing, the goal of this chapter is to introduce self- and socially shared regulation of learning (S-SRL) as a relevant and practical lens for both understanding common challenges and guiding instructional design in interdisciplinary education. By bridging research and practice and by highlighting actionable design principles, we hope this chapter offers educators a useful foundation for creating more supportive, responsive, and evidence-informed interdisciplinary learning environments.

The authors contribution:

Conceptualization: EO, SA, AS.

Writing - Original Draft: EO.

Writing - Review & Editing: SA, AS.

Supervision: SA, AS.

Acknowledgments

The research is supported by the TU Delft IDEE (Innovation in Delft Engineering Education) Initiative, Theme 1: "Students Taking Responsibility for Their Own Learning Process." We would like to extend our sincere gratitude to Dr. Margreet Docter, Dr. Muhterem Dindar, and Dr. Olga Ioannou for their valuable comments and feedback during the development and revision of this chapter.

Conflict of Interest

The authors declare no conflict of interest.

References

1. S. Oliveira, L. Olsen, L. Malki-Epshtein, D. Mumovic, and D. D'Ayala, "Transcending disciplines in architecture, structural and building services engineering: A new multidisciplinary educational approach," *International Journal of Technology and Design Education*, vol. 32, no. 2, pp. 1247-1265, 2022, doi: 10.1007/s10798-020-09645-3.
2. A. Van den Beemt et al., "Interdisciplinary engineering education: A review of vision, teaching, and support," *Journal of Engineering Education*, vol. 109, no. 3, pp. 508-555, 2020, doi: 10.1002/jee.20347.
3. W. H. Newell, "Designing interdisciplinary courses," *New Directions for Teaching and Learning*, no. 58, pp. 35-51, 1994.
4. L. R. Lattuca, L. J. Voigt, and K. Q. Fath, "Does interdisciplinarity promote learning? Theoretical support and researchable questions," *The Review of Higher Education*, vol. 28, no. 1, pp. 23-48, 2004.
5. M. MacLeod and J. T. van der Veen, "Scaffolding interdisciplinary project-based learning: A case study," *European Journal of Engineering Education*, vol. 45, no. 3, pp. 363-377, 2020, doi: 10.1080/03043797.2019.1646210.
6. M. T. O'Connell, C. Stöhr, P. Wallin, and R. Negretti, "Social regulation of learning in interdisciplinary groupwork," *European Journal of Engineering Education*, vol. 49, no. 4, pp. 683-699, 2024, doi: 10.1080/03043797.2023.2292258.
7. B. J. Zimmerman, "Becoming a self-regulated learner: An overview," *Theory Into Practice*, vol. 41, no. 2, pp. 64-70, 2002, doi: 10.1207/s15430421tip4102_2.
8. A. Hadwin, S. Järvelä, and M. Miller, "Self-regulation, co-regulation, and shared regulation in collaborative learning environments," in *Handbook of Self-Regulation of Learning and Performance*: Routledge, 2017, pp. 83-106.
9. B. J. Zimmerman, "A social cognitive view of self-regulated academic learning," *Journal of Educational Psychology*, vol. 81, no. 3, pp. 329-339, 1989, doi: 10.1037/0022-0663.81.3.329.
10. P. R. Pintrich and E. V. De Groot, "Motivational and self-regulated learning components of classroom academic performance," *Journal of Educational Psychology*, vol. 82, no. 1, p. 33, 1990.
11. M. Boekaerts, "Bringing about change in the classroom: strengths and weaknesses of the self-regulated learning approach—EARLI Presidential Address, 2001," *Learning and Instruction*, vol. 12, no. 6, pp. 589-604, 2002, doi: 10.1016/S0959-4752(02)00010-5.
12. E. Panadero, "A review of self-regulated learning: Six models and four directions for research," *Frontiers in Psychology*, vol. 8, 2017, doi: 10.3389/fpsyg.2017.00422.

13. N. Sandrine, F. Mariane, and B. Etienne, "Task value, self-efficacy and goal orientations: Impact on self-regulated learning, choice and performance among university students," *Psychologica Belgica*, vol. 47, no. 1, pp. 95-117 doi: 10.5334/pb-47-1-95.

14. D. H. Schunk and B. J. Zimmerman, "Motivation: An essential dimension of self-regulated learning," *Motivation and Self-Regulated Learning: Theory, Research, and Applications*, pp. 1-30, 2008.

15. B. J. Zimmerman and A. R. Moylan, "Self-regulation: Where metacognition and motivation intersect," in *Handbook of Metacognition in Education*: Routledge, 2009, pp. 299-315.

16. J. Dunlosky, K. A. Rawson, E. J. Marsh, M. J. Nathan, and D. T. Willingham, "Improving students' learning with effective learning techniques: Promising directions from cognitive and educational psychology," *Psychological Science in the Public Interest*, vol. 14, no. 1, pp. 4-58, 2013, doi: 10.1177/1529100612453266.

17. B. Weiner, "The development of an attribution-based theory of motivation: A history of ideas," *Educational Psychologist*, vol. 45, no. 1, pp. 28-36, 2010, doi: 10.1080/00461520903433596.

18. S. Volet, V. Marja, and P. and Salonen, "Self- and social regulation in learning contexts: An integrative perspective," *Educational Psychologist*, vol. 44, no. 4, pp. 215-226, 2009, doi: 10.1080/00461520903213584.

19. S. Järvelä and A. F. Hadwin, "New frontiers: Regulating learning in CSCL," Educational Psychologist, vol. 48, no. 1, pp. 25-39, 2013, doi: 10.1080/00461520.2012.748006.

20. C. A. Wolters, "Regulation of motivation: Evaluating an underemphasized aspect of self-regulated learning," *Educational Psychologist*, vol. 38, no. 4, pp. 189-205, 2003, doi: 10.1207/S15326985EP3804_1.

21. H. Järvenoja et al., "Capturing motivation and emotion regulation during a learning process," *Frontline Learning Research*, vol. 6, no. 3, pp. 85-104, 2018, doi: 10.14786/flr.v6i3.369.

22. S. J. Priniski et al., "The benefits of combining value for the self and others in utility-value interventions," *Journal of Educational Psychology*, vol. 111, no. 8, pp. 1478-1497, 2019, doi: 10.1037/edu0000343.

23. A. Ben-Eliyahu and L. Linnenbrink-Garcia, "Extending self-regulated learning to include self-regulated emotion strategies," *Motivation and Emotion*, vol. 37, no. 3, pp. 558-573, 2013, doi: 10.1007/s11031-012-9332-3.

24. A. R. Costa, M. Ferreira, A. Barata, C. Viterbo, J. S. Rodrigues, and J. Magalhães, "Impact of interdisciplinary learning on the development of engineering students' skills," *European Journal of Engineering Education*, vol. 44, no. 4, pp. 589-601, 2019, doi: 10.1080/03043797.2018.1523135.

25. L. R. Lattuca, I. Bergom, and D. Knight, "Developing a measure of interdisciplinary competence," *International Journal of Engineering Education*, vol. 29, no. 3, pp. 726-739, 2013.
26. I. Ashby and M. Exter, "Designing for interdisciplinarity in higher education: Considerations for instructional designers," *TechTrends*, vol. 63, no. 2, pp. 202-208, 2019, doi: 10.1007/s11528-018-0352-z.
27. E. J. H. Spelt, H. J. A. Biemans, H. Tobi, P. A. Luning, and M. Mulder, "Teaching and learning in interdisciplinary higher education: A systematic review," *Educational Psychology Review*, vol. 21, no. 4, pp. 365-378, 2009, doi: 10.1007/s10648-009-9113-z.
28. J. R. Savery, "Overview of problem-based learning: Definitions and distinctions," *Interdisciplinary Journal of Problem-Based Learning*, vol. 1, no. 1, 2006, doi: 10.7771/1541-5015.1002.
29. S. Järvelä et al., "Socially shared regulation of learning in CSCL: understanding and prompting individual- and group-level shared regulatory activities," *International Journal of Computer-Supported Collaborative Learning*, vol. 11, no. 3, pp. 263-280, 2016, doi: 10.1007/s11412-016-9238-2. (CC-BY license)
30. C. Phielix, F. J. Prins, P. A. Kirschner, G. Erkens, and J. Jaspers, "Group awareness of social and cognitive performance in a CSCL environment: Effects of a peer feedback and reflection tool," *Computers in Human Behavior*, vol. 27, no. 3, pp. 1087-1102, 2011, doi: 10.1016/j.chb.2010.06.024.
31. M. Miller and A. Hadwin, "Scripting and awareness tools for regulating collaborative learning: Changing the landscape of support in CSCL," *Computers in Human Behavior*, vol. 52, pp. 573-588, 2015, doi: 10.1016/j.chb.2015.01.050.
32. R. N. Blasiman, J. Dunlosky, and K. A. Rawson, "The what, how much, and when of study strategies: Comparing intended versus actual study behaviour," *Memory*, vol. 25, no. 6, pp. 784-792, 2017, doi: 10.1080/09658211.2016.1221974.
33. S. D. Rea, L. Wang, K. Muenks, and V. X. Yan, "Students Can (Mostly) Recognize Effective Learning, So Why Do They Not Do It?," *Journal of Intelligence*, vol. 10, no. 4, 2022, doi: 10.3390/jintelligence10040127.
34. E. L. Bjork and R. A. Bjork, "Making things hard on yourself, but in a good way: Creating desirable difficulties to enhance learning," *Psychology and the real world: Essays illustrating fundamental contributions to society*, vol. 2, no. 59-68, 2011.
35. S. K. Carpenter, S. C. Pan, and A. C. Butler, "The science of effective learning with spacing and retrieval practice," *Nature Reviews Psychology*, vol. 1, no. 9, pp. 496-511, 2022, doi: 10.1038/s44159-022-00089-1.
36. M. S. Birnbaum, N. Kornell, E. L. Bjork, and R. A. Bjork, "Why interleaving enhances inductive learning: The roles of discrimination and retrieval," *Memory & Cognition*, vol. 41, no. 3, pp. 392-402, 2013, doi: 10.3758/s13421-012-0272-7.

37. M. Brunmair and T. Richter, "Similarity matters: A meta-analysis of interleaved learning and its moderators," *Psychological Bulletin*, vol. 145, no. 11, pp. 1029-1052, 2019, doi: 10.1037/bul0000209.

38. A. B. H. de Bruin, F. Biwer, L. Hui, E. Onan, L. David, and W. Wiradhany, "Worth the effort: The start and stick to desirable difficulties (S2D2) framework," *Educational Psychology Review*, vol. 35, no. 2, p. 41, 2023, doi: 10.1007/s10648-023-09766-w.

39. E. Onan, W. Wiradhany, F. Biwer, E. M. Janssen, and A. B. H. de Bruin, "Growing out of the experience: How subjective experiences of effort and learning influence the use of interleaved practice," *Educational Psychology Review*, vol. 34, no. 4, pp. 2451-2484, 2022, doi: 10.1007/s10648-022-09692-3.

40. A. Kirk-Johnson, B. M. Galla, and S. H. Fraundorf, "Perceiving effort as poor learning: The misinterpreted-effort hypothesis of how experienced effort and perceived learning relate to study strategy choice," *Cognitive Psychology*, vol. 115, 2019, doi: 10.1016/j.cogpsych.2019.101237.

41. C. D. Zepeda, R. S. Martin, and A. C. Butler, "Motivational strategies to engage learners in desirable difficulties," J*ournal of Applied Research in Memory and Cognition*, vol. 9, no. 4, pp. 468-474, 2020, doi: 10.1016/j.jarmac.2020.08.007.

42. F. Biwer, M. G. A. o. Egbrink, P. Aalten, and A. B. H. de Bruin, "Fostering effective learning strategies in higher education – A mixed-methods study," J*ournal of Applied Research in Memory and Cognition*, vol. 9, no. 2, pp. 186-203, 2020, doi: 10.1016/j.jarmac.2020.03.004.

43. M. A. McDaniel, G. O. Einstein, and E. Een, "Training college students to use learning strategies: A framework and pilot course," *Psychology Learning & Teaching*, vol. 20, no. 3, pp. 364-382, 2021, doi: 10.1177/1475725721989489.

44. S. C. Weissgerber and M.-A. Reinhard, "Pilot study on the relationship of test anxiety to utilizing self-testing in self-regulated learning," *International Journal of Psychological Studies*, vol. 10, no. 4, p. 95, 2018, doi: 10.5539/ijps.v10n4p95.

45. E. Panadero, A. Jonsson, and J.-W. Strijbos, "Scaffolding self-regulated learning through self-assessment and peer assessment: Guidelines for classroom implementation," in *Assessment for Learning: Meeting the Challenge of Implementation*, 2016, ch. 18, pp. 311-326, doi: 10.1007/978-3-319-39211-0_18.

46. E. Panadero, J. A. Tapia, and J. A. Huertas, "Rubrics and self-assessment scripts effects on self-regulation, learning and self-efficacy in secondary education," *Learning and Individual Differences*, vol. 22, no. 6, pp. 806-813, 2012, doi: 10.1016/j.lindif.2012.04.007.

47. R. Krebs, B. Rothstein, and J. Roelle, "Rubrics enhance accuracy and reduce cognitive load in self-assessment," *Metacognition and Learning*, vol. 17, no. 2, pp. 627-650, 2022, doi: 10.1007/s11409-022-09302-1.

48. D. Kostons, T. van Gog, and F. Paas, "Training self-assessment and task-selection skills: A cognitive approach to improving self-regulated learning," *Learning and Instruction*, vol. 22, no. 2, pp. 121-132, 2012, doi: 10.1016/j.learninstruc.2011.08.004.
49. S. F. Raaijmakers, M. Baars, L. Schaap, F. Paas, J. van Merriënboer, and T. van Gog, "Training self-regulated learning skills with video modeling examples: Do task-selection skills transfer?," *Instructional Science*, vol. 46, no. 2, pp. 273-290, 2018, doi: 10.1007/s11251-017-9434-0.

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Hands-On Approaches in Architectural Education: Reflections from Urgent Design Studio

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This paper reviews the experiences of volunteers involved in Urgent Design Studio (UDS), a voluntary initiative at the Middle East Technical University (METU). Established in response to the 2023 earthquakes in Türkiye and Syria, the UDS provides temporary post-disaster spatial solutions in a collaborative, non-hierarchical, and interdisciplinary environment. The initiative brought together individuals from various academic levels and disciplines, with members contributing to all project phases. Volunteers engaged in hands-on practices and developed essential skills such as collaboration, design development, material selection, testing, implementation, and sponsor engagement. The initiative's learning-by-doing approach fostered problem-solving competencies and practical expertise. The UDS takes place at the intersection of education and practice by integrating academic theories with real-world applications. The collaborative nature of the initiative created a network of volunteers, academics, and professionals, with productive discussions on prototypes and projects. The initiative's presence in the academic environment shows that disaster relief design, including emergency architecture and 1:1 scale practice, needs to have a more significant place in architectural education.

Keywords: Architectural Education, Learning-by-Doing, Hands-on Practices, Collaborative Learning, Voluntary Network

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Introduction

Natural hazards such as earthquakes, floods, hurricanes, droughts, and heat waves become destructive when they intersect with human vulnerabilities, particularly in contexts lacking resilient infrastructure and effective management systems. Vulnerable settlements, especially in developing countries, often face heightened risks, resulting in significant losses of life and economic consequences. This vulnerability underscores the importance of integrating disaster resilience into architectural education to mitigate the impacts of these events[1].

Natural disasters claim approximately 40,000 to 50,000 lives globally each year and are often exacerbated by inadequate disaster preparedness and recovery strategies[2]. For instance, in 2023, the EM-DAT database reported 399 natural hazards that caused 86,473 deaths, affecting over 93 million people. Among these, the earthquake in Türkiye and Syria was the most devastating, resulting in 56,683 fatalities, affecting over 18 million individuals, and incurring economic losses of approximately 43 billion USD[3]. These statistics emphasize the urgent need for effective and applicable disaster management strategies, particularly for designing and planning resilient environments.

As discussed in the literature, disaster management strategies are defined under four main headings: "preparedness, mitigation, response, and recovery"[4-12]. While preparedness and mitigation can be grouped under pre-disaster strategies, response and recovery can be classified as post-disaster. Both strategies have various responsible parties, ranging from government bodies to individuals. However, the application of disaster management strategies is essential, and architectural education plays a crucial role[13].

Preparedness and mitigation in architectural education involve designing and planning built environments with disaster risks. This includes incorporating resilience strategies that minimize vulnerabilities and enhance recovery capacity. However, it was demonstrated that architectural curricula differ significantly across countries. For example, Japan, places considerable emphasis on disaster resilience, whereas Türkiye, despite its susceptibility to natural disasters, has not fully integrated this approach[14]. Although courses and programs provide interdisciplinary perspectives on spatial and architectural responses to disasters, these efforts often lack practical application. To bridge this gap, architectural education needs to prioritize hands-on learning opportunities that address disaster management, resilience, and temporary shelter[15].

Post-disaster strategies can be divided into two main phases: temporary and permanent. Temporary housing, a critical component of response strategies, requires detailed planning and collaboration among stakeholders to ensure availability, cost-effectiveness, and integration into the recovery process. Effective temporary housing provides basic comfort, proximity to essential services, and opportunities for community interaction. Hence, it fosters resilience and a long-term recovery. Strategies for temporary housing range from short-term solutions such as tents to long-term options such as container housing. These approaches must also consider sustainability, cultural sensitivity, and community involvement to ensure that they are aligned with local contexts and needs[16-18].

There are two main ways to provide temporary housing: top-down, provided by government agencies under official criteria, and bottom-up, in which the community participates in management and decision-making while concentrating on local resources and needs[19]. Architects must understand the local social and economic conditions to design structures that address community needs while adhering to regulations and building codes. Reconstruction should prioritize environmental and community resilience, leverage local resources, and rebuild infrastructure to enhance a community's ability to withstand future disasters[20-22].

Given the critical role that architects play in disaster management, it is essential to integrate pre- and post-disaster strategies into architectural education. While disaster relief, rehabilitation, and risk assessment have historically been overlooked in architectural curricula, the increasing frequency of disasters highlights the need for specialized knowledge in these areas[23,24]. Recent experiences indicate that such topics are often addressed only after catastrophic events, leading to temporary adaptations in the curriculum rather than becoming a permanent part of the architectural discourse. Informal and non-compliant reconstruction practices often exacerbate vulnerabilities, emphasizing the importance of equipping architects with skills to address disaster-related challenges.

The inherently transdisciplinary nature of disaster management presents challenges to its integration into architectural education. While many graduate programs in Türkiye focus on specific aspects of disaster management, such as its social, environmental, and technical dimensions, they often fail to address its multidisciplinary scope in practice. To overcome this, architectural programs need to collaborate with professionals from various fields to provide comprehensive training in disaster risk mitigation and reconstruction.

Effective disaster management education is further limited by a lack of industry engagement and professionals' research and development efforts in built environments[23-25]. Institutions are trying to develop programs that unite students and professionals, aiming to address gaps in education and raise awareness of the impact of disasters on the built environment[26]. Incorporating these subjects into architectural education permanently provides students with tools to understand how buildings interact with their environment and the role architects play in society. Nevertheless, initiatives become more active and visible in the absence of such systems. International and national initiatives, such as Architecture Sans

Frontières International, Architecture for Humanity, Habitat for Humanity, Article 25, and Herkes İçin Mimarlık (Architecture for All), actively bridge these gaps by involving built-environment professionals in disaster relief and risk management.

Hands-on learning is particularly crucial for architectural education in immediate disaster response scenarios. Design-build programs enable students to engage with both the theoretical and practical aspects of project design, providing them with valuable construction experience[27]. These programs promote the development of context-sensitive solutions by encouraging adaptation to the local climatic and cultural conditions. Furthermore, they foster teamwork and prepare students for the professional challenges of disaster response. Graduates of such programs are better equipped to address real-world problems, particularly in the dynamic and critical fields of disaster recovery and resilience[28,29].

These programs, initiatives, and approaches train students in collaborative learning environments by encouraging teamwork and cooperation. Exposure to material applications, construction procedures, and project delivery methodologies expands their skill sets, and they are better equipped to handle various real-life problems [30]. Architectural graduates who engage in experiential, hands-on learning along with theoretical frameworks may be better equipped to address real-world challenges, particularly in the evolving and critical field of disaster response.

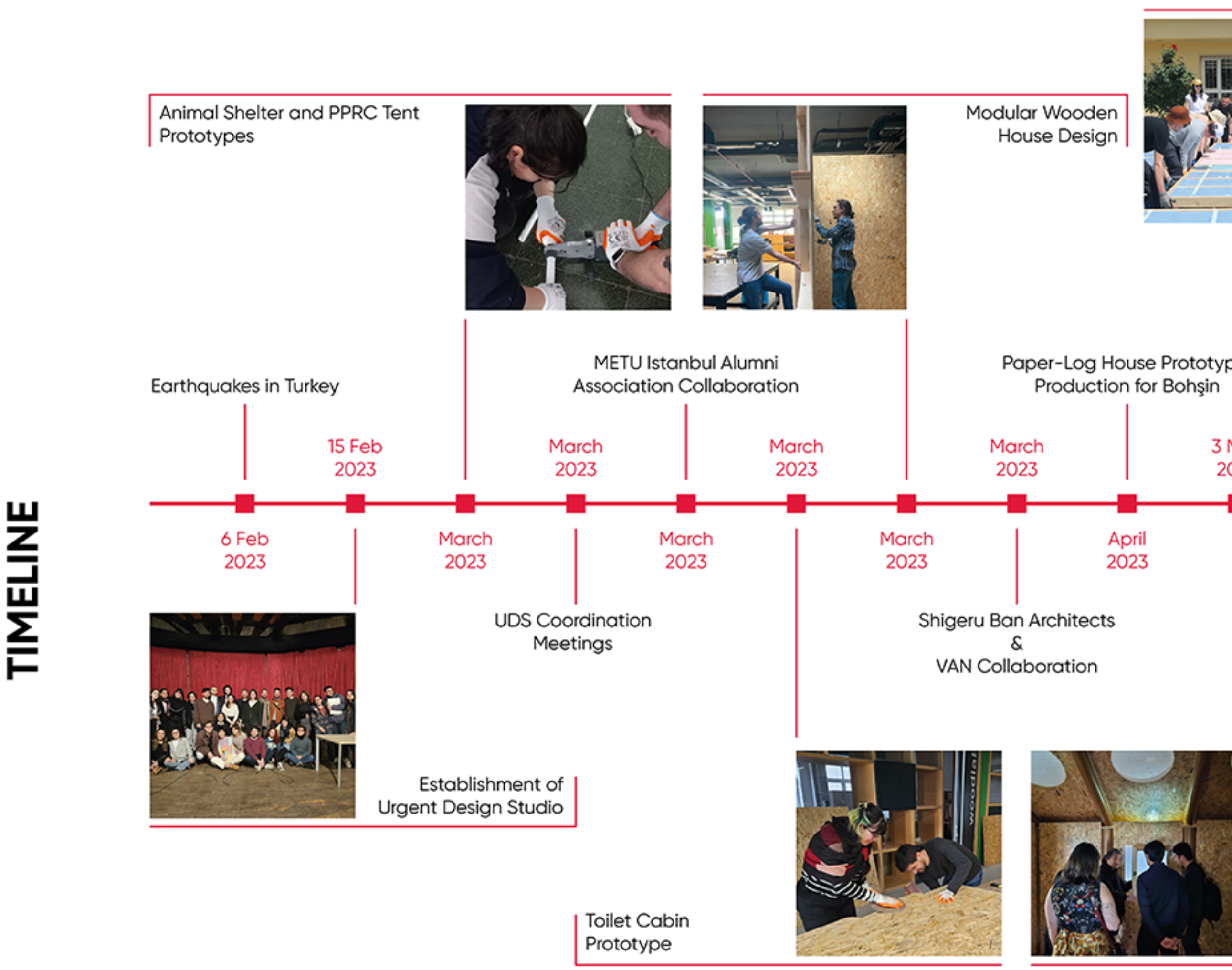
Urgent Design Studio (UDS), also known as Acil Tasarım Stüdyosu (ATS) in Turkish, was established in response to the lack of disaster management, pre/post-disaster strategies, and hands-on learning in architectural education in Türkiye. Since its inception, UDS has aimed to develop temporary post-disaster solutions through a bottom-up approach by integrating hands-on learning. This study examines the establishment and evolution of the volunteer initiative UDS, reflecting on the experiences of four volunteers. Through various perspectives such as interdisciplinarity, adaptation, production, and construction management, the volunteers deepen their engagement, emphasizing the initiative's collaborative learning environment.

Establishment and Development of a Voluntary Initiative: Urgent Design Studio

The devastating major earthquakes of February 2023, centered on Kahramanmaraş, affected multiple urban and rural areas of Türkiye and Syria. This has led to post-disaster relief efforts by NGOs, civil society organizations, and volunteers. Among these efforts, Urgent Design Studio (UDS) was established. From first-year undergraduates to Ph.D. candidates, volunteers and academics from different educational backgrounds gathered to develop temporary spatial solutions for earthquake-affected areas.

Since its initiation, the UDS has built a network of volunteers and experts across multiple fields, creating a non-hierarchical platform for collaborative learning. This effort, enriched by the contributions of individuals, institutions, and organizations, has fostered diverse perspectives and expertise to enhance the outcomes. Over time, the initiative has undertaken a wide range of projects, including easy-to-

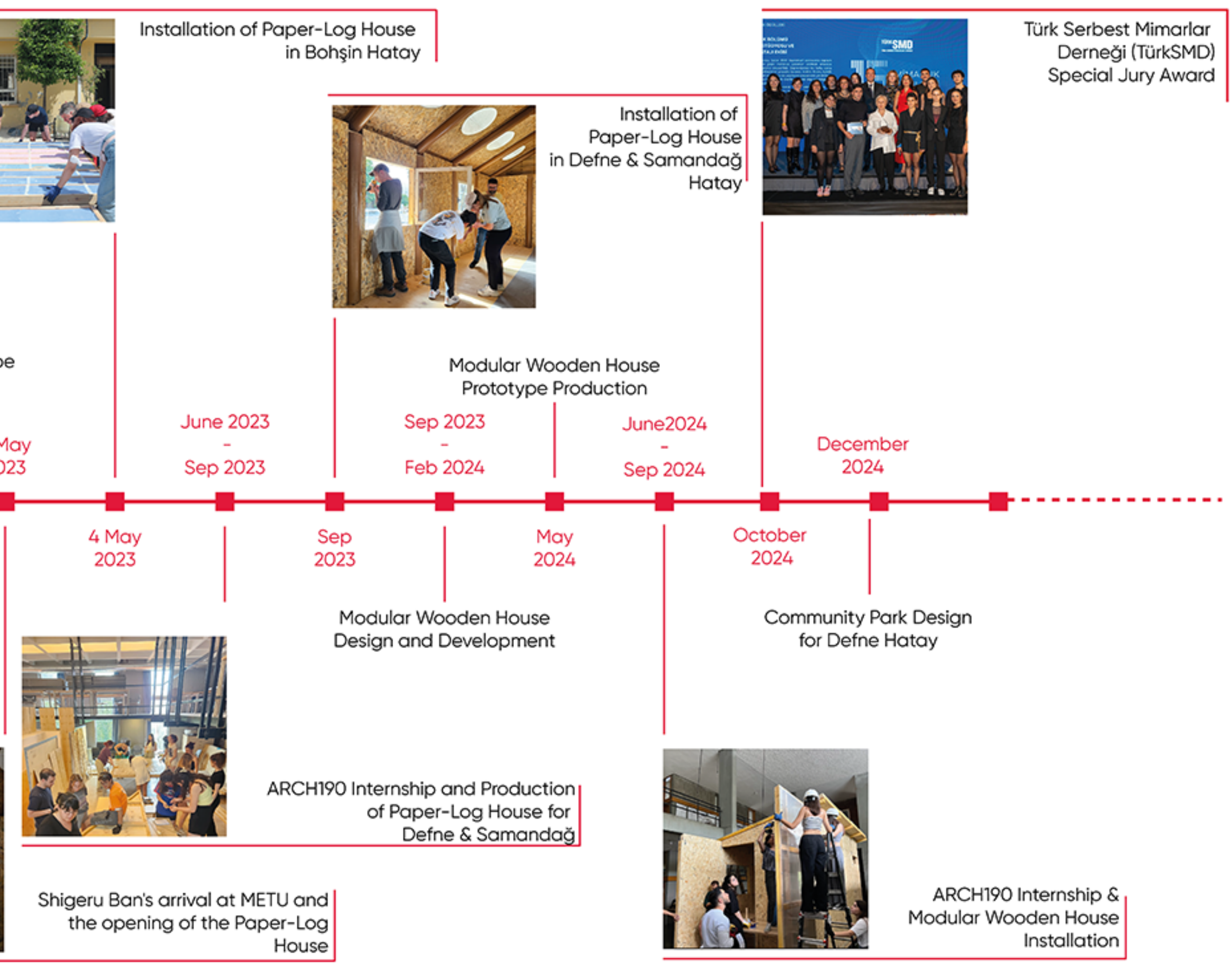
Figure 1. The timeline of the works of Urgent Design Studio. Image credit: Urgent Design Studio.



install dry toilets, PPRC tents, animal shelters, community park design, and post-disaster temporary housing solutions such as the Paper Log House and the Wooden Housing Unit (Figure 1).

Before introducing these two temporary post-disaster shelter projects, it is essential to examine the history of the hands-on summer internship program, “Introduction to Surveying and Construction Techniques,” at METU. Initiated in 1958, the program was conducted at the end of the second year of architectural education to bridge theoretical learning and practical application. Its purpose was to enable students to apply their skills to real-life scenarios, address underserved areas of the country, and support interactions among students, academics, and the community[31].

After being suspended between 1974 and 1999, the program resumed with first-year students replacing second-year students in 1999[31]. This continued until 2005, when faculty members designed buildings and coordinated the entire construction process, guiding students through the implementation of



small-scale structures built on-site[32] (Figures 2, 3)[33,34]. From 2005 to 2023, the summer internship program was conducted in different ways due to various practical, economic, and political challenges. However, with the efforts of the UDS and department, the 2023 and 2024 summer practices were conducted in a hands-on manner, involving the production and construction of a 1:1 scale Paper Log Houses and Wooden Housing Unit at the faculty.

The existence of hands-on summer internships has long served as both a source of motivation and a valuable educational experience in architectural training. The UDS has revitalized this heritage by reintroducing critical topics such as disaster management, pre-and post-disaster strategies, and practical learning. This revival was achieved through two main projects: the Paper Log Houses and the Wooden Housing Unit. In these projects, volunteers collaborated during the adaptation, design, and construction phases utilizing practical and hands-on approaches. Before delving into the individual reflections of the volunteers, this section provides an overview of two key temporary post-disaster shelter solutions.

Figure 2. METU Summer Construction Practice, Rize, Türkiye, 2003. Image credit: Onur Yüncü Architects, Source: 33. (No further use allowed)

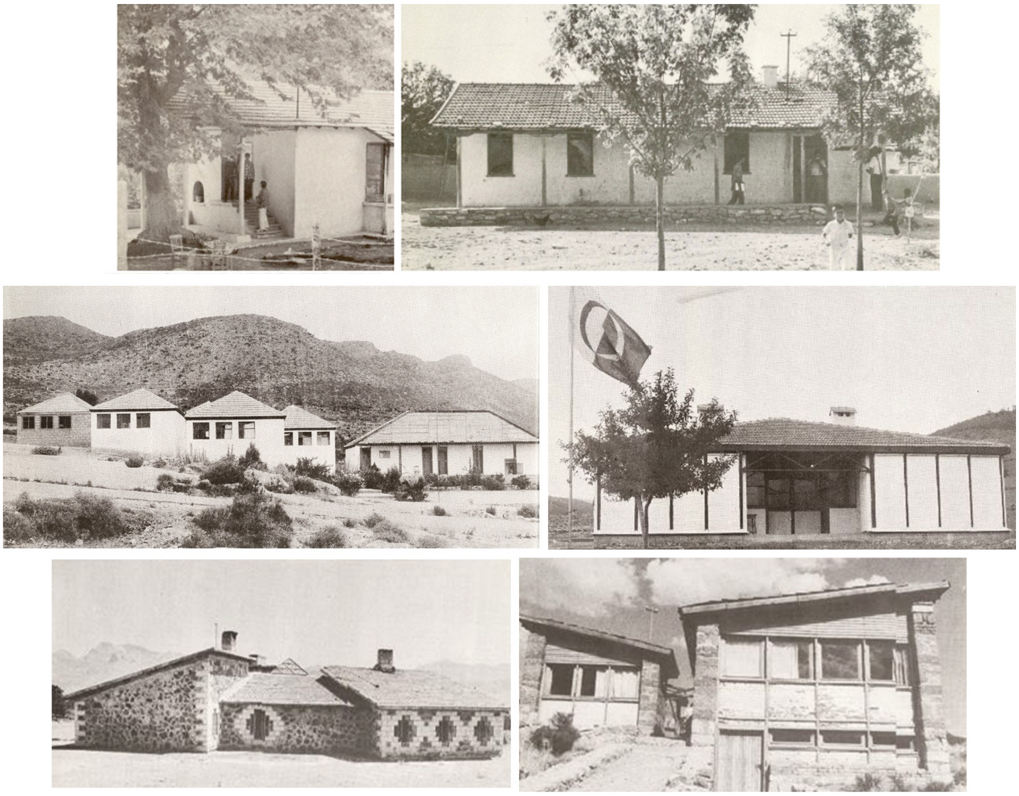


Figure 3. Examples from METU Faculty of Architecture Summer Practices. Image credit: Süha Özkan, Source: 34. (No further use allowed)

Paper Log House

Designed by Shigeru Ban Architects and the Voluntary Architects' Network (VAN), the Paper Log House was adapted with the UDS to address the local context. This collaborative effort was part of the UDS's broader initiative to explore alternative building materials for post-disaster emergency applications. Paper tube partition systems and temporary housing units were used in Türkiye for the first time after the 1999 earthquake[35]. Knowing this, the UDS reached the office for potential collaboration. The VAN and Shigeru Ban Architects expressed interest in collaborating with UDS volunteers, as they were already engaged in design and prototyping efforts for the 2023 earthquakes in Türkiye with the students at the Shibaura Institute of Technology in Tokyo. This collaboration began with a meeting on February 22, 2023, in which design modifications were discussed to accommodate locally available materials and address the specific needs of the affected region[36]. This collaboration was particularly significant as wood and paper tubes are rarely used in Türkiye's emergency shelter designs. With this guidance, the project underwent revisions informed by mutual discussions and the UDS-led market research. A dedicated group of volunteers finalized the adaptation process quickly, demonstrating the value of rapid, collaborative prototyping. After the adaptation phase, the construction of the first Paper Log House prototype began with the support of volunteers on April 3, 2023, at the METU Faculty of Architecture. The prototype was completed on May 3, 2023, before being dismantled and relocated to the Bohşin Primary School in Hatay. The following day, it was reassembled as shown in Figure 4. Following the integration of the initiative into the 2023 summer internship, two additional Paper Log Houses were produced. UDS volunteers and faculty members coordinated the construction of these houses for the Defne and Samandağ districts of Hatay. They were joined by new volunteers who participated after the internship. The houses now serve as spaces for art and play ateliers in the three schools in need of such facilities. The locations of these houses are shown in Figure 5.

Wooden Housing Unit

The Wooden Housing Unit was designed as a modular shelter to address the post-disaster housing needs in rural areas, particularly in remote villages. To ensure accessibility in regions where disaster-damaged infrastructure impedes transportation, these units are designed to fit approximately four units in a single small truck, compared with the need for a large truck to transport only two container houses[37-39].

The project adopts a phased approach, beginning with immediate relief through a quickly deployable initial module, akin to a tent. Additional modules can be added

Figure 4. Urgent Design Studio, Shigeru Ban Architects and Voluntary Architects' Network in Paper Log House Construction in Hatay, Türkiye 2023. Photo credit: Kenan Kantarcı. (No further use allowed)

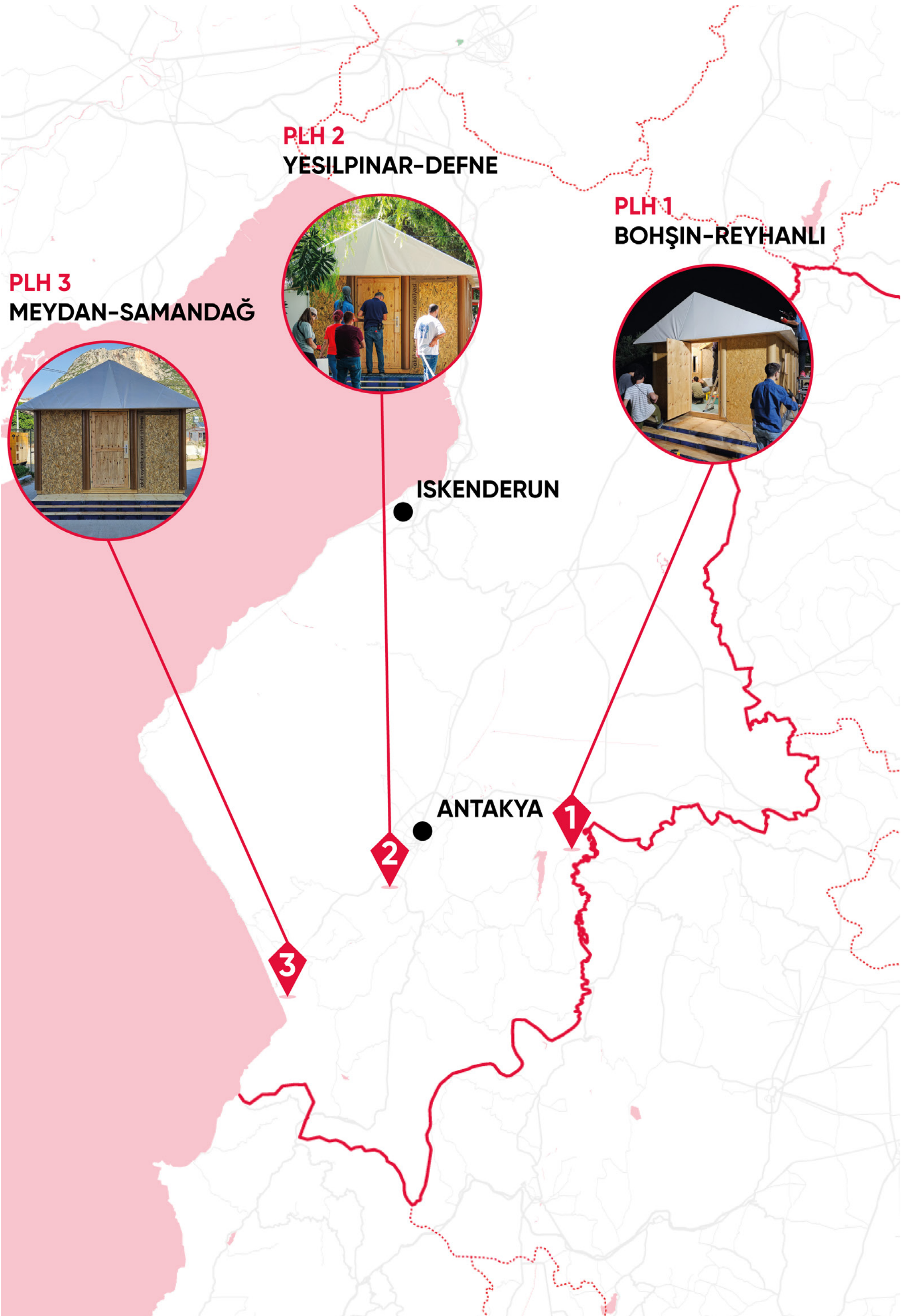


Figure 5. Constructed Paper Log Houses in Türkiye, 2023. Image credit: Urgent Design Studio.

over time to enhance functionality, thereby providing a flexible alternative to traditional container housing units. This modular design offers several advantages including lower logistics costs and increased adaptability. The design emphasizes modularity, standardization, and ease of construction, significantly reducing reliance on skilled labor. By incorporating standardized panel dimensions, the manufacturing process becomes more efficient, costs are reduced, and structural rigidity is enhanced. In addition, this modular approach supports user customization, allowing units to adapt and evolve into long-term living spaces (Figure 6).

Following the earthquake, factories across Türkiye shifted their focus to producing metal structures, tent materials, and containers, which led to a scarcity of commonly used materials. Therefore, wood was selected as the primary material for this project and served as a viable alternative. The materials were chosen based on their thermal insulation, water resistance, and structural stability to enhance the resilience of the unit to harsh environmental conditions and seismic activity.

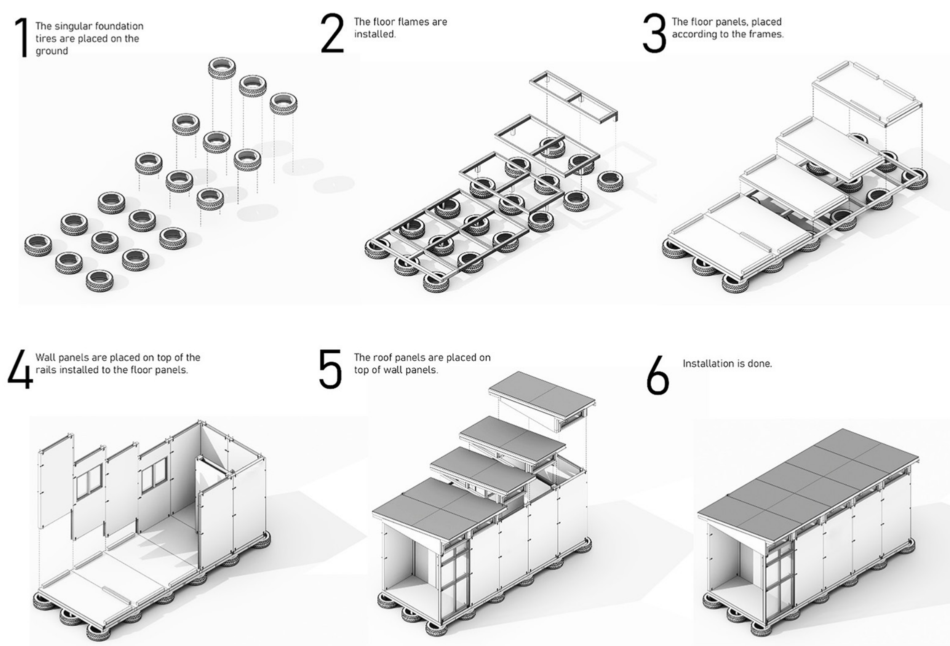


Figure 6. Axonometric diagram showing the installation process of the Wooden Housing Unit.
Image credit: Urgent Design Studio.

Reflections

Following the establishment of Urgent Design Studio (UDS), volunteers began developing temporary post-disaster solutions that could easily be assembled with minimal construction knowledge and experience, ensuring rapid deployment in disaster-affected areas. As volunteers engaged in these projects, a collaborative learning environment emerged. This chapter explores the insights of volunteers regarding disaster relief design, hands-on applications, and 1:1 construction processes within this context. Volunteers reflected on their experiences from various perspectives based on their involvement in two key temporary post-disaster projects.

Interdisciplinarity, the network between professional practices and academia

The network developed between academics and volunteers of UDS, and their interaction with professionals enriched the learning environment through topics such as collaboration, collectivity, and interdisciplinarity. From its beginning, the UDS became a hub in which volunteers collaborated to propose spatial solutions for disaster relief areas. The need for collaboration and an interdisciplinary approach arose from the situation's complex and practical challenges. It is essential to note that this collaboration was entirely volunteer-driven and did not have a hierarchical structure.

In its early days, the UDS focused on alternative materials and construction techniques by researching and consulting academics specializing in these areas. The initiative benefited from numerous presentations and lectures. Thus, lectures by Asst. Prof. Sibel Yıldırım Esen (Disaster Management and Planning), Nil Akdede (Post-Disaster Temporary Shelter Solutions), and Prof. Dr. Ali Gökmen and Prof. Dr. İnci Gökmen (Eco Villages and Compost Toilets) enhanced the knowledge of UDS members. These sessions provided valuable insights into disaster response strategies, sustainable materials, and innovative shelter solutions[36].

To translate these insights into practice, the UDS visited construction markets and industries to assess feasibility and merge academic knowledge with practical considerations. During these visits, volunteers gained firsthand experiences of critical factors, such as material availability, necessary tools, and transportation challenges. This knowledge was incorporated into design proposals, followed by prototyping and testing. The process equipped initiative members with skills to manage real-world constraints, including budget limitations and logistical issues.

Once design proposals were developed, collaboration with other practitioners became essential for production. The METU Faculty of Architecture Atelier and METU Campus Ateliers provided access to labs and tools. Volunteers worked alongside woodworkers, adhering to safety protocols while gaining hands-on experience. These craftspeople also volunteered their expertise and offered insights into the material properties, production processes, and tools. Collaboration and interaction with craftspeople were unique experiences for volunteers during their education.

Volunteers took on various roles throughout the installation of the Paper Log Houses and Wooden Housing Units. These projects have enabled UDS members to understand the potential of alternative materials. Shigeru Ban's visit and the accompanying public lecture brought together UDS members, academics, local architects, and students to foster collaboration on a larger scale (Figure 7). Additionally, integrating the UDS into an internship and elective course allowed more people to become familiar with the initiative, with some deciding to participate as volunteers. The involvement of these new members and the opportunity to interact with a variety of people have contributed to the continuity of volunteer-based initiatives.

The network developed through the UDS extended beyond Türkiye's building sector and academia. The initiative has engaged with various local and international associations and individuals, including the Architecture for All Association (Herkes İçin Mimarlık Derneği), the Architectural Recovery Team (ART) at TU Delft, and Prof. Ali Höcek of Höcek Architecture and Spitzer School of Architecture. Volunteers were active in meetings, where they not only shared their ongoing efforts and insights but also learned from the experiences and expertise of others. UDS's interdisciplinary approach, combined with its network, has been instrumental in encouraging collectivity and solidarity. By engaging with diverse stakeholders and real-world challenges, volunteers develop critical skills through mutual discussions in a non-hierarchical, collaborative learning environment.

Figure 7. Paper Log House opening in METU, 03 May 2023. Image credit: Turgut Polatel.
(No further use allowed)

Adaptation, production, and implementation

The adaptation processes for the two housing units followed distinct paths, reflecting the challenges of the post-disaster solutions. The Wooden Housing Unit emerged through iterative discussions and constructive feedback from professors and practitioners, emphasizing collaborative design. Factors such as wood types, clamp size, and logistics were evaluated throughout the design process to determine their economic and practical implications. Based on these considerations, the design was refined multiple times. In contrast, the Paper Log House was adapted from an existing design, with a focus on improving its practicality and resilience in earthquake-prone regions in Türkiye. This adaptation process prioritizes maintaining the integrity of the design while addressing local context and logistical constraints.

In this adaptation process, the UDS leveraged university resources to ensure practicality and integration of alternative techniques. The process focused on two key objectives: adapting building components for production and testing the durability of locally sourced materials. This involved selecting materials that were readily available in the Turkish market. Material thickness, size, and affordability were carefully considered to ensure feasibility and scalability. This approach aims to facilitate rapid and cost-effective production.

To validate the performance of the materials, the panels of the Wooden Housing Unit and paper tubes underwent rigorous strength testing at the METU Civil Engineering Faculty laboratories. These tests were used to evaluate the behavior of the materials under tensile and compressive loads, along with environmental testing on paper tubes. This environmental testing included exposure to a humidity chamber to evaluate durability under varying conditions (Figures 8 and 9). Based on these findings, the design was adapted to comply with Türkiye's building standards by incorporating test results into the final structure. These tests were conducted with the support of civil engineering faculty members and were observed by volunteers, with the results serving as valuable input to the process. This process also served as an introduction for volunteers to a laboratory environment, offering insights into how materials are performed under different conditions.

The 1:1 prototype testing, production, and implementation phases have become rare examples of architectural education in Türkiye in recent years, because of the economic and social challenges in the field. The UDS embraced a 1:1 practice with alternative construction materials and temporary spatial solutions for earthquake-affected areas. Additionally, its members were involved in the projects from the initial design phase. The volunteers managed small-scale projects, such as toilets and animal shelters, and handled the Paper Log Houses

Figure 8. Durability testing in the METU Civil Engineering Department. Photo credit: Urgent Design Studio.

Figure 9. Material in the humidity test chamber in the METU Civil Engineering Department. Photo credit: Urgent Design Studio.

and Wooden Housing Unit's development, production, and construction (Figure 10). These educational experiences significantly enhanced the practical skills of volunteers.

Design strategies, construction techniques, and detailing

Material experimentation and real-world challenges were central to projects of varying scales. Testing different materials allowed members to assess their durability, cost-effectiveness, and practicality for disaster relief applications. Addressing real-world needs, such as alternative temporary housing, required innovative and functional solutions. For example, the Wooden Housing Unit was designed to facilitate rapid installation while maintaining an adaptable modular structure. This objective guided decision-making throughout the design process, particularly in material selection. A key feature of the design was using clamps to connect the panels, enabling quick installation and a flexible modular system. In addition, the UDS opted for identical or similar sandwich panels that were easy to manufacture, transport, and install. To further streamline construction, the clamps allowed for quick assembly, disassembly, and potential expansion of the units without the need for electrical tools or specialized equipment. As shown in Figure 11, the installation process was designed to minimize labor and time using pre-constructed panels. These panels were composed of OSB surfaces, insulation layers, and timber frames. The incorporation of alternative materials enhanced efficiency and sustainability. Considering the region's infrastructure challenges, the unit was designed to be built without cranes, electrical devices, or heavy machinery, making it easy for anyone to assemble. This approach

Figure 10. Dismantling of the Paper Log House in the METU Faculty of Architecture, 2023. Photo Credit: Beril Kapusuz. (No further use allowed)

emphasized the importance of scalable, adaptable, and sustainable solutions. Integrating photovoltaic (PV) and sandwich panels addressed environmental and energy concerns, making the unit suitable for disaster relief scenarios in which the electrical grid is damaged.

The Wooden Housing Unit project serves as a crucial link between disaster strategies and practical applications. Volunteers gained a deeper understanding of the material properties, allowing them to optimize material use based on their behavior. The project also highlighted the complexities of developing temporary

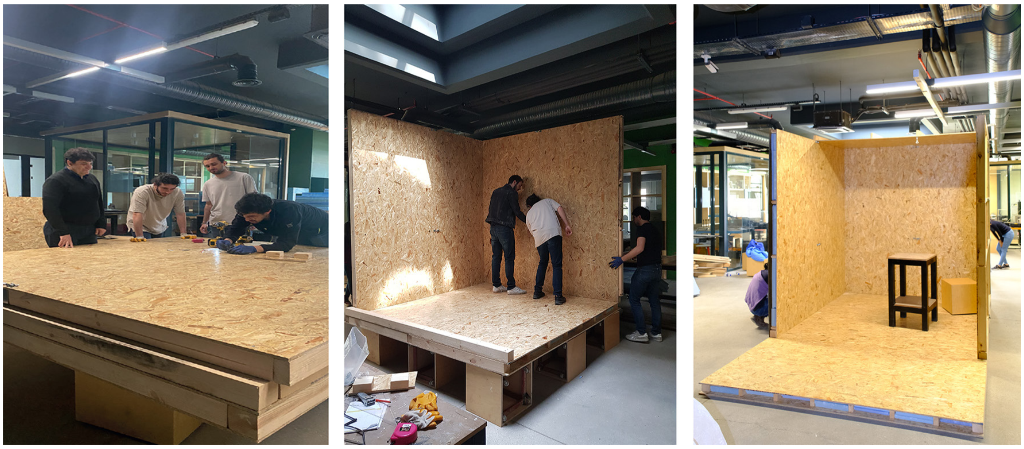


Figure 11. Wooden Housing Unit in the METU Faculty of Architecture, 2023. Photo Credit: Urgent Design Studio.

shelters, particularly the difficulty in integrating alternative building materials into a system that requires minimal construction skills. These challenges underscore the need for continued research on innovative shelter solutions for earthquake-affected regions.

Market research, sponsor engagement, and construction management

Market awareness and sponsorship are crucial factors in UDS' design and construction processes. Material selection and design must align with project budgets and adapt to the market conditions. By working on 1:1-scale projects, volunteers gain direct exposure to the local market and learn how to create affordable design solutions while ensuring that resources are accessible to those in immediate need.

Volunteers developed valuable communication and negotiation skills through their involvement in the sponsorship process. They participated in every stage from identifying project requirements to conducting quantity calculations for construction projections. They also engaged with potential sponsors and navigated the economic challenges of securing support. This collaborative approach fosters innovative thinking while balancing diverse stakeholder interests.

Projects often require adjustments to address unforeseen challenges and volunteers to solve problems efficiently within budget constraints and material shortages. Through this process, volunteers gained essential skills in resource management, strategic planning, and stakeholder negotiations. These experiences provide significant professional growth opportunities and offer practical insights into the design, construction, and project management.

Construction management is a critical component of the UDS workflow (Figure 12). Given the changing number of volunteers for different tasks, they need to follow the entire process seamlessly. Therefore, preparing a guidebook, breaking down workloads into daily tasks, and reorganizing schedules were crucial steps to provide valuable lessons for project management. Volunteers contributed to the designated shifts in their available time, as all participants were continuing academic responsibilities.

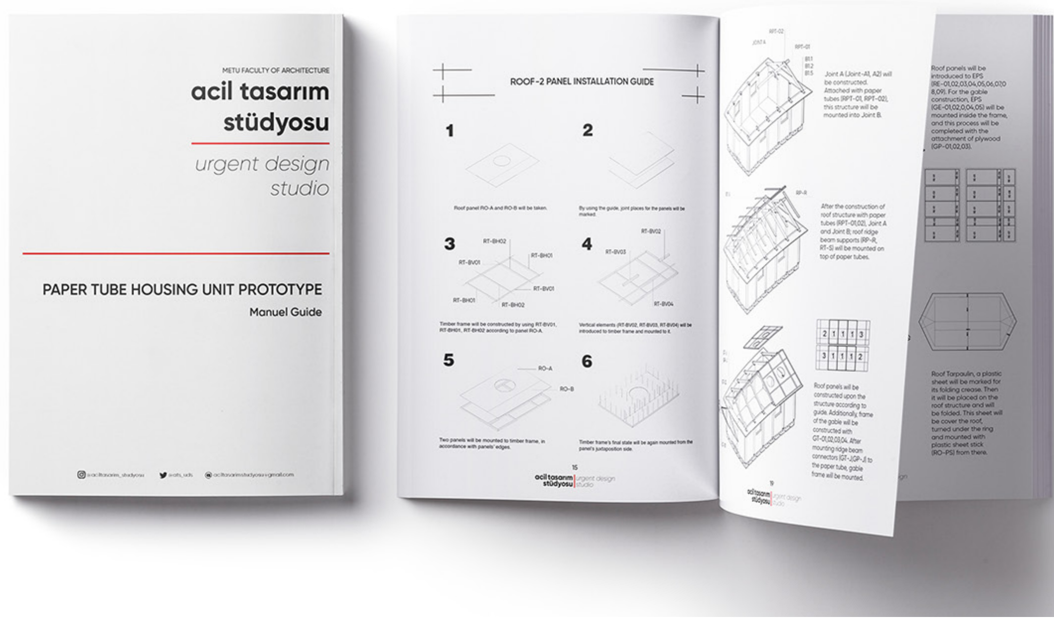


Figure 12. Construction Guidebook for the volunteers in the Paper Log House Construction, 2023.
Image credit: Urgent Design Studio.

Discussion and conclusion

Following the 2023 earthquake in Türkiye and Syria, nations faced the urgent task of addressing immediate relief efforts and long-term recovery strategies. In response, various individuals, institutions, and initiatives were mobilized to support affected communities. Among these efforts, Urgent Design Studio (UDS) was established to develop temporary, adaptable spatial solutions for post-disaster scenarios. Rooted in a "learning-by-doing" framework, the UDS fosters problem-solving skills and enhances practical expertise through hands-on engagement with practical constraints. Through this process, UDS has emerged as a dynamic, interdisciplinary network that connects academics and professionals, while enabling participants to contribute to the iterative development of prototypes and projects. This review examines the development, impact, and innovative methodologies of UDS while exploring its broader implications for architectural education and practice. Additionally, it reflects on volunteers' experiences, analyzes their engagement, and the challenges encountered throughout the different project phases.

Despite these achievements, the UDS also reveals gaps and limitations that warrant further exploration. One primary challenge is the scalability and long-term viability of solutions developed within the initiative. Further research is needed to assess the long-term durability, affordability, and effectiveness of materials and construction techniques in varying climatic and socio-economic conditions. In addition, integrating disaster-relief projects into architectural education faces institutional barriers. The non-hierarchical and interdisciplinary nature of UDS challenges conventional pedagogical structures, necessitating a broader curricular shift to incorporate experiential learning, engagement in practice, and collaborative problem solving. Additional studies should examine how architectural programs can institutionalize and sustain these methodologies on a larger scale.

Another critical challenge is securing funding and sponsorship for post-disaster intervention. While the UDS has successfully engaged sponsors, maintaining consistent financial and material resources remains a persistent struggle, particularly amid economic fluctuations. Developing a sustainable funding model is essential for the continuity beyond emergency responses and expanding the impact of initiatives.

Conducting post-occupancy evaluations of UDS-designed structures can provide insights into their effectiveness in disaster recovery scenarios. Strengthening community involvement in the design and decision-making processes can lead to more socially and culturally responsive solutions. Furthermore, analyzing how academic initiatives can be integrated into broader disaster preparedness strategies at municipal, national, and international levels can ensure long-term impact and policy alignment.

Although the UDS primarily aims to enhance post-disaster efforts, its significance extends beyond individual projects. The initiative serves as a prototype for rethinking architectural education, demonstrating the capacity of hands-on, interdisciplinary, and collaborative learning to address global challenges. As catastrophic events become more frequent, academic institutions, policymakers, and professional organizations need to prioritize emergency architecture and 1:1 scale practices within their frameworks. By fostering a new generation of architects equipped with both technical expertise and social responsibility, UDS exemplifies how architectural education can extend beyond the classroom, actively contributing to the development of more resilient, equitable, and sustainable communities in times of crisis.

Author Contributions

In this article, the reflections under the heading “Interdisciplinarity, the network between professional practices and academia” were written by Nusret Atakan Harmancı. Bilge Arslan discussed her experience in the “Adaptation, production, and implementation.” Arda Fidansoy contributed to his reflections in the section “Design strategies, construction techniques, and detailing.” Damla Turgut expressed her experience in “Market research, sponsor engagement, and construction management” part of the reflections. Gizem Nur Aydemir performed the copy editing of the manuscript and incorporated a literature review relevant to the topic. All authors reviewed the manuscript and contributed to the content.

Funding

This research received no external funding.

Ethics Committee Approval

This work does not require ethics committee approval.

Acknowledgments

We would like to express our sincere gratitude;

To all the volunteers who dedicate their time and support to the UDS,

To members of the Department of Architecture, Faculty of Architecture, and Department of Civil Engineering at Middle East Technical University (METU) for their support,

To METU Construction and Technical Department for their support in production, METU Rectorate, METU Transportation for their support and logistics,

to Shigeru Ban Architects and Voluntary Architects’ Network for their collaboration with the UDS for the Paper Log House construction in Türkiye and their financial support for the first Paper Log House,

to Mozaik Design, the primary sponsor of the Paper Log Houses in Bohşin, Defne, and Samandağ, for providing materials, logistics, and installation support,

to Bütün Çocuklar Bizim Derneği for sponsoring the interior furnishing and lighting equipment for the Paper Log Houses in Bohşin, Defne, and Samandağ,

to İstanbul ODTÜ Mezunları Derneği (ODTÜMİST) for being a connection with the UDS and sponsors and providing essential expenditures and construction materials,

To Türk Serbest Mimarlar Derneği (TSMD) for their support on construction equipment,

To Canpa, Anadolu Efes, Tridomes, Togaysan, and İmge Boya, where each played a vital role in insulation materials, beer crates, polycarbonate sheets, hand tools and insulation, paint and coating materials, respectively, To AdımODTÜ for their financial support for the Wooden Housing Unit's research and construction,

To Nil Tiritoğlu for their support in creating contact with other organizations and construction materials,

To Elif Rot Balans, Han Polikarbon, Akpa, Günebakan, İZODER Isı Su Ses ve Yangın Yalıtımcıları Derneği, OPTENG Proje Mühendislik for their support in providing tires, polycarbonate sheets, doors and windows of Wooden Housing Unit, clamps, insulation materials, and metal footings for Wooden Housing Units respectively,

To BAYMİM Mühendislik Mimarlık and BASAŞ Yalıtım for their support,

To all the other supporters who may have been overlooked,

To PhD candidate Res. Ömer Faruk Ağırsoy (TU Delft) (a member of the UDS since its first day) for their support and guidance in writing this paper.

Conflict of Interest

The authors declare no conflicts of interest.

References

1. G. Lizarralde, C. Johnson, and C. Davidson, *Rebuilding After Disasters*, London: Routledge, 2009, doi: 10.4324/9780203892572.
2. H. Ritchie and P. Rosado, "Natural disasters," *Our World in Data*, 2022. [Online]. Available: https://ourworldindata.org/natural-disasters.
3. CRED, "2023 Disasters in numbers: A significant year of disaster impact," *EM-DAT: The International Disasters Database*, 2024. [Online]. Available: https://www.emdat.be/categories/adsr/.
4. A. Center, Comprehensive Emergency Management. National Governors Association, 1979.
5. D. M. Neal, "Reconsidering the phases of disaster," *International Journal of Mass Emergencies and Disasters*, vol. 15, no. 2, pp. 239–264, 1997. doi: 10.1177/028072709701500202.
6. A. M. Beauchesne, "A Governor's guide to emergency management: Volume one, natural disasters," *Bts.gov*, 2001. [Online]. Available: https://rosap.ntl.bts.gov/view/dot/34038.
7. P. Shrivastava, "Principles of emergency planning and management," *Risk Management*, vol. 5, no. 2, pp. 67–67, 2003. doi: 10.1057/palgrave.rm.8240152.
8. D. P. Coppola, *Introduction to international disaster management*, 3rd ed. S.L.: Butterworth-Heinemann Inc., 2021.
9. E. Lettieri, C. Masella, and G. Radaelli, "Disaster management: Findings from a systematic review," *Disaster Prevention and Management: An International Journal*, vol. 18, no. 2, pp. 117–136, 2009. doi: 10.1108/09653560910953207.
10. "European disaster risk management," *Civil Protection and Humanitarian Aid, European Commission*. [Online]. Available: https://civil-protection-humanitarian-aid.ec.europa.eu/what/civil-protection/european-disaster-risk-management_en.
11. M. Sakurai and Y. Murayama, "Information technologies and disaster management – Benefits and issues," *Progress in Disaster Science*, vol. 2, p. 100012, 2019. doi: 10.1016/j.pdisas.2019.100012.
12. I. H. Sawalha, "A contemporary perspective on the disaster management cycle," *Foresight*, vol. 22, no. 4, pp. 469–482, 2020. doi: 10.1108/fs-11-2019-0097.
13. D. E. Geis, "By design: The disaster resistant and quality-of-life community," *Natural Hazards Review*, vol. 1, no. 3, pp. 151–160, 2000. doi: 10.1061/(asce)1527-6988(2000)1:3(151).
14. F. Özdoğan and D. Güney, "The importance of architecture education for disaster mitigation," in The Sustainable City XI, Southampton, UK: WIT Press, Jul. 2016, pp. 373–384, doi: 10.2495/SC160321.

15. G. Tunçbilek, “(Re)Generations of architecture by disasters: Designing an ephemeral shelter,” presented at the *LIVENARCH VIII Livable Environments & Architecture 8th International Congress*, Sep. 2023.
16. H. Arslan, “The evaluation of community participation in housing reconstruction projects after the Duzce earthquake,” Ph.D. dissertation, İstanbul Technical University, 2007.
17. C. Johnson, “Strategic planning for post-disaster temporary housing,” *Disasters*, vol. 31, no. 4, pp. 435–458, 2007. doi: 10.1111/j.1467-7717.2007.01018.x.
18. C. Johnson, G. Lizarralde, and C. H. Davidson, “A systems view of temporary housing projects in post-disaster reconstruction,” *Construction Management and Economics*, vol. 24, no. 4, pp. 367–378, 2006. doi: 10.1080/01446190600567977.
19. A. H. Abulnour, “The post-disaster temporary dwelling: Fundamentals of provision, design and construction,” *HBRC Journal*, vol. 10, no. 1, pp. 10–24, 2014. doi: 10.1016/j.hbrcj.2013.06.001.
20. D. Félix, J. M. Branco, and A. Feio, “Temporary housing after disasters: A state of the art survey,” *Habitat International*, vol. 40, pp. 136–141, 2013. doi: 10.1016/j.habitatint.2013.03.006.
21. A. Bashawri, S. Garrity, and K. Moodley, “An overview of the design of disaster relief shelters,” *Procedia Economics and Finance*, vol. 18, pp. 924–931, 2014. doi: 10.1016/s2212-5671(14)01019-3.
22. F. Özdoğan and D. Güney, “The role of architecture education in natural disaster mitigation,” presented at the *2nd International Conference on Architecture, Structure and Civil Engineering (ICASCE-16)*, 2016. doi: 10.17758/ur.u0316305.
23. M. Siriwardena, C. Malalgoda, M. Thayaparan, D. Amaratunga, and K. Keraminiyage, “Disaster resilient built environment: Role of lifelong learning and the implications for higher education,” *International Journal of Strategic Property Management*, vol. 17, no. 2, pp. 174–187, 2013. doi: 10.3846/1648715x.2013.806373.
24. E. Charlesworth and J. Fien, “Design and disaster resilience: Toward a role for design in disaster mitigation and recovery,” *Architecture*, vol. 2, no. 2, pp. 292–306, 2022. doi: 10.3390/architecture2020017.
25. N. Hamilton, “Post-disaster shelter: A studio-based response to emergency shelter in natural disaster zones,” in *Sustainable Futures: Architecture and Urbanism in the Global South*, Kampala, Uganda, 2012, pp. 250-254.
26. E. Wagemann and M. Ramage, “Relief for the curriculum. Architecture education and disaster recovery,” 2013. doi: 10.17863/cam.6437.
27. D. Hinson, “Design as research,” *Journal of Architectural Education*, vol. 61, no. 1, pp. 23–26, 2007. doi: 10.1111/j.1531-314x.2007.00124.x.

28. J. Erdman, R. Weddle, T. Mical, J. S. Poss, K. Hinders, K. McCown, and C. Taylor, "Designing/Building/Learning," *Journal of Architectural Education*, vol. 55, no. 3, pp. 174–179, 2002, doi: 10.1162/10464880252820037.

29. V. B. Canizaro, "Design-build in architectural education: Motivations, practices, challenges, successes and failures," *International Journal of Architectural Research*: Archnet-IJAR, vol. 6, no. 3, pp. 20–36, 2012. doi: 10.26687/archnet-ijar.v6i3.113.

30. N. Emami and P. Von Buelow, "Teaching structures to architecture students through hands-on activities," presented at the *Canadian International Conference on Advances in Education, Teaching & Technology*, Jul. 2016.

31. M. H. Zelef et al., "METU summer practices: A model of integrating theory and practice in architectural education," *Re-Integrating Theory and Design in Architectural Education: EAAE Transactions on Architectural Education*, no. 11, pp. 277–281, 2001.

32. Ö. Turgay, "Hands-on building practices in architectural education: METU summer construction practices," M.Arch. - Master of Architecture, Middle East Technical University, 2005.

33. O. Yüncü, "Arılı primary school computer workshop," Onur Yüncü Architects, 2003. [Online]. Available: https://www.onuryuncu.com/project/07-2003-ariliprimaryschool.

34. S. Özkan, "ODTÜ Mimarlık Fakültesi Yaz Uygulamaları (METU Faculty of Architecture Summer Practices)". Ankara: Arp Yayınevi, 1974.

35. A. Kosuge, "Paper Log House - Turkey," Shigeru Ban Architects, 2000. [Online]. Available: https://shigerubanarchitects.com/works/paper-tubes/paper-log-house-turkey/.

36. T. Özer, Ö. F. Ağırsoy, G. N. Aydemir, İ. E. Şahin, and G. Güner, "ODTÜ acil tasarım stüdyosu'na ilk bakış: Kağıt masura evi'nin öğrettikleri", *Mimarlık*, vol. 431, pp. 24–28, 2023.

37. Z. Sofia, "Container technologies", *Hypatia*, vol. 15, no. 2, pp. 181–201, 2000. doi: 10.1111/j.1527-2001.2000.tb00322.x.

38. G. Zhang, S. Setunge, and S. van Elmpt, "Using shipping containers to provide temporary housing in post-disaster recovery: Social case studies", *Procedia Economics and Finance*, vol. 18, pp. 618–625, 2014. doi: 10.1016/s2212-5671(14)00983-6.

39. "ISO 830:2024(en) freight containers — Vocabulary", ISO.org, 2024. [Online]. Available: https://www.iso.org/obp/ui/#iso:std:iso:830:ed-3:v1:en.

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The Ardıç Project: Post-Disaster Social Architecture for a Small Community in Antakya

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This chapter describes the conception, design, production, assembly, and disassembly of a 1:1 timber prototype created as a social gathering space for the community of Dikmece, Antakya, following the 2023 Kahramanmaraş earthquake sequence in Türkiye. It describes the motivation for establishing an architectural studio focused on post-disaster recovery, encouraging students to integrate practical learning with social responsibility through small-scale interventions. Finally, the chapter provides technical information to enable the replication and installation of the project in other locations.

Keywords: Earthquake awareness, Architectural education, Pop-up architecture, Design-for-disassembly, Timber construction, Prototype.

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Introduction

Post-disaster response & the need of social areas

The devastating Kahramanmaraş earthquake sequence in Türkiye, which struck in February 2023, highlighted the region's vulnerability to seismic activity and the profound impact such disasters have on communities. Measuring 7.7 and 7.6 in magnitude, the earthquakes caused extensive damage to residential, commercial, and public structures, resulting in significant loss of life and the displacement of thousands of people[1]. In the aftermath of such catastrophic events, emergency responses usually involve the establishment of temporary shelters, such as tents and container units, which can be quickly deployed to accommodate displaced families[2]. While these emergency housing solutions provide immediate relief, they frequently lack the communal and social spaces (Figure 1) necessary to foster a sense of normalcy and connection among displaced residents[3]. Deprived of the familiar urban fabric, daily routines, and family connections, earthquake victims often struggle with feelings of helplessness, isolation and anxiety[4]. Consequently, social activities should be a central spatial component of any post-disaster intervention. The success of emergency solutions, such as container-based temporary housing, depends heavily on their integration with the social fabric of a given community, through the simultaneous provision of public socialization areas.

Pop-up architecture & design-for-disassembly

Pop-up architecture refers to a broad range of small-scale interventions that appear suddenly in public spaces, designed to engage users with a distinct yet recognizable aesthetic. These interventions share two key characteristics that make them ideal for providing social spaces in disaster-affected communities: first, they are temporary by nature, but they have the potential to become permanent structures if they harmonize with the surrounding environment; second, they are highly context-responsive, meaning their success depends on how well they understand and integrate with both the physical and social environment[5]. Pop-up interventions have the potential to address both the immediate and long-term needs of disaster-affected areas, by creating spaces that are not only functional but also adaptable and responsive to the social needs of a community.

In addition to the temporary nature of pop-ups, the need for projects that can be quickly erected, and easily dismantled when necessary, leads to the principle of Design for Disassembly (DfD). This principle focuses on facilitating the reuse and recycling of materials and components at the end of a building's life[6]. In the context of temporary architecture, DfD emphasizes constructive reversibility—or, at the very least, the use of reversible connections—to enable disassembly and the reuse of the structure's components[7]. Avoiding complex connections ensures quick installation with minimal materials and labour, both of which are essential in disaster-affected areas. Furthermore, this approach allows non-experts to assemble structures manually, thereby increasing the potential for community participation. At the design level, applying DfD involves conceptualizing the project as an assembly of modular components that are easy to transport, assemble and disassemble[7,8,9].

This article describes the conception, design, and partial realization of Ardıç, an architectural project developed by undergraduate students as a social gathering space for the Dikmece community in Antakya. Created within the framework of an architectural studio focused on post-disaster recovery, the project emphasizes practical learning and social responsibility through the design of a pop-up intervention. The article details the production, assembly, and disassembly of a full-scale timber prototype, intended as a replicable social space for other locations. It highlights architectural education's role in disaster recovery by showcasing a proof-of-concept for practical, socially conscious design addressing post-disaster needs.

Figure 1. Examples of container and tent cities implemented in Antakya, May 2023.

Studio settings

The 3rd Year Architectural Studio at YU's Department of Architecture involved 42 students, two PhD assistants, and four instructors with expertise in timber construction and structural engineering. While it was known that the project would be located in an earthquake zone, the brief remained undefined until a voluntary field trip to Antakya in the second week of the studio. Following the field trip, the studio was divided into three stages. The first stage focused on developing conceptual design proposals based on site and community information, pop-up architecture case studies, and team collaboration. Given the limited budget and construction skills, students were encouraged to minimize the use of steel and prioritize timber as the primary building material. The second stage involved refining two selected proposals. The class was divided into two units, each supervised by an instructor, with teams working on design development, scale models, and assembly processes. This stage led to the development of the Ardıç project. The third stage involved the construction of the prototype and the completion of the construction drawings. For an extended description of the studio settings, the reader is referred to[10].

Computational tools & prototyping

Although the use of computational tools has become commonplace in architectural education[11], the team recognized an additional and fundamental role for digital models in this particular studio. This was not only because the conceptualization phase of the project needed to be quick and efficient, but also because site data—particularly regarding the post-earthquake situation—were scarce. Official sources were outdated or unreliable, and the information collected by the on-site team had to be effectively shared with other students, who were unfamiliar with the project's location. However, the most significant contribution of digital tools was in guiding the prototyping stage. More specifically, they provided coherent data and served as a collective framework for the various teams working on the full-scale prototype.

A social place for a small community

The team chose to work in a small community like Dikmece rather than Antakya, in order to focus on areas that often receive less attention and resources in the aftermath of disasters. Smaller communities are frequently overlooked during larger recovery efforts, despite their significant need for support. In addition, working in the village of Dikmece allowed for direct engagement with residents, ensuring that the project aligned with their specific needs and provided a manageable scale to test and refine the design before tackling larger urban environments. In such communities, social spaces are essential for rebuilding connections, fostering emotional recovery, and preserving a sense of belonging. These spaces help strengthen community ties, encourage cultural activities, and support long-term development by transforming temporary settlements into permanent communities[12]. Additionally, it is crucial to address the psychological impact on children and also to recognize the post-earthquake shift in users' preferences from urban to rural areas[4].

Dikmece Village

Dikmece is a small village located in the Antakya district of Hatay Province, Türkiye (Figure 2). Situated high in the hills about 20 kilometres north of the historic city centre of Antakya, the village is home to around 2,500 inhabitants[13], the majority of whom are bilingual Turkish-Arabic speaking Alevis* . According to a local villager, their ancestors have lived here for approximately five hundred years[15]. Dikmece is part of a rural area historically reliant on agriculture, where figs, avocados, and lemons are grown, primarily for personal use, and whose main source of income is olive cultivation.

The demographics of Dikmece reflect a close-knit, traditional community with a significant number of elderly people. Younger generations often migrate to larger cities in search of better economic opportunities, resulting in a gradually aging population. Despite its small size, Dikmece maintains a vibrant social life, where communal gatherings and activities play a central role. This makes the need for a dedicated social space particularly important, especially in the aftermath of recent earthquakes[15].

Dikmece after the earthquakes

Like Antakya, Dikmece was severely affected by the earthquakes. According to villagers, nearly two hundred people lost their lives, and many homes were destroyed[13, 15]. Several months after the disaster, some residents were still living in tents. However, the greatest threat to the village arose not directly from the earthquakes but from the government's expropriation of its arable land. In Dikmece, as in many earthquake-affected regions, agricultural and private land is being cleared to make way for new residential complexes, built by TOKI, the state construction company. According to government sources, these new developments will provide housing for the hundreds of thousands displaced by the February 2023 earthquakes[15]. However, as a result of the expropriations, 80% of the original village has effectively disappeared[13].

Interviews with villagers & program definition

Eight months after the earthquakes (October 2023), seven students and two instructors travelled to Dikmece. The team was warmly welcomed by the local school principal and community leader, who served as both host and guide. To make the most of their brief 3-day visit, the team split into three groups based

*Alevis are people who follow Alevism, an Islamic tradition that has its roots in the early periods of Islam. Alevism developed in Anatolia and possesses its own unique beliefs, rituals, and values. While there are differences between Alevism and Sunni Islam—the most widely practiced branch of Islam—both are grounded in the Quran and the Sunnah, the foundational texts of Islam[14] on the village's geomorphological distribution: upper, middle, and lower zones (Figure 2), with the lower zone having suffered the most extensive damage. The students' primary task was to engage with the inhabitants to better understand their wishes and needs. They spoke with approximately 50 people, including those whose homes were damaged by the earthquake. These conversations were documented through photographs and detailed notes.

The residents' daily routines provided valuable insights into defining the program. For adults, mornings typically began by sending children to school, followed by tending to their gardens, preparing food, and spending time with neighbours. Social gatherings are a regular part of daily life, with people often coming together in their home gardens to prepare and eat food, chat, and share stories. For children, their days revolved around school, playing with friends in the streets or gardens, and completing homework in the evenings. Probably due to their constant activity and lack of playgrounds, when asked about the village's most pressing social needs, the most common request was for something to be done for the children.

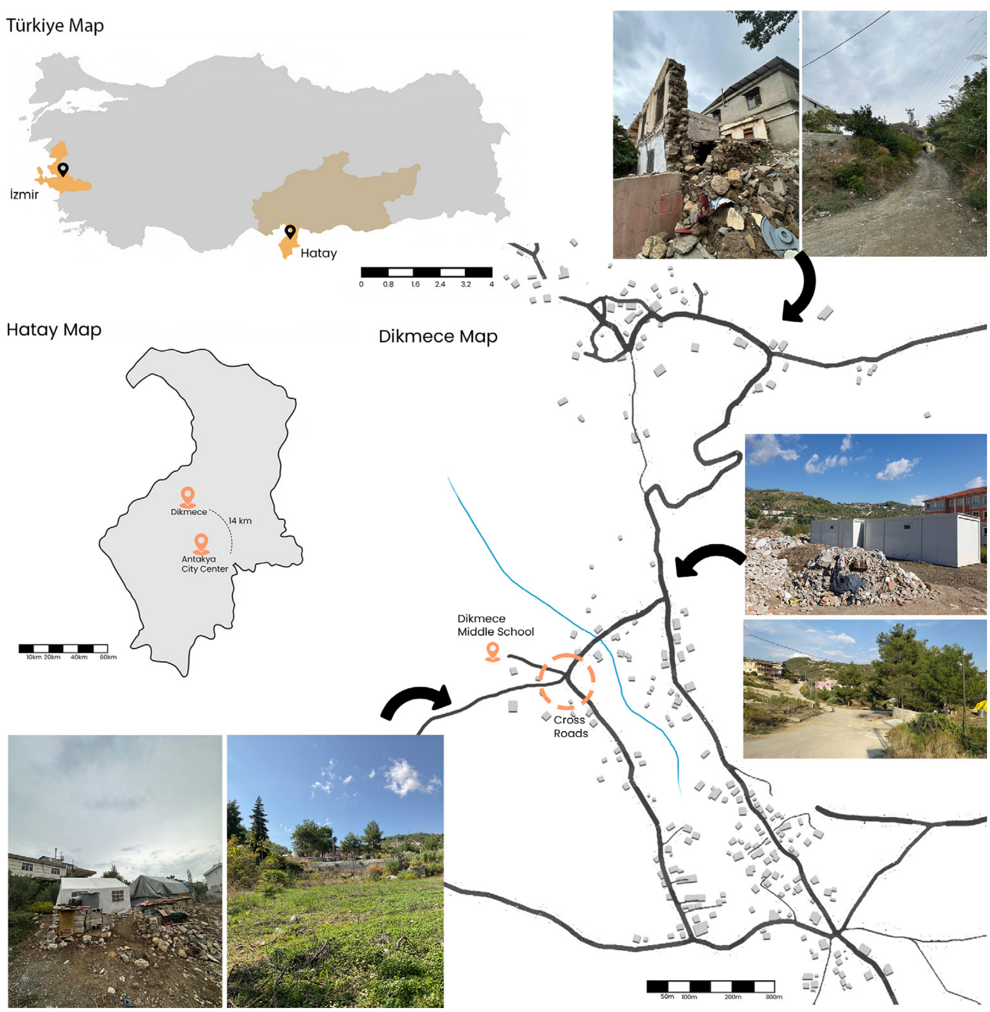

Figure 2. Location of Dikmece village and distribution of local areas.

The interviews revealed the central role of food in the social dynamics of the village. This was evident in the warm invitations extended by residents to share food and drinks with the team in their homes (Figure 3). Food is not merely a necessity but a cultural tradition, deeply embedded in their daily lives and social interactions. Residents emphasized the importance of communal meals and celebrations, particularly during traditional holidays. As is common in Turkish culture, social gatherings and interactions are centred on preparing and sharing food, especially during traditional celebrations, which hold great significance for the community. All of these observations led to the program's second focus: creating community spaces for social gatherings centred on food-related activities.

Figure 3. Interviews with children and social activities around sharing food in Dikmece.

The third aspect of the program relates to religious activities. As an Alevi village, the residents of Dikmece worship at the local Cemevi*. However, the existing building is relatively small and can not accommodate large gatherings. One recurring topic of discussion was their most important holiday, along with their desire for a space where they could celebrate together.

Given these needs, the program was defined as a social gathering space that includes both a children's area and a communal dining area, capable of accommodating large social events such as weddings, where food preparation, eating, dancing, and socializing take place. However, this space needed to be flexible, able to serve different functions depending on the community's needs. For example, it could be used daily as a playground for children, as a communal dining area, as an open-air cinema, or occasionally for religious holidays and official ceremonies.

*Unlike mosques, which are used by Sunni Muslims, Cemevis are the places of worship for Alevis, serving as central hubs for both religious and community gatherings. Alevis perform their distinct rituals in Cemevis, including the Cem ceremony, which involves prayers, spiritual music, and the Semah dance. In addition to their religious role, Cemevis also serve as cultural and social centres, hosting events, communal meals, and educational activities for the Alevi community. They play a crucial role in preserving and passing down Alevi traditions and beliefs[14,16].

This need for flexibility brought multifunctionality to the forefront as a central them, addressing the adaptation of areas for various community activities while fostering integration across diverse age groups. Based on the team's site observations, the village had a significant number of children and adults between the ages of 30 and 65, but fewer young people aged 12-20. By considering the village's lifestyle, daily routines, and social needs, the program sought to create a social space that could cater to all age groups and accommodate a wide range of activities within the community.

Site selection & data collection

During the field trip, the team identified two potential project sites in the central area of the village (Figure 2). One was located between the so-called "crossroad", where the main circulation routes intersect, and the river, which came to be known as the "river site." The other potential location was directly in front of the Cemevi, and was subsequently referred to as the "Cemevi site." To determine the precise location and boundaries of these sites, the students used the parcel inquiry web page of the Turkish General Directorate of Land Registry and Cadastre[17]. Additionally, they employed Google Earth for in-depth site analysis, utilizing satellite imagery and topographical data to assess the surrounding environment and landscape.

The Ardıç project

Modular configuration & birth of the Ardıç

Flexible modularity is the response to the need for multifunctionality in the design. At a functional level, the project was designed without assigning fixed functions, instead defining general zones to make it adaptable for a variety of activities. To achieve this flexibility of use, or multifunctionality, the project is based on modular units, which allow for multiple configurations, offering flexibility based on the specific needs of the community. The design concept followed a whole-to-part principle, by which modules' layouts are obtained from a regular subdivision of a circle; the proposed configuration is, nonetheless, an asymmetrical arrangement resembling partial sections of that original circle (Figure 4). The design includes two main modules: one for multi-functional areas and another for an open-air cinema—the "amphi module." In this final version, both open and semi-open areas were connected, while creating three distinct zones. However, the configuration can easily be adjusted to accommodate different activities.

In order to optimize both the placement and performance of the modular structure, students employed various simulation techniques. For instance, to explore different configurations within the site context, renders were created using SketchUp[18] and Lumion[19], enabling the team to assess the aesthetic and spatial impact of each design iteration. Sunlight analysis was conducted using Rhinoceros®-Grasshopper® plugins[20], with simulations set up to track sun paths and assess the modules' orientation for optimal seasonal natural light exposure and shade. These simulations were essential not only for ensuring the integration of the project with its physical environment but also for ensuring that the placement of the modules enhanced usability and comfort under varying light conditions.

During the design development phase, the team noticed that placing two modules back-to-back created a shape resembling the open wings of a bird. This gesture, symbolizing the act of embracing and uniting people, aligned with the overall concept of a space meant to bring people together during cultural and special events, much like the communal gatherings in Alevi culture. The name Ardıç , the Turkish word for a common local bird, was chosen for the project. This name not only reflects the symbolic connection to unity but also aligns with the project's design philosophy, which is simple, unadorned, and rooted in functionality.

Design for easy assembly & for disassembly

The design of each module for disassembly addresses the structure of the components, the choice of materials, and the type of joints and connections. In line with the principle of flexibility, the structure's components can be easily assembled, disassembled, and reconfigured, allowing it to serve various purposes and to adapt to the community's changing needs. The modular design also facilitates easy transportation and relocation, enabling the structure to be reused in different contexts while prioritizing sustainability and practicality.

Each module consists of three main components: the floor, roof, and columns (Figure 5). The floor and roof are made up of smaller sections called cassettes

Figure 4. Renders depicting the final version of the project.

(rather than complete elements, which would be too heavy), allowing components to be carried short distances by a few people—particularly important since trucks and large vehicles cannot access areas near the river. By separating the pieces into smaller, lighter sections, the project minimized transportation challenges and made the structure more portable and efficient to install.

Connections design & the choice of timber

The structure is designed so that all connections are easily accessible, allowing the components to be taken apart and reassembled without difficulty[7]. Bolts were chosen as the primary connectors between the different timber components of the prototype, mainly because they allow for easy assembly and disassembly. Additionally, bolts can be secured using only hand tools, which is particularly useful in post-earthquake scenarios, where power tools are in high demand, and power shortages are unfortunately common. This design not only enabled the studio team to assemble the structure efficiently but also empowers community members to assemble it themselves, fostering a sense of ownership and involvement.

To support this, readily available, relatively low-cost timber materials were selected to ensure that the modular design remains affordable and accessible across various contexts. The choice of timber also follows the principle of using "green" materials, which have been shown to significantly reduce the environmental impact of short-lifespan structures[8]. The use of timber also facilitates a design that is optimized for low to medium skill levels, allowing local labour to handle assembly and maintenance with minimal training. Once the initial manufacturing is complete, no specialized tools are required for reassembly or modification, further simplifying the process and enabling rapid deployment or alterations as necessary.

Transportation

To prepare for the logistics of transporting and assembling the structure on-site in Dikmece, detailed diagrams and simulations were created to anticipate potential challenges. Using digital models, students visualized possible routes for trucks to access the site, identifying viable entry points and manoeuvring paths for the safe delivery of materials. Calculations for module transport were also crucial; specific diagrams were created to plan the placement of components within each truck, minimizing confusion and improving efficiency during unloading. Based on these calculations, it was estimated that two trucks would be sufficient to transport all the modules (Figure 5).

Temporary foundations

Given the temporary nature of the project, no permanent foundation is used. Instead, an adaptable foot system was developed using concrete blocks that

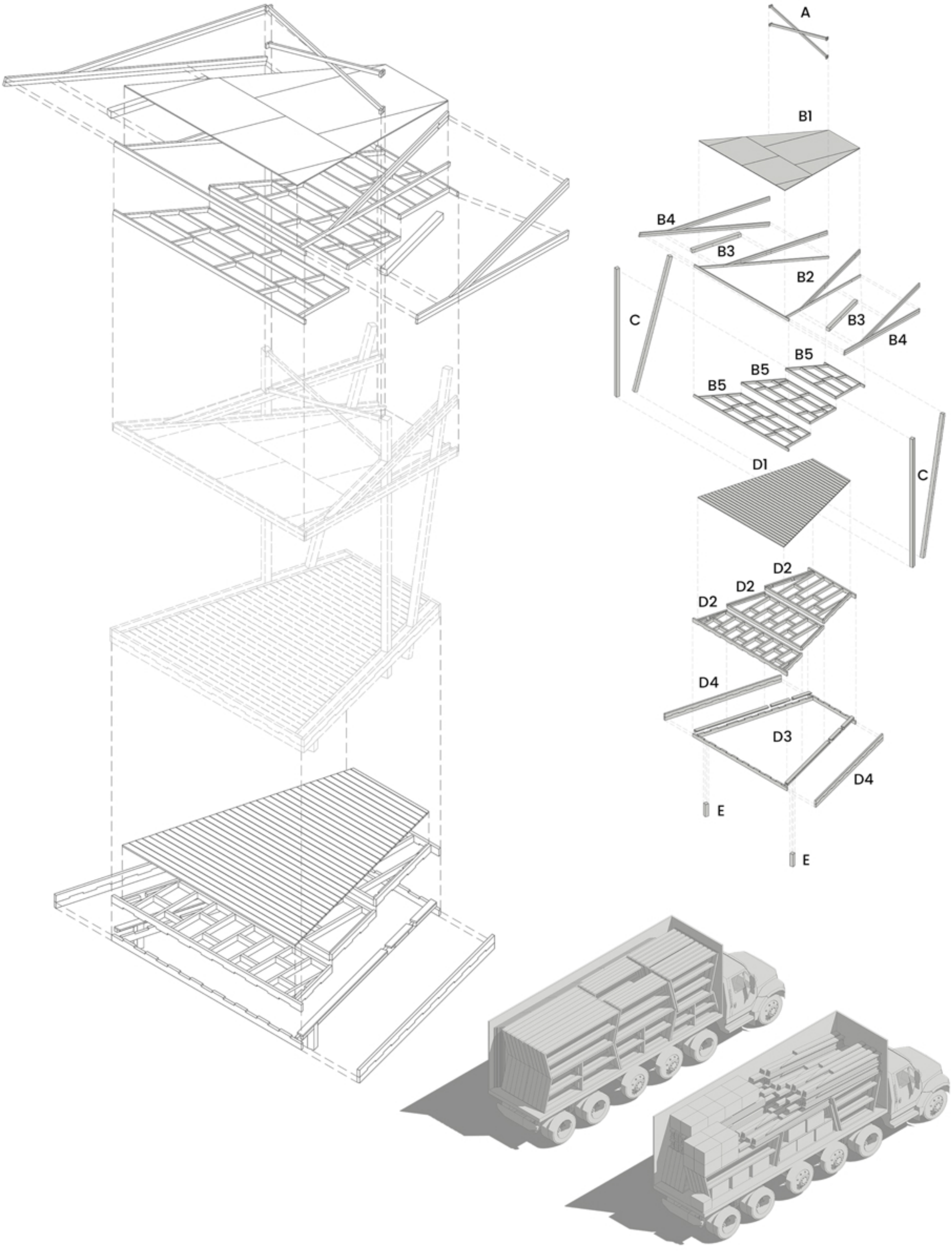

Figure 5. Exploded basic module of the Ardıç, the tagging system for easy identification of the parts, and planned transportation.

can adjust to the site's slope (see Appendix). By not being fixed to a specific location, the modular system's adaptability allows it to be easily moved or modified for different occasions, ensuring that it can continue to meet the needs of communities in various settings. The absence of a permanent foundation also offers practical advantages in terms of regulatory and property considerations. By avoiding permanent footings or foundations, the need for building permits is eliminated, making the project easier to implement in a wide range of locations.

Prototype construction

Planning & organization

The construction of the module prototype served as a proof of concept for the proposed project. The construction team, consisting of 18 students and two instructors, planned to complete the prototype within four weeks, coinciding with the final month of the academic semester. However, since this activity was only one of many duties, neither instructors nor students were expected to work full-time on the construction.

The construction process was originally planned as a sequence of major steps, as outlined in the flowchart in Figure 6. In the first phase, timber components were produced based on the information provided by the 3D SketchUp model. Most of the work in this phase took place in the university's main workshop,

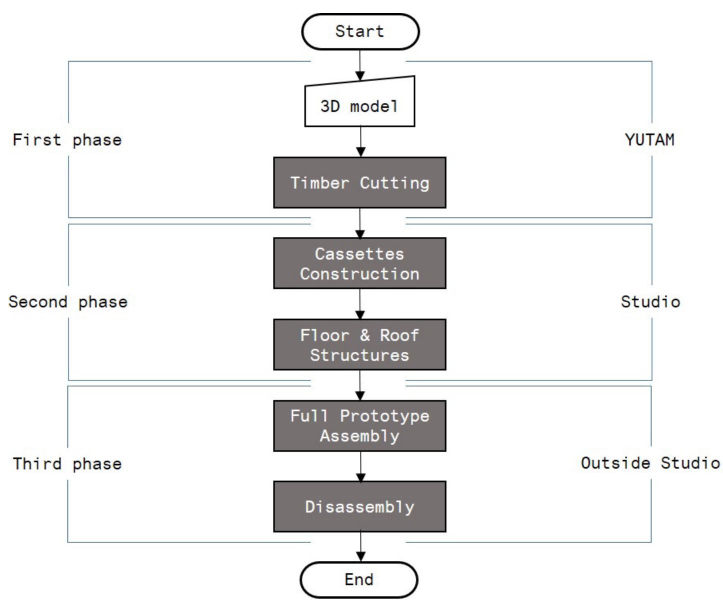

Figure 6. Flowchart of the planned construction process of the prototype.

YUTAM, which was equipped with power tools. Working in this space not only provided a controlled environment for the initial manufacturing but also allowed for precise cutting of the pieces according to the digital models.

In the second phase, the major timber components—cassettes, columns, floor, and roof structures—were to be assembled in the studio space, which offered ample room for both working and storing the components during the process. The third phase involved the assembly and further disassembly of the full prototype. Given its approximate height of 4 meters, this phase had to be carried out in an open area, directly outside the studio.

Fabrication

Material delivery & preparation of timber components

The delivered raw timber (see Table 1) had smaller dimensions than those required for the prototype. For example, according to the digital model, the beams were 19 cm x 4 cm, whereas the available timber was 9.5 cm x 4 cm. For this reason, timber pieces were glued and screwed together to create larger components, such as beams and columns, ensuring structural integrity (Figure 7). During the following cutting process, leftover materials were stored for future reuse in

Material	Quantities	Use
9.5 cm x 9.5 cm timber (4m)	5	4 for columns; 1 for floor / roof
9 cm x 4 cm timber (4m)	20	floor
6 cm x 3 cm timber (4m)	25	roof
5 cm x 5 cm timber (4m)	2	floor
4 cm x 3 cm timber (4m)	10	floor
4.5 cm x 4.5 cm timber (4m)	2	floor
20 mm planks (4m)	20	floor
13 mm OSB panel	5	roof
M-10 threaded rod 25 cm	36	assembly / disassembly
M-10 nuts	150	assembly / disassembly
M-10 washers	150	assembly / disassembly
M-10 threaded rod 12.5 cm	12	assembly / disassembly
M-5 HEX head bolt 15 cm	50	assembly / disassembly
M-5 washer	100	assembly / disassembly
M-5 nuts	100	assembly / disassembly
Partial threaded wood screw 15 cm	150	cassettes
6 mm x 80 mm chipboard screw	150	cassettes
Material	Quantities	Use
3 mm x 40 mm chipboard screw	200	fixing planks / OSB panels

Table 1. Updated list of materials required for the construction of a single module.

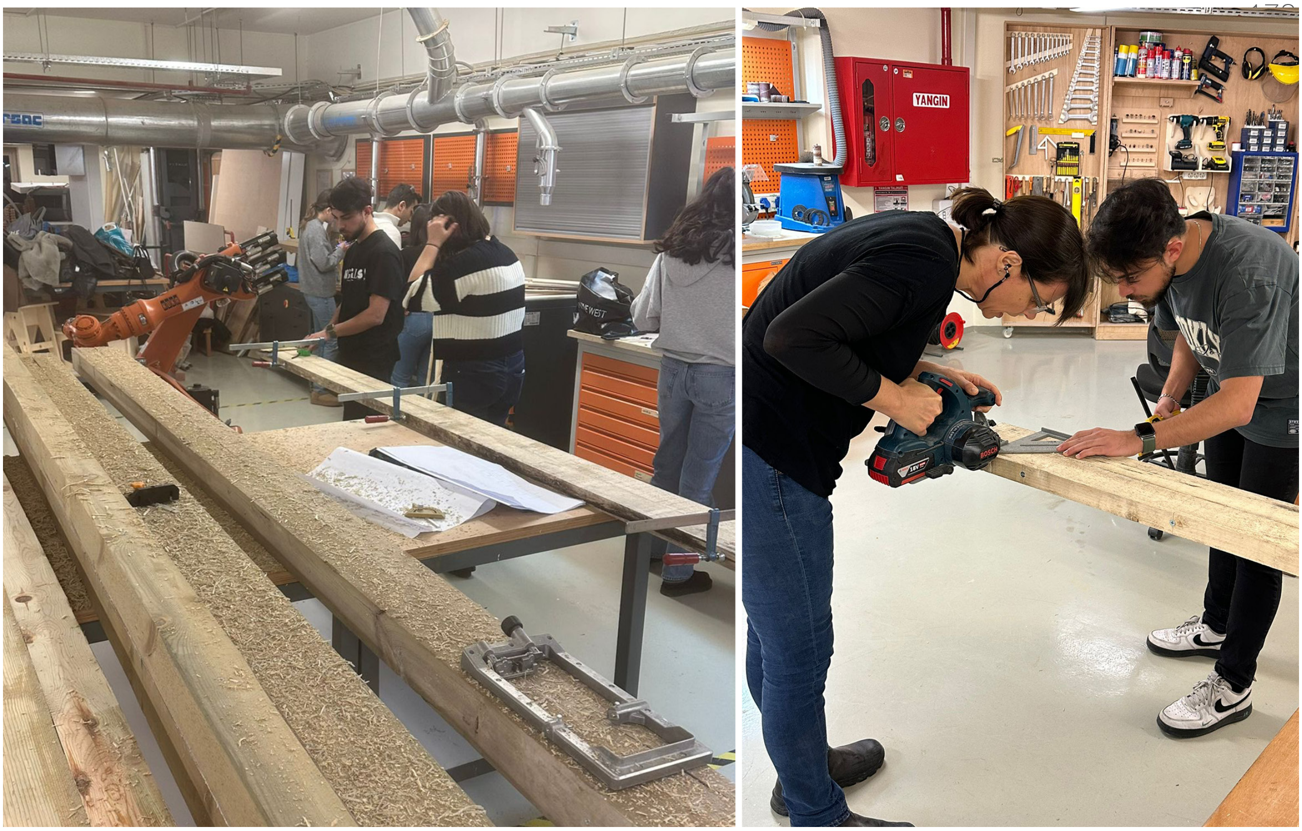

Figure 7. Fabrication of beams and columns at YUTAM.

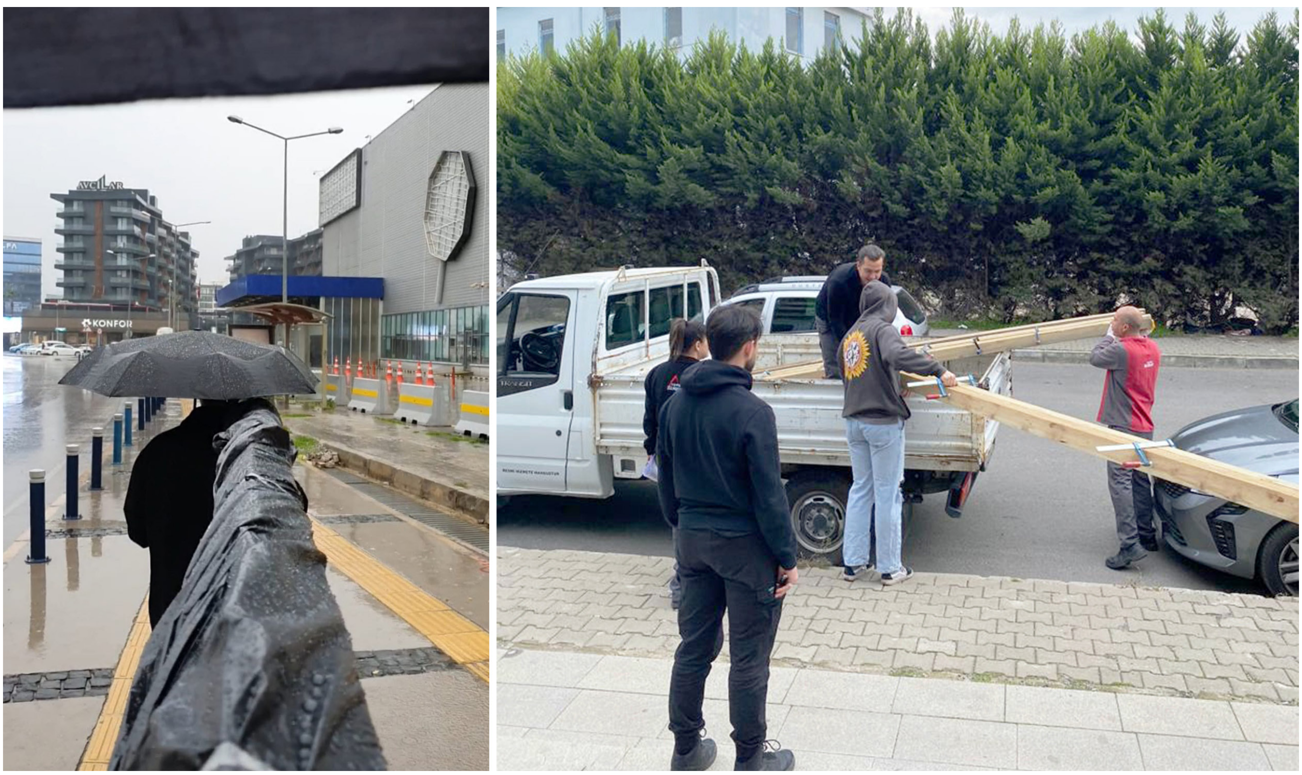

Figure 8. Transportation of materials and components.

secondary components of the prototype, such as smaller beams, diagonal roof supports, temporary ground supports, and roof cassettes. Once the components were ready, they were transported to the studio (Figure 8).

Cassette construction & iterative process

Each cassette consists of an outer frame, inner beams, and joists. In the studio, a platform, consisting of plywood sheets fixed to a 5 cm x 5 cm timber frame, was first built to protect the studio floor and provide a stable, flat base for constructing the cassettes. The main beams were temporarily attached to this base to serve as a template, ensuring the correct shape of the cassette frames during assembly. Once the frame was constructed, the inner beams and joists were installed to complete the cassette structure. This process was nearly identical for all cassettes in both the floor and roof structures (Figure 9). However, during the roof cassette construction, additional joists were required within the frames due to the irregular geometry of some plywood panels.

Although initially conceived as straightforward, both the construction and assembly processes quickly became highly iterative. As soon as physical assembly began, on-site adjustments were often necessary to match the measurements and alignments depicted in the model. Conversely, variations in the sawn timber dimensions required adjustments to be made in the digital model itself. The process quickly evolved into an iterative cycle: the team would cross-check the 3D model, cut the timber pieces accordingly, and then refine dimensions and angles in the 3D model based on real-world conditions encountered during assembly.

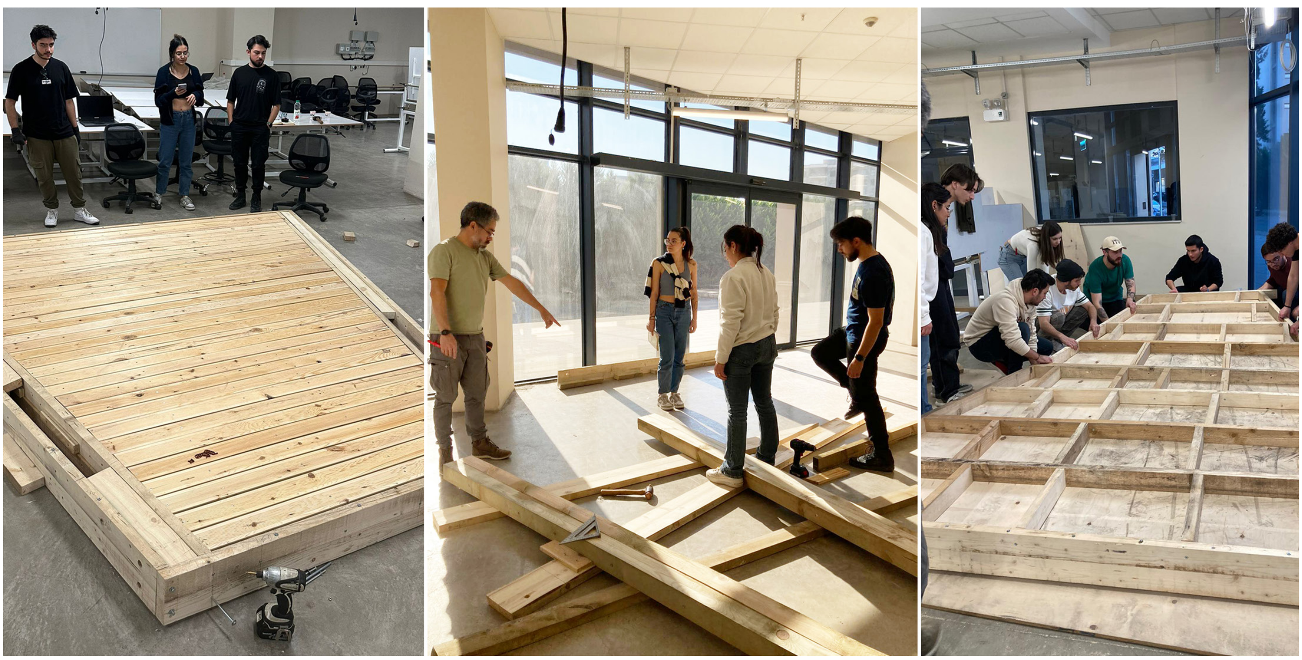

Figure 9. Construction process of the cassettes.

Connections & preparation of the bolts

Screws were primarily used for fabricating components that would not be disassembled in the future, such as planks for the floor cassettes or plywood panels for the roof cassettes. Nails were also used, although less frequently. Bolts, which are more reliable for supporting heavy loads, were used to connect all components that would be disassembled. These connections included those in the floor and roof structures, as well as key assembly connections such as column-to-floor, column-to-roof, cassette-to-cassette, and frame-to-frame joints. The bolts were made from threaded bars, which were cut using power tools in YUTAM (Figure 10).

Assembly

Assembly of floor, roof, and additional structures

The structure of the floor presents a flat area facing upwards, and an irregular zone—facing downwards (see Appendix). For this reason, the team decided to assemble the floor structure upside down as it was easier to maintain a flat surface when the area was resting directly on the platform. After attaching the cassettes to the main and secondary floor beams with bolts, the team flipped the entire structure into its final position. The floor was then completed by fixing the finished floor planks in place.

The roof structure was also assembled upside down, but for a different reason. The main perimeter beams, which attach the roof structure to the module's main columns, have an in-plane inclination of 15°. If assembled in its final position, the team would have been forced to work on a 15° inclined surface. Unlike the

Figure 10. Cutting the metal rods for producing bolt connections to be used in the assembly process.

floor, the roof was covered with plywood panels, which were fixed directly to the cassettes. For this reason, once flipped, the roof structure was ready to be connected to the columns.

Power tools were generally used to reduce construction time. Electric drills were employed for most tasks, including drilling holes and tightening screws and bolts. Wrenches were used to tighten bolt nuts. When the availability of drills was limited, screws could also be fastened manually with a screwdriver.

Combining floor & columns outside the studio

Although the team briefly considered the possibility of carrying out the entire floor structure out at once, this was not possible due to its weight and being too wide to pass through the standard double-wing doors. As a result, each part of the structure was disassembled and moved outside the studio. The floor cassettes were bolted together and placed on top of the short columns. Additional temporary columns were added for support. The main columns were then assembled and installed onto the floor structure with the help of temporary supports (Figure 11). Once the columns were secured, the exterior beams of the floor structure were bolted to the previously connected exterior beams. With the floor structure and columns in place, the team to assembled the roof structure directly over the module’s floor. The entire process took approximately 10 hours.

Figure 11. Assembly of floor structure and columns.

Raising the roof using only human power

After the roof structure was assembled on top of the module's floor, the team faced one final challenge: how to raise the whole roof to its final position without the assistance of a forklift or small crane. Although such equipment was indeed unavailable, the primary goal of this challenge was to test whether this last part of the assembly could be performed using only human force and basic tools, such as clamps and ladders. This scenario is highly probable after a major earthquake, as heavy machinery is often required for urgent debris removal and demolition tasks.

The solution considered two key factors: the roof's final position is inclined by 15° with respect to a horizontal plane, and the columns had already been inserted into the roof structure. By clamping the higher side of the roof (in this case, the front) to temporary timber supports, the lower side could be raised using the columns as vertical rails. Once this previously lower side had reached the required 15° inclination, and thus being higher, it was clamped to additional temporary vertical supports.

As depicted in Figure 12, this was essentially the approach the team followed: some members were positioned at the front and rear of the prototype, controlling the lift, while others handled the clamps and tools for temporary fastening. The process was repeated until the roof reached the correct height, at which point it

Figure 12. Raise and assembly of the roof structure.

was connected to the columns. Finally, the temporary supports were removed, and the prototype was completed. This entire process took approximately 8 hours.

Disassembly

The disassembly process of the prototype was essentially the reverse of the assembly. First, the bolts connecting the roof to the columns were removed, and the roof was lowered incrementally. The columns were unbolted from the floor beams and removed. Finally, the cassettes that formed the roof and floor were dismantled, completing the process.

Although the disassembly was significantly faster than the assembly—taking only 2 to 3 hours—and required only 10 people (Figure 13), there were some troubles during the process. For instance, the roof, rather than dropping down under its own weight, remained stuck after all the bolts had been removed. Therefore, after securing it with temporary vertical supports, the team pulled it down manually, which turned out to be the most time-consuming task. Additionally, some bolts had been overly tightened, while others were difficult to remove because the diameter of their holes was too small to allow easy access by hand. Unfortunately, the force applied with hammers and mallets caused damage to some of the timber pieces.

Final Remarks

The construction process as a constant switch between digital models and carpentry

In the Ardıç project, computational design tools played a critical role in guiding both the design and production processes. 3D modelling was used to design

Figure 13. Process of disassembling the prototype.

the modules, determine the overall configuration, and finalize the sizes and connection types of each component. Although this digital approach was invaluable for visualizing the structure, exploring different design options, and making informed decisions before physical assembly, the construction process itself was far from linear. In fact, the entire workflow alternated between 3D models, construction drawings, and carpentry, with the three phases feeding back into each other (Figure 14).

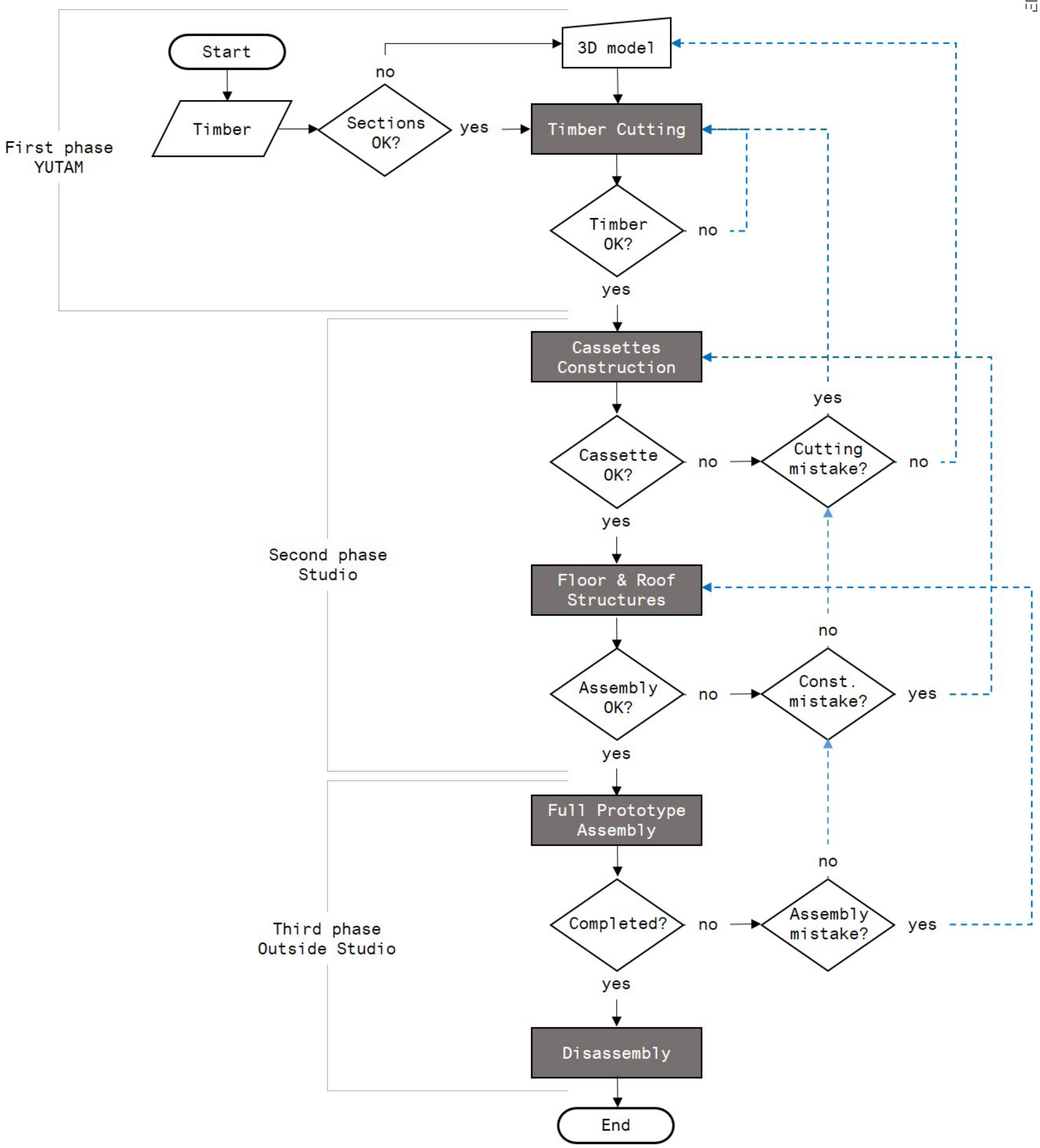

Figure 14. Flowchart revisited – the actual workflow from 3D digital model to full-scale prototype.

One of the best examples of this continuous loop between digital tools and carpentry occurred when problems were encountered during assembly. The 3D model was adjusted in response to these issues. The team often found themselves double-checking measurements from the computational model and adjusting them as necessary during the construction phase. This process became an iterative cycle: designing the prototype in the modelling software, cutting the pieces according to the model, and refining the design (digital model) based on real-world conditions.

During the fabrication phase, the 3D model served as an essential guide for every step—from cutting the timber pieces to assembling the module parts on-site. The model allowed the team to visualize the entire structure, explore various design configurations, and precisely plan dimensions, angles, and distances between the structural elements. For example, the 3D model was referenced to ensure the correct spacing of the planks on the floor structure, aligning them carefully with the design specifications. This thorough approach to simulation and visualization enabled a more efficient assembly process, reduced waste, and helped the team anticipate and address logistical challenges in advance.

Students' learning gains despite the setbacks

For the students involved in the Ardıç project, the journey was both challenging and deeply rewarding. Working on a project of this scale allowed them to merge theoretical knowledge with practical applications, particularly in the context of post-disaster recovery. Witnessing the transformation from conceptual design to a tangible, functional space has been an inspiring experience. The opportunity to contribute to a modular design that addresses real community needs—especially in a culturally rich setting like Dikmece—has deepened their understanding of architecture's role in societal well-being.

However, the project was not without challenges and limitations. One major constraint was the defined timeframe, as it was a semester-long project. Due to time restrictions, the students had to be divided in to groups for specific tasks, meaning that not all participants were involved in every phase of the project. Additionally, the short duration did not allow for iterative feedback from the villagers. While design decisions were based on site visits and conversations, more time on-site and more regular dialogue would have enriched their understanding and provided opportunities to test ideas with the community.

Another limitation was the lack of financial resources and proper facilities. Without external funding, the design and construction process had to adapt to the availability of materials, which sometimes meant compromising on certain aspects of the project. The prototype phase highlighted another challenge: the lack of adequate indoor spaces for assembly. Due to the large scale of the project, much of the work had to be carried out outdoors, regardless of weather conditions (which did, however, provide some real-world construction experience).

Despite these challenges, the project's emphasis on modularity, ease of assembly, and community involvement not only aligns with sustainable practices but also reflects the essence of traditional Turkish values, such as the importance of communal gatherings. This experience expanded the students' technical skills, particularly in modular design and construction. They also recognized areas for improvement: more immersive engagement with the local community, iterative feedback loops, and a more robust logistical and financial support system.

Author Contributions

Buse Beste Aydınoğlu: Writing - Original Draft, Methodology, Investigation, Resources, Software, Visualization, Funding acquisition; Mauricio Morales-Beltran: Conceptualization, Writing - Original Draft, Writing - Review & Editing, Methodology, Investigation, Resources, Supervision, Funding acquisition; Utku Özer: Writing - Original Draft, Methodology, Resources, Software, Visualization; Elizabeth Cunningham: Writing - Review & Editing, Methodology, Resources, Supervision; Göktuğ Ünlü: Methodology, Resources, Software, Visualization; Buse Ecem Gönülalan: Methodology, Resources, Software, Visualization, Funding acquisition; Denizhan Şallı: Methodology, Resources, Software, Visualization.

Funding

This research received no external funding.

Ethics Committee Approval

This work does not require an ethics committee approval.

Available Data

A SketchUp model of the Ardıç module is available at

https://doi.org/10.4121/22600238-c543-4e4d-9ad0-302cea24d1e5

Acknowledgements

The authors thank Ahmet Abi, from Dikmece, for his hospitality, willingness to help, and overwhelming kindness while visiting the village. The authors also thank the studio instructors Ecenur Kızılörenli, Ömer Can Bakan, Matthieu Pedergnana, and Arzu Cilasun Kunduracı for their contributions to the project. And to all students who were involved in the development and/or construction of the prototype (in alphabetic order): Aleyna Su Karabıyık, Alp Kuştan, Ata Bozkurt Atik, Batuhan Yaş, Bilge Günay, Ege Aktuğlu, Enes Karaca, Hazar Karabulut, Mustafa Küçük, Seval Dalgın, Sezin Akgün, Yiğiter Bülbül, and Zeynep Naz Alkan. A final thanks to Soner Batı (YUTAM), for his kind assistance during the production of the prototype.

Conflict of Interest

The authors declare no conflicts of interest.

References

1. O. C. Celik et al., "Multidisciplinary reconnaissance investigation covering structural, geotechnical, and architectural based damage to mid-rise residential buildings following the February 6th, 2023 Kahramanmaraş, Türkiye earthquake doublets (Mw 7.8, Mw 7.6)," *Soil Dynamics and Earthquake Engineering*, vol. 182, p. 108738, 2024, doi: 10.1016/j.soildyn.2024.108738.
2. A. Y. Çetinkaya and L. Bilgili, "Comparative life cycle assessment of container cities and tent cities for earthquake victims: Environmental impacts and sustainability considerations," *Circular Economy and Sustainability*, vol. 4, no. 1, pp. 149–161, 2024, doi: 10.1007/s43615-023-00286-x.
3. Z. Aslan, K. Demiröz, and S. Demiröz, "An examination of temporary shelter units in terms of minimum standards: The case of Kahramanmaraş earthquake," *SSRN*. [Online]. Available: https://ssrn.com/abstract=4911109
4. A. Sığın and N. A. Akyıldız, "Effects of February 6, 2023 Kahramanmaraş earthquakes on housing preferences vis-à-vis sociology of disasters," *Journal of Economy Culture and Society*, no. 69, pp. 1–14, 2024, doi: 10.26650/JECS2023-1344821.
5. M. Morales-Beltran and J. Łątka, "Pop-ups can be ugly: temporary architecture built with emotions," *The Journal of Architecture*, vol. 29, no. 4, pp. 630–653, 2024, doi: 10.1080/13602365.2024.2406325.
6. P. Crowther, "Design for disassembly – Themes and principles," *Environment Design Guide*, pp. 1–7, 2005.
7. T. Bryans, E. Berwyn, P. Swallow, and C. Rose, "Flatpack architecture: Investigating circularity through temporary, demountable buildings," *Technology|Architecture + Design*, vol. 7, no. 2, pp. 160–166, 2023, doi: 10.1080/24751448.2023.2245709.
8. A. Arrigoni, M. Zucchinelli, D. Collatina, and G. Dotelli, "Life cycle environmental benefits of a forward-thinking design phase for buildings: The case study of a temporary pavilion built for an international exhibition," *Journal of Cleaner Production*, vol. 187, pp. 974–983, 2018, doi: 10.1016/j.jclepro.2018.03.230.
9. S. Brancart, A. Paduart, A. Vergauwen, C. Vandervaeren, L. De Laet, and N. De Temmerman, "Transformable structures: Materialising design for change," *International Journal of Design & Nature and Ecodynamics*, vol. 12, no. 3, pp. 357–366, 2017.
10. M. Morales-Beltran, Ö. C. Bakan, M. Pedergnana, and E. Kızılörenli, "Pop-up earthquake architecture for integrating practical experience and social responsibility into architectural education," presented at the *ARCC/EAAE Conference 2024*, Aarhus School of Architecture, Aarhus, Denmark, 2024, p. 8.
11. I. Caetano, L. Santos, and A. Leitão, "Computational design in architecture: Defining parametric, generative, and algorithmic design," *Frontiers of Architectural Research*, vol. 9, no. 2, pp. 287–300, 2020, doi: 10.1016/j.foar.2019.12.008.

12. A. Saltzman, “Beyond the tents: Community spaces in post-disaster temporary settlements,” University of Cincinnati, 2011. [Online]. Available: http://rave.ohiolink.edu/etdc/view?acc_num=ucin1306500942

13. V. Cuzdan and A. Dinç, “Hatay One Year After the Earthquake – Reconstruction: Dreams and Reality,” *bianet.org*. [Online]. Available: https://bianet.org/haber/reconstrucion-dreams-and-reality-291458. Accessed: Sep. 24, 2024.

14. I. N. Grigoriadis and P. Akdeniz, “Universal faith or islamic denomination: On the struggle to define alevism,” J*ournal of Church and State*, vol. 63, no. 1, pp. 47–69, 2021, doi: 10.1093/jcs/csaa028.

15. Pledge Times, “After the Earthquake, the Olive Trees of Dikmece Have to Make Way for Housing.” [Online]. Available: https://pledgetimes.com/after-the-earthquake-the-olive-trees-of-dikmece-have-to-make-way-for-housing/. Accessed: Sep. 18, 2024.

16. O. Aydin and B. Gurpinar, “The right to have places of worship: The Cemevi case in Turkey,” *Religions*, vol. 13, no. 8, 2022, doi: 10.3390/rel13080758.

17. TKGM, “Tapu ve Kadastro Genel Müdürlüğü – Parsel Sorgu Uygulaması.” [Online]. Available: https://parselsorgu.tkgm.gov.tr. Accessed: Oct. 18, 2024.

18. Trimble Inc., *SketchUp*, 2023. [Online]. Available: https://www.sketchup.com/en

19. Act-3D B.V., *Lumion*, 2023. [Online]. Available: https://lumion.com

20. R. McNeel, *Rhinoceros 3D*, 2022. [Online]. Available: https://www.rhino3d.com/

Appendix

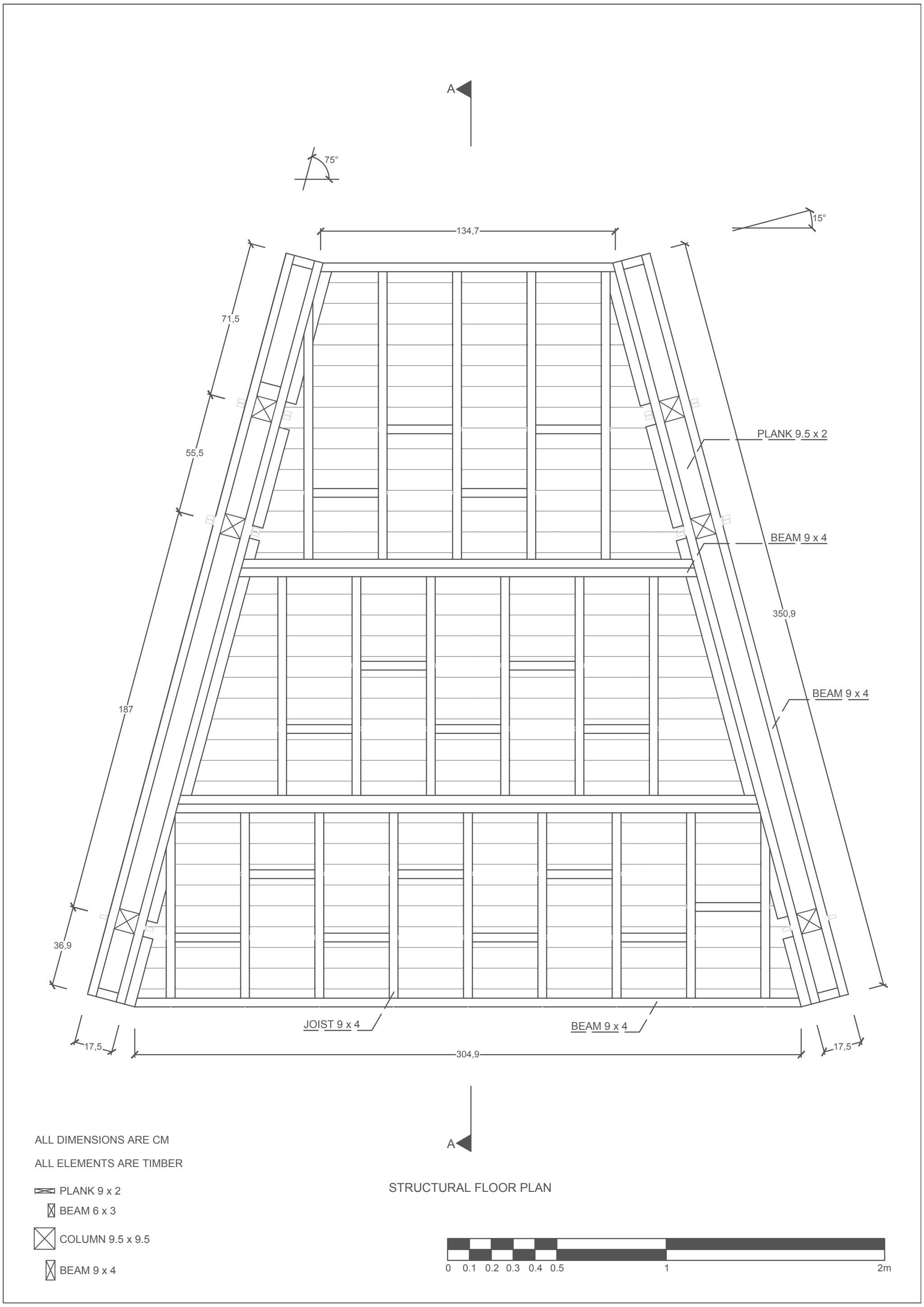

Figure a) Single module drawings of the Ardıç project, Structural floor plan.

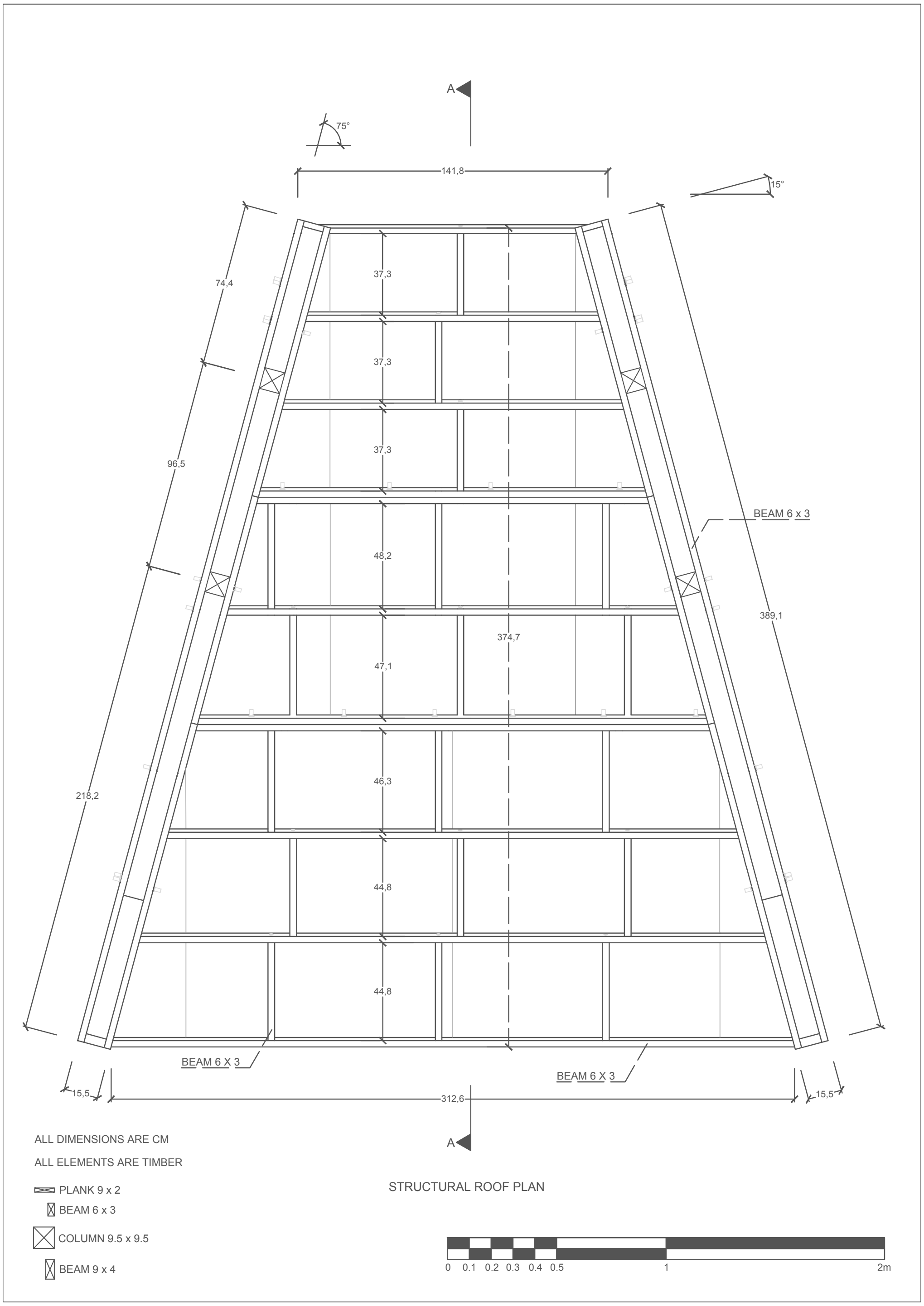

Figure b) Single module drawings of the Ardıç project, Structural roof plan.

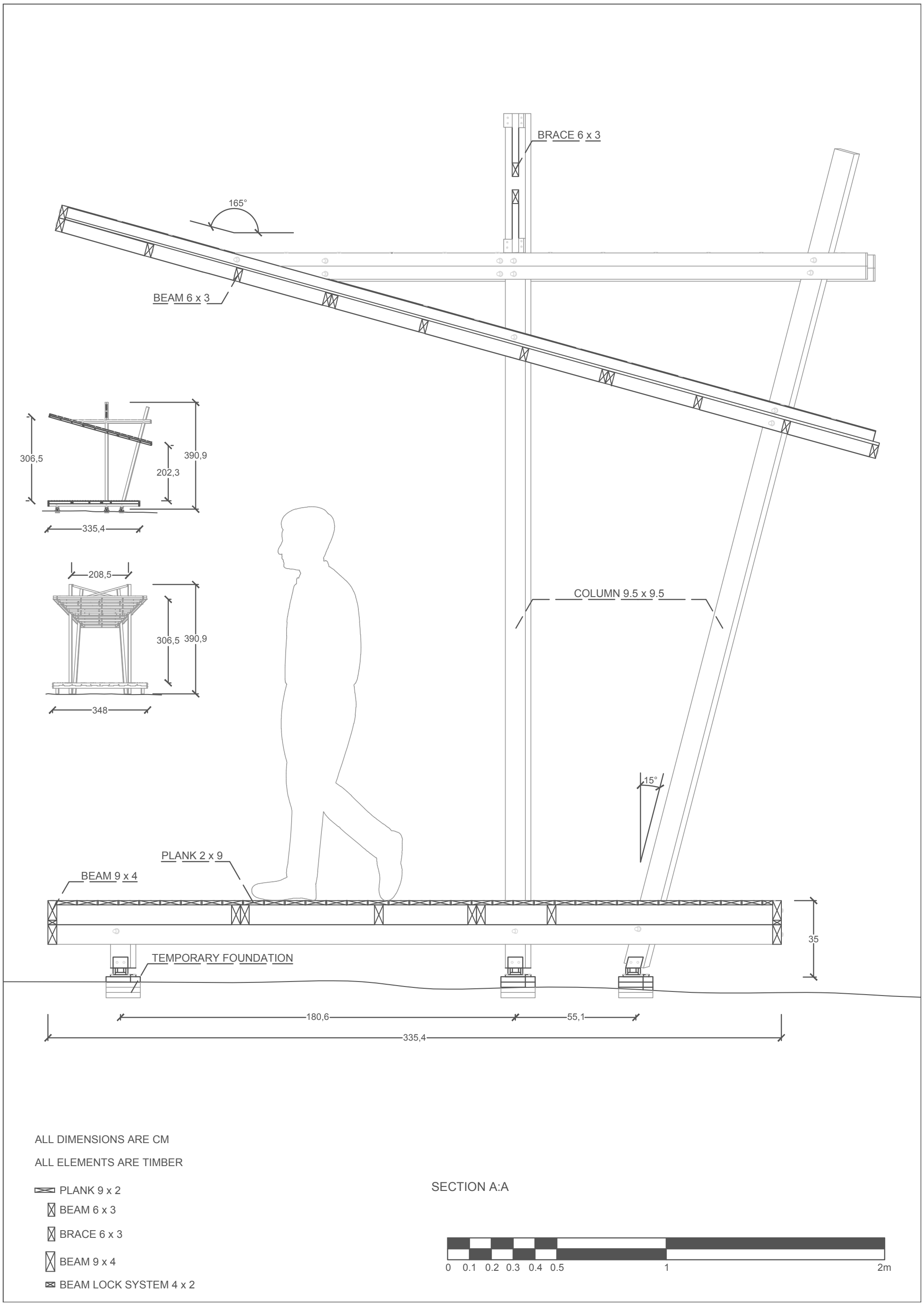

Figure c) Single module drawings of the Ardıç project, Section A-A.

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Part II

Research Insights

Earthquake-Resilient & Sustainable Buildings: Current Trends and Future Directions

Simona Bianchi*

The shift toward a more resilient and sustainable built environment is a global priority. In seismic-prone regions, this requires prioritizing seismic resilience by adopting building technologies that can withstand earthquakes with minimal business disruption and limited casualties, financial losses and carbon emissions. For new buildings, modular systems with low-damage plug & play connections show great promise in reducing post-earthquake damage, thereby minimizing the expected consequences. Recent innovations in these solutions have significantly enhanced the resilience of both structural and non-structural components, and their integration can lead to buildings that are cost-effective, safer and more sustainable in the long term. This paper explores low-damage techniques and their application to a building's main load-bearing structure, envelope and contents, providing design concepts for creating effective damage-control mechanisms. Dynamic experimental shake-table results on scaled buildings and full-scale components are presented to demonstrate the potential of such technologies. To advance the next generation of earthquake-resilient sustainable buildings, the paper discusses the integration of bio-based components and sustainability-oriented performance criteria into the seismic design process, as well as the need for multifunctional integrated technologies to address real-world multi-hazard challenges.

Keywords: Seismic resilience, Seismic design, Building technology, Low-damage, Low-carbon

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Introduction

Recent earthquake disasters have once again confirmed the vulnerability of the built environment and the profound impact these events have on our communities. Earthquakes rank among the deadliest natural disasters, causing over 200,000 deaths and more than 250 billion Euros in direct and indirect financial losses in Europe alone during the 20th century[1]. Beyond the human and economic toll, these events also result in significant environmental damage, highlighting the urgent need for more resilient structures. Modern structures, while technically performing as expected in recent earthquakes, often sustained severe damage and were deemed too costly to repair, leading to many being demolished[2]. This reveals limitations in the current performance-based design approach, which has primarily focused on life safety but should also aim to minimize overall losses. In particular, a significant portion of post-earthquake losses is attributed to non-structural damage. These elements are frequently overlooked in seismic design despite their high vulnerability and substantial capital investment relative to structural costs[3]. Inadequate seismic detailing and poor dynamic performance can lead to their functionality loss during low-to-moderate intensity earthquakes and severe damage or collapse in moderate-to-strong events, resulting in prolonged downtime, economic losses and life-safety risks for building occupants and pedestrians. Particularly, among non-structural components, building envelopes (or façades) are crucial as interfaces between the external and internal environments, making them also highly vulnerable to climate change-induced events, that are causing increased energy consumption, building overheating and higher carbon emissions. As awareness of these issues grows, there is an increasing demand from individuals, facility managers and policymakers for high levels of earthquake protection - not only for main load-bearing structure, but also for the building non-structural components - to prevent functionality loss in low-intensity earthquake scenarios. Achieving this requires integrating resilient and eco-friendly building technologies, now a key objective of risk reduction and management policies reflecting the dual goals of enhancing seismic resilience and promoting environmental sustainability.

In recent years, research has therefore increasingly focused on advancing seismic design to improve performance for modern structures, aiming to reduce overall expected losses. This goal involves adopting either improved design methodologies or earthquake-proof (low-damage) technologies, which may entail a slight increase in initial costs but lead to more sustainable impacts[4]. To develop high-performance buildings, seismic design philosophies and technologies must adopt a damage-control approach (Figure 1) that encompasses the entire building system. Within this framework, two main areas of focus have emerged: (1) design methods that prioritize displacement control over force control, providing better management of building behaviour in the inelastic domain[5], and (2) low-damage technologies aimed at reducing post-earthquake damage. In the latter area, recent decades have seen growing interest in innovative solutions that combine unbonded post-tensioned rocking mechanisms with dissipative systems for structural components[6].

However, to create resilient low-damage buildings, it is essential to harmonize performance across structural and non-structural components. This means that architectural components, mechanical and electrical equipment and building contents must adhere to damage-control principles, driving the development of advanced integrated buildings with enhanced seismic resilience. The advantages of these solutions have been demonstrated through performance-based numerical studies and loss modeling of multi-story building archetypes[7,8]. These studies reveal that low-damage technologies results in over 50% reduction in economic losses during the building's life and significant reductions in downtime (2–7 months) for a modest increase (5–10%) in initial investment costs. Furthermore, using low-carbon materials, such as timber, can lead to even greater environmental benefits. Low-carbon low-damage systems could contribute to over 50% reductions in damage-related emissions by minimizing post-earthquake damage and enhancing sustainability from a life-cycle perspective, including ease of recyclability and reduced waste during demolition[9].

To aid in understanding low-damage solutions, this paper provides an overview of these technologies for structural and non-structural components, with a focus on modern Reinforced Concrete (RC) and timber buildings. It examines the expected damage mechanisms of traditional earthquake-resistant components and presents low-damage techniques for improving their performance. The practical application of such solutions is explored through building and component prototypes subjected to dynamic experiments, demonstrating the efficacy and resilience of these solutions. The paper also highlights the need for further

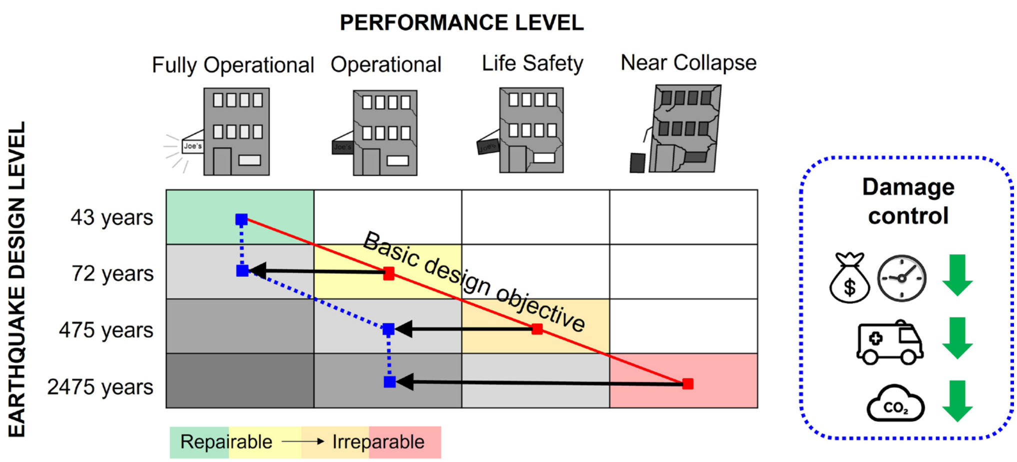


Figure 1. Damage-control design objective (Modified after Pampanin et al. [6]).

research, particularly in integrating bio-based components and establishing multidisciplinary performance criteria. This will contribute to developing solutions that are well-equipped for future multi-hazard scenarios.

Reducing Building Damage Through Low-Damage Solutions

Structural components

Modern buildings are designed using a performance-based design framework targeting life safety. This approach conceptualizes structures as ductile systems where inelastic behavior is concentrated in plastic hinge regions, such as beam end sections and bases of walls and columns. This framework is based on capacity-design principles, allowing buildings to sway and remain standing during an earthquake and occupants to evacuate safely. Recent earthquakes have demonstrated that modern buildings perform as expected under severe shaking, with plastic hinges forming in designated sections of RC structural members. However, RC structural walls designed with minimal boundary zone confinement reinforcement (limited ductility), have been observed to fail due to brittle shear-compression or through premature tensile or compressive fractures of the reinforcement[2]. A critical weakness in many structures has been identified as the displacement incompatibility between lateral load-resisting systems and gravity elements, such as floors and transfer beams. The elongation effects resulting from the expected ductile behavior of lateral systems can compromise the integrity of flooring diaphragms[10]. Despite their generally acceptable performance in earthquakes, the life-safety design approach allows for severe damage to structural components (Table 1). Consequently, repairing these structures post-earthquake can often be less economical than opting for demolition and reconstruction. This issue also complicates the process of assessing a building's capacity and safety during severe aftershocks.

To address these challenges, the objectives within the performance-based design framework must be revised to target damage-control systems. In addition to technologies such as base isolation and dissipative braces, there is growing interest in alternative, recently developed "low-damage" systems. These systems replace the plastic hinge formation in ductile design with a controlled rocking mechanism at key structural interfaces (beam-to-column, column-to-foundation, wall-to-foundation). The initial concept for this technology was developed by Stanton et al.[11] and Priestley et al.[12] during the PRESSS (PREcast Seismic Structural System) program at the University of San Diego in the 1990s. The program introduced jointed ductile connections, where precast components are connected through unbonded post-tensioning tendons or bars. To ensure adequate ductility, energy dissipation was incorporated using internal mild steel bars in the first-generation technology, then evolved to include externally

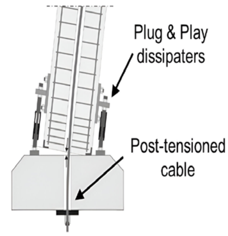
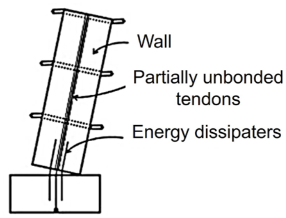
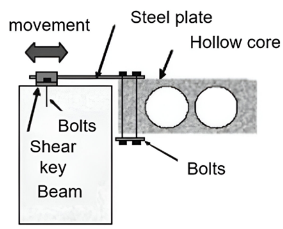
Component	Traditional design solution		Low-damage design solution	
RC Frame	Monolithic connections with capacity design principles	 Kam et al. [2]	Rocking-dissipative connections (beam-column, column-to-foundation)	 Marriott et al. [13]
RC Wall	Monolithic connections with capacity design principles	 Kam et al. [2]	Rocking-dissipative connections (wall-to-foundation)	 fib [14] (copyrighted)
RC Floor	Rigid flooring diaphrams, for load distribution	 Kam et al. [2]	Articulated floor system with shear keys	 Amaris et al. [16]

Table 1. Traditional vs. low-damage structural components.

replaceable so-called Plug & Play dissipators[13-15]. The result is a hybrid connection that combines self-centring and energy dissipation capabilities. Designers can tailor the properties of these connections by adjusting the ratio between re-centring and dissipative moment contributions, provided by post-tensioned tendons or bars (and/or axial load) and dissipators. During an earthquake, these connections permit rocking motions through the controlled opening and closing of gaps. The dissipator devices ensure the necessary system ductility, reducing residual deformations. With this approach, the building's structural skeleton can remain undamaged after strong earthquakes, eliminating the need for extensive repairs.

Due to the self-centering capabilities of rocking systems, jointed ductile connections may experience beam elongation, albeit less than that of traditional cast-in-situ systems. To address this issue and minimize damage to floor while ensuring reliable diaphragm action, innovative solutions have been proposed. An Articulated Floor Solution was introduced by Priestley et al.[12] with discrete metallic connectors that concentrate shear transfer between floor diaphragms and the lateral load-resisting system. Amaris et al.[16] developed an articulated "jointed" floor system featuring a double hinge mechanism at the beam-column interface, acting as a shear key transfer mechanism. Sliding shear keys in the horizontal plane serve as frame-floor connectors. Another approach is creating a Non-Tearing Floor Solution, which involves separating beams and columns with small gaps, partially grouted at the bottom to mitigate geometrical elongation effects. However, this does not prevent tearing of the floor caused by gap opening at the top of the beam[17], and lacks re-centering capabilities due to the tendon location and profile. Improved versions of this solution combine an inverted gap to prevent tearing in the floor with an antisymmetric tendon profile to address the re-centering issue.

These low-damage solutions can be effectively applied to engineered timber frame and wall multi-story buildings, as demonstrated by the Pres-Lam (Prestressed Laminated Timber) technology[18,19]. Since 2004, extensive research studies at the University of Canterbury have validated this low-damage solution on various timber subassemblies and large-scale specimens. These investigations have proved excellent results, highlighting the high potential of this technology for creating timber buildings that offer large open spaces, exceptional living and working environments, and robust resistance to multiple hazards (earthquakes, fires and extreme weather)[20]. The rapid advancement of low-damage connections has led to a diverse array of alternative arrangements available for practical applications. This technology has begun to be implemented in various seismic-prone regions worldwide, including America, Europe and New Zealand, offering designers and contractors a range of options for on-site applications.

Building envelope

Building envelopes (or façades) can be classified as heavy or light components depending on the potential impact of their failure. Heavy façades, such as masonry infill walls or precast concrete claddings, pose a significant threat to life safety if they fail. In contrast, the failure of lightweight façade systems may not pose the same level of risk to life safety, but the associated economic losses can be substantial. Since exterior enclosures are attached to or constructed between building floor levels, inter-story drift ratios during earthquakes can lead to displacement incompatibilities. Initially, movements are managed by internal gaps, deformations or components shifts. However, as displacement continues, stresses concentrate in certain areas of the building envelope, triggering damage.

In curtain wall systems, typical damage includes falling glass caused by insufficient allowable movement of the panels. Another common issue is warping of the internal frame, which can lead to its total or partial disconnection from the building's load-bearing structure[21]. This often results from improperly designed connections that fail to accommodate displacement incompatibilities. Additionally, stress concentrations in localized areas can cause glass breakage, particularly in façades with point connections. For cladding systems, damage mechanisms depend on the system configuration. Lightweight panels are prone to damage when there is inadequate allowance for relative movement between the structural system and the panels. This damage typically manifests as cracking, tearing or disconnection at the interfaces between panels. In brick veneer systems, insufficient lateral restraint can result in out-of-plane failure of the panels. Connections with low flexibility to accommodate seismic movements may distort, leading to cracking, spalling, or the dislodgement of veneer units. Heavy precast concrete claddings can experience a range of damage states, including cracking of the panels, corner crushing caused by pounding between panels, bolt failure and panel disconnection due to bolts that cannot slide to accommodate inter-story deformations, ejection or rupture of sealing joint, component damage due to beam elongation effects[22]. For infill walls, lightweight components such as timber or steel often damage due to a lack of in-plane movement allowance. Heavy systems (e.g., masonry infill walls) have shown high levels of damage in post-earthquake reports, with the damage ranging from minor cracks to full collapse due to compression, shear sliding, diagonal tension or out-of-plane failure[23]. This damage is primarily caused by the interaction with the building's main structure during earthquakes. The stiffness and strength of masonry walls can also lead to unexpected mechanisms, such as column failure, joint damage or the formation of soft story mechanisms, resulting in significant seismic losses[24].

The connection between a building envelope and its primary structure is crucial for managing interactions between structural and non-structural components. To minimize these interactions, the exterior envelope is treated as dead weight, while additional systems are employed to incorporate the stiffening and damping properties of non-structural components. Strategies to reduce façade damage [25] include: (i) disconnecting the façade using seismic gaps or connections that allow lateral movement; (ii) partially disconnecting it with dissipation devices that yield before the façade is damaged; and (iii) fully integrating the façade with the structure through strengthening, particularly for masonry infill walls. Based on these concepts, low-damage façade technologies have been proposed (Table 2).

For curtain walls, advanced façade connections can enhance seismic performance by distributing energy more evenly across the building height and limiting the force transmitted to the panels. Examples include friction damping connectors[26] and viscoelastic dampers[27]. Alternatively, simple modifications to non-structural detailing can create low-damage solutions. For instance, incorporating internal horizontal and vertical gaps in steel plate assemblies for point-fixed façades[28,29],

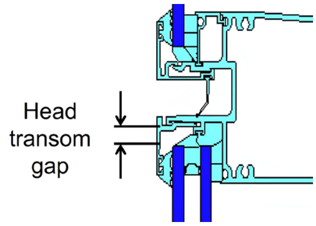
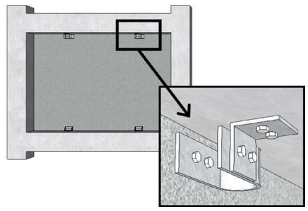
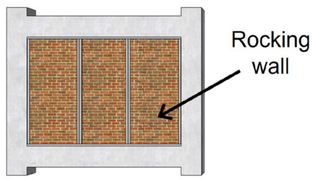
Component	Traditional design solution		Low-damage design solution	
Curtain Wall	Glass panel connected to aluminum frame with insufficient clearance	 Baird et al. [25]	Glass panel with internal gaps in head/sill transoms and mullions	 Bianchi et al. [30]
Precast Concrete Cladding	Cladding panel with bearing (bottom) and tie-back (upper) con-nections	 Baird et al. [25]	Cladding panel with upper dissipative connections	 Baird et al. [34]
Masonry Infill Wall	Monolithic masonry wall bonded through mortar	 Baird et al. [25]	Rocking walls built in a steel frame with lateral gaps	 Tasligedik and Pampanin [39]

Table 2. Traditional vs. low-damage building envelopes.

designing flexible connections with internal gaps between glass panels and aluminium sub-frames or using structural silicone as bonding[30] can enhance the seismic performance of unitized curtain walls.

Concerning precast concrete cladding systems, minimizing the interaction between cladding and structural components can be achieved by employing a combination of connections. Bearing connections at the bottom of the panels transfer vertical loading, while tieback or slotted connections at the upper part allow for lateral movements of the panels. These upper connections should be designed with specific ductility and capacity to prevent failure[31,32]. However, even when designed according to the latest connection design practices, these can inadvertently increase the building stiffness. An alternative approach involves leveraging this interaction to dissipate energy[33]. Connections should be designed to absorb energy effectively without failing in strong earthquakes, thereby limiting the forces transmitted to the cladding panel. To this end, Baird et al.[34] developed a low-damage solution involving U-shaped Flexural Plates (UFP) as upper connections. These devices are designed to dissipate seismic energy and accommodate displacements between the structure and the panel while limiting maximum displacements, consequently reducing damage to other non-structural components.

For exterior masonry infill walls, various solutions have been explored to address their brittle nature and limited deformation capacity. Aliaari and Memari[35] proposed an isolation system with steel studs and an isolator - while the system transitioned to bare frame behavior after isolator failure, it exhibited brittleness in practice. Mohammadi and Mahalleh[36] developed a sliding system with frictional sliding fuses, enhancing deformation capacity and promoting ductile failure, although proper design is crucial to avoid wall crushing. Preti et al.[37] introduced horizontal sliding joints acting as weak planes in the wall, which reduced frame interaction and improved ductility; however practical application requires further research. Morandi et al.[38] tested horizontal panels with sliding and deformable joints on RC frames. While this approach addressed certain issues, it encountered challenges related to out-of-plane stability and shear failure at high drift levels. Tasligedik and Pampanin[39] proposed a low-damage solution made of vertical panel systems with a rocking mechanism to handle inter-story drift through internal seismic gaps. This system demonstrated moderate-to-high deformation capacity and showed no visible cracking or damage under design-level earthquakes.

Internal non-structural components

In past earthquakes, internal building components have suffered moderate to extensive damage, resulting in significant financial losses due to repair or replacement costs. Partition walls, in particular, have suffered from such damage, causing blocked corridors and endangering occupants. If not properly detailed, lightweight partitions are vulnerable to both in-plane and out-of-plane movements, often resulting in damaged fasteners, dislodged studs, cracked linings, and failed anchorage[40]. Cracking often occurs at door and window openings and intersections of beams and walls. Heavy partitions, like masonry walls, can alter the building's overall seismic response and may crack and spall, creating dangerous debris. Glazing systems are also susceptible to damage if they lack lateral support and are not isolated from the primary structure's movement.

Damage to ceiling systems is another common consequence of earthquakes [41]. For suspended ceilings, typical issues include dislodged or broken ceiling tiles, failure of grid members and connections, displacement incompatibilities and interactions with other components. T-rails, especially in large areas, can fail due to inertia forces exceeding their capacity. Interaction with services, partitions and the primary load-bearing structure can further damage ceiling tiles and grids. Both light and heavy tiles have been observed to fall, with heavy components posing significant life safety risks. For ceilings directly attached to structural elements, inadequate anchoring can lead to falling hazards. Common damage includes panel cracking or cracks around the edges and seismic joints. Heavy suspended ceilings are particularly vulnerable to accelerations and deformations, posing a serious risk if they collapse, potentially endangering building occupants.

Building services and contents can also suffer significant damage during earthquakes. Mechanical and electrical systems, including heating and cooling units, ducts, tanks and HVAC systems, are particularly vulnerable. Reports from Taghavi and Miranda[3], FEMA E-74[32], Baird and Ferner[42] detail various damage scenarios, often linked to inadequate system detailing. Common issues include unanchored systems that may move or fall, shifting and falling components, impact damage between components, and failures in anchorages or connections. For egress systems, stairs typically suffer damage to stairwell walls, starting with plaster cracks and potentially extending to wallboard or infill damage. Elevators

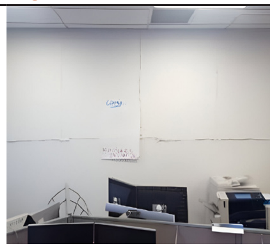
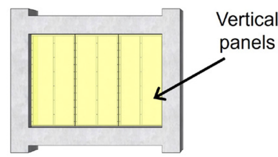
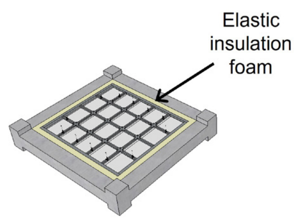
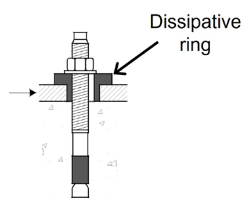
Component	Traditional design solution		Low-damage design solution	
Partition Wall	Gypsum with full height studs, fixed below and above	 Tasligedik et al. [40]	Glass panel with internal gaps in head/sill transoms and mullions	 Tasligedik et al. [46]
Suspended ceiling	Unbraced system, pop rivet or seismic clip connections	 Dhakal et al. [41]	Unbraced system, acoustic insulation in the lateral gaps	 Pourali et al. [49]
Building contents	Contents with poor fixing systems	 Baird and Ferner [42]	Contents connected through dissipative connectores	 Quintana-Gallo et al. [52]

Table 3. Traditional vs. low-damage building envelopes.

often become inoperable due to mechanical failures or power loss, with damage usually affecting components like controllers, motors, stabilizers, and their supports and anchorages.

In recent years, various strategies have been explored to mitigate damage to internal non-structural components, including low-damage techniques (Table 3). Filiatrault et al.[43] suggested using slip tracks and gaps at the top of drywall panels to reduce damage between floors. However, this approach can lead to damage at the vertical joints where panels meet orthogonally. Araya-Letelier et al. [44] proposed a sliding frictional connection that enabled drywall panels to remain undamaged up to a 1.52% drift, compared to just 0.1% for conventional panels. Petrone et al.[45] introduced an innovative locking device for drywall partitions. This device, comprising a steel plate with lateral flaps and a bolt, prevents panels from unhooking from the studs under uplift and out-of-plane movements. The locking mechanism tightens to secure the panels, reducing slot width and improving stability. Tasligedik et al.[46] explored a low-damage drywall solution incorporating internal gaps and design modifications. Their tests demonstrated that the system could withstand drifts of up to 2.5% without significant damage.

To enhance the seismic performance of suspended ceilings, alternative solutions have been explored. These include diagonal braces[47], lateral constraints through perimeter boundaries[48], perimeter gap fillers made of compressible materials [49]. Other approaches involve the use of seismic joints[50] and anti-falling clips to prevent ceiling drops[51], or connection methods that facilitate the disassembly and reassembly of ceilings.

Regarding building components, various techniques can be proposed to improve their restraint systems, as outlined in FEMA E-74[32]. A key focus is on the fixings, which are often the weakest link. Properly designed fasteners are crucial to minimize the forces and accelerations transferred to non-structural components (e.g., air conditioning system). A novel low-damage solution developed by Quintana-Gallo et al.[52] involves adding supplemental damping to traditional anchors. This approach incorporates an external damper to increase the system's overall damping. As a result, the spectral response amplitude and acceleration experienced by building contents are reduced during seismic events.

Application and Testing of Low-Damage Solutions

Low-damage structural system

As part of the Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe (SERA) EU-funded project, which aimed to evaluate and mitigate the risks posed by earthquakes through innovative research and development, a novel structural system with low-damage post-tensioned dissipative connections was implemented and tested on a tri-directional shake table[53]. The test specimen featured low-damage timber-concrete frames and low-damage timber walls (Figure 2a), both equipped with external Plug & Play dissipaters and internal post-tensioning. Two types of timber-concrete slabs were used: a Timber-Concrete Composite (TCC) system for the first floor and a Pre-stressed Timber-Concrete (3PT) system for the second floor.

The Test Building was designed as a scaled version of a Prototype Building, representing the inner core of multi-story commercial structures. The specimen dimensions were also adjusted to meet the size and weight constraints of the shake table at the National Laboratory for Civil Engineering (LNEC) in Lisbon. The seismic forces on each structural component was identified using the Direct Displacement-Based Design (DDBD) approach[5], and the hybrid connections were designed following the procedures outlined in the NZCS PRESS Design Handbook54 for concrete elements and the STIC Design Guidelines[55] for timber components. This process involved designing the post-tensioned tendons/ cables - type and initial force - as well as the dissipaters - diameter and internal fuse dimensions. Structural detailing was designed to ensure the correct implementation of hybrid connections, incorporating steel assemblies such as plates, bolts, screws, nails and welding. The TCC floor was designed according to the STIC[55] and AS/NZS 1170[56] standards, with a deflection control criterion of L/Δ (span-to-deflection ratio) > 300. To ensure proper diaphragm action, reinforcing bars were embedded in the concrete slab. The 3PT prestressed timber-concrete floor[57] comprised timber-concrete beams with wire strands running through a central bottom hole in the timber and a steel tube embedded in the lateral concrete blocks.

The benefits of low-damage connections were already evident during the construction phase. Designed as a Lego system, this solution allows for quick and efficient assembly, significantly reducing construction time compared to traditional monolithic structures. The combination of concrete and timber proved to be an effective solution: (i) concrete provides the necessary stiffness, particularly beneficial for high-rise buildings; (ii) while timber's lightweight nature reduces seismic demands on the superstructure and foundation system. Timber also allows for easy recyclability and minimal waste generated during demolition. Additionally, dry-jointed precast structural connections enable modular, replaceable and easily relocatable components. This approach enhances the construction process by improving quality control, speeding up erection and creating safer, cleaner work environments.

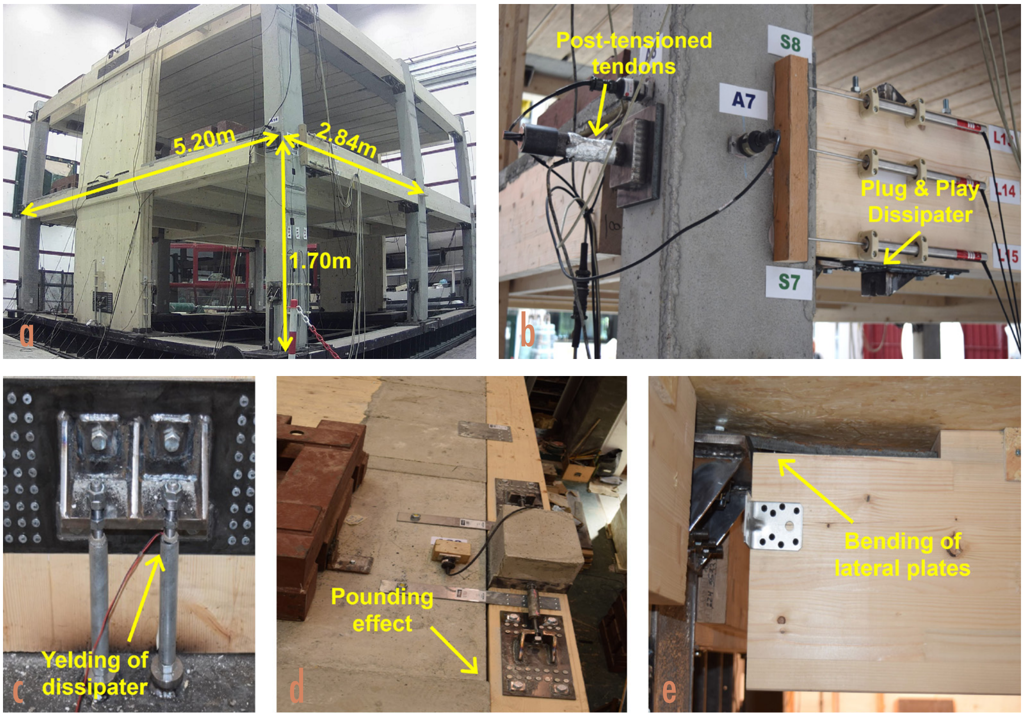


Figure 2. (a) Specimen configuration (Skeleton Building); (b) Connection details, including monitoring system, of a beam-column joint; (c-e) observed damage to the main load-bearing structure.

The specimen was tested on a 5.60m x 6.20m shaking table and subjected to earthquake motions of increasing intensity (6.3 to 7.3 moment magnitude), with input motions applied alternately in the orthogonal directions, simultaneously in both directions and with the addition of vertical shaking. The selected seismic records represented spectral-compatible earthquakes, covering code-based limit states up to Collapse Prevention. As discussed in Pampanin et al.[53] and Bianchi et al. [58], seismic demand parameters (floor accelerations, inter-story drift ratios, along with force and strain values in the hybrid connections) were derived from a range of sensors - including potentiometers, accelerometers, load cells and strain gauges (Figure 2b). These sensors were placed in the low-damage connections and on building floors at each story, capturing data for each shaking direction and intensity level. Experimental data were compared to numerical predictions, confirming that the numerical model - developed using a simple lumped-plasticity approach[59] - accurately predicted the response of the low-damage structural system (Figure 3). This accuracy is attributed to the model's ability to capture the straightforward behavior, where dissipation and recentering capacity are concentrated at the element end sections.

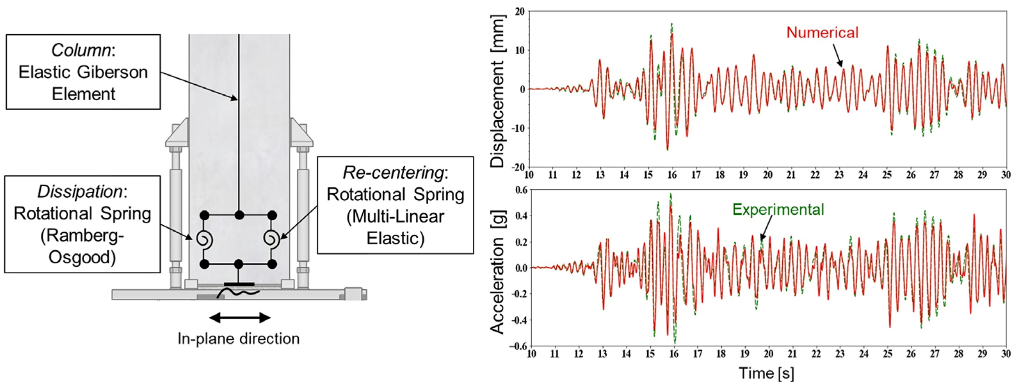


Figure 3. Modelling approach used to simulate the hybrid connections, and numerical vs. experimental results in terms of displacement and acceleration (e.g., frame direction - second floor)(Modified after Ciurlanti et al. [59]).

Overall, the specimen performed as anticipated, with demand parameters aligning closely with the design approach and modeling predictions, as discussed in Pampanin et al.[53]. In the low-damage connections, the tests induced the expected yielding and permanent deformations in the Plug & Play dissipaters (Figure 2c). During the rocking-dissipative mechanism, the inelastic demand was effectively absorbed by these sacrificial fuses. After an earthquake, these fuses can be easily replaced at minimal cost, particularly when compared to the extensive repairs needed for plastic hinging in traditional monolithic connections. However, it is highlighted that the observed capacity loss was due to the large number of shakings simulated during the experimental campaign, which included over 400 seismic tests - far exceeding the typical number a building would experience in its 50 to 100 year lifespan - up to 2% inter-story drift ratio. Despite this intense testing, no collapse of the dissipaters occurred. Aside from the dissipaters, damage was noted in the 3PT timber-concrete beams due to pounding against the supporting lateral timber beams (Figure 2c) during seismic testing. This issue was attributed to overly heavy steel supports and the absence of additional plates needed to improve shear force transfer to the structural frame. Another damage observed in the central beam of the TCC floor was primarily attributed to the testing apparatus. The six steel masses, totaling approximately 3.6 tons (placed on the floor to ensure prototype-specimen scalability[53]), contributed to the horizontal seismic load but also induced additional vertical accelerations on the floor. This led to increased vertical forces on the central timber beam, resulting in lateral plate bending and partial withdrawal of some coach screws (Figure 2c).

Integrated low-damage building

The goal for future buildings is to incorporate low-damage solutions across all components, thus creating an integrated earthquake-resilient building. Current research focuses on developing such integrated solutions and evaluating their overall performance and feasibility. In one of the initial studies, Johnston et al.[60] conducted mono-directional shaking table tests on a scaled post-tensioned rocking frame, which included articulated floors and low-damage partition walls and façades. Tested under various configurations and subjected to hundreds of earthquakes with differing intensities, the system showed no significant damage. However, further research is needed to fully demonstrate the potential of integrated low-damage buildings and to optimize connection details and construction practices.

As part of the above-mentioned SERA project, the seismic behavior of various low-damage building configurations was analyzed. The Test Building was equipped with different vertical architectural components, including building envelopes and partition systems. One configuration featured internal fiber-reinforced gypsum partition walls with low-damage detailing (Figure 4a). This partition, located on the first floor, consisted of a steel sub-frame with horizontal profiles secured to the top floor with screws and to the bottom floor with post-installed anchors (Figure 4b). The vertical profiles were left free to move within the horizontal channels. The design included seismic gaps between the vertical studs and the top horizontal profile, and seismic gaps between the top/bottom horizontal channels and the concrete columns[58]. The partition was finished with fiber-reinforced ceramic gypsum panels, joined using male-female connections and adhesive glue, and attached to the steel frame with screws applied only to the vertical studs. Acoustic adhesive tape was placed on the vertical studs and the bottom of the horizontal channels, potentially affecting the partition's behavior during seismic motions, and silicone foam was inserted in the lateral gaps.

A second specimen configuration incorporated both envelope and partition wall systems (Figure 4c). The gypsum wall was replaced with an unreinforced masonry partition featuring low-damage detailing. Glass Fiber Reinforced Concrete (GFRC) façades were installed in the frame direction. The concrete panels featured a central opening and were attached to an internal steel frame using stirrups. This steel frame was designed with upper sliding connections and bottom restraint connections. The weight of the façade was fully transferred to the concrete columns through the sliding connections, while the bottom connections were designed to keep the façade in the correct position. The assembly process was straightforward, starting with the attachment of the steel assemblies to the columns and beams; the concrete panels were then lifted and set onto their anchorages.

Figure 4. (a, b) Specimen configuration including a low-damage drywall partition on the first floor; (c, d) Integrated building configuration with concrete and glazed façades, and an internal low-damage masonry wall. (e) Observed non-structural damage.

In the wall direction, spider glazing curtain walls were constructed from 10+1.52Pvb+10 mm glass panels, with a 13 mm gap between them. The façades were secured to the lateral beams and steel foundation using custom-designed steel plates. The façade system used "rotules" (spherical joints) fitted into holes in the glass and bolted to spider connectors. These connectors were then attached to the structural system using steel plates. Spider glazing curtain walls are typically designed to resist out-of-plane wind loads and perform well during earthquakes, thanks to the movement and rotation of the glass panels. The construction process of the system involved few phases but required high precision. The steel anchorages were connected to the main structure and the rotules were inserted into glass panel holes. The glass panels were then lifted and attached to the spider-plate connection system. To complete the wall, sealing tape was applied to the gaps around the glass panels. While silicone gaskets covered with silicone sealant are typically used for this purpose, sealing tape was chosen as an alternative to prevent potential contact between the glass panels during seismic events, effectively simulating the presence of an internal buffer material. Silicone sealant would have further enhanced the seismic performance by uniformly distributing forces across the façade[30], while also offering weatherproofing and insulation.

The internal masonry partition was designed according to Tasligedik and Pampanin[39] and featured rocking vertical panels separated by horizontal seismic gaps (Figure 4d). The wall consisted of a steel sub-frame system with horizontal steel tracks, bolted to the concrete slab and screwed to the timber floor. Vertical steel studs were inserted into the horizontal channels without direct connections, allowing them to move freely within the upper and lower steel profiles. To develop a low-damage solution, horizontal gaps were introduced between the lateral vertical studs and horizontal channels, a vertical gap was implemented between all steel studs and the top horizontal channel, and horizontal gaps were incorporated between all internal vertical studs[58]. The masonry panels were constructed within the steel frame without mortar at the top, bottom or sides of the panel infill zone to facilitate sliding behaviour. Polyurethane joint foam was used to fill the lateral gaps between the steel studs and the adjacent columns. The wall was finished by filling the horizontal gaps between the vertical studs and concrete columns with polyurethane foam. One side of the wall was coated with light white paint to facilitate crack detection during seismic shaking tests.

Both specimen configurations (Figure 4a, c) were tested using a similar protocol to the Skeleton Building. The results showed that the low-damage detailing effectively reduced the structural/non-structural interaction. Their efficacy was demonstrated by the slight-to-moderate reduction in frequencies, as measured by hammer tests conducted between seismic events. The glass panels showed no reduction in frequencies, indicating no damage; the gypsum partition and GFRC façade exhibited only minimal reductions; and the masonry partition wall displayed changes in natural vibration mainly when shifting from Serviceability to Life-Safety intensity levels. The frequency shift was attributed to the rocking motion of the masonry walls within the steel frame, which expanded the boundary clearances and led to a reduction in stiffness. Overall, the observed damage (Figure 4e) was significantly lower compared to traditional construction methods, even under higher seismic demands – up to 1.7% inter-story drift ratio. Damage to the gypsum partition mainly consisted of diagonal cracking at door corners, detachment of the silicone sealant, and localized panel crushing at the wall corners by the end of the tests. The GFRC façade demonstrated excellent seismic performance, remaining undamaged throughout the entire experimental campaign. The spider glazing façade also performed well, with no glass breakage observed in the panels. However, residual out-of-plane displacements occurred due to the yielding and elongation of the spherical joints under high forces. The masonry wall demonstrated the potential of low-damage detailing for heavy partitions, showing no significant in-plane damage or loss of out-of-plane capacity. Only after reaching the final collapse prevention intensity level did minor cracking of mortar around one brick occur.

Shake table tests provided strong evidence that low-damage partition and façade systems delay damage and failure mechanisms to higher seismic demands compared to conventional non-structural systems. However, to achieve a fully integrated earthquake-proof building, damage to internal contents - crucial for the rapid recovery of building functionality, particularly in critical structures as hospitals - should also be minimized. To address this, a low-damage solution was developed for connecting building contents to concrete walls and floors, as part of an industry-funded experimental campaign[61]. This solution features dissipative anchor rods designed to protect non-structural components across a range of fastening systems (expansion and chemical anchors) (Figure 5).

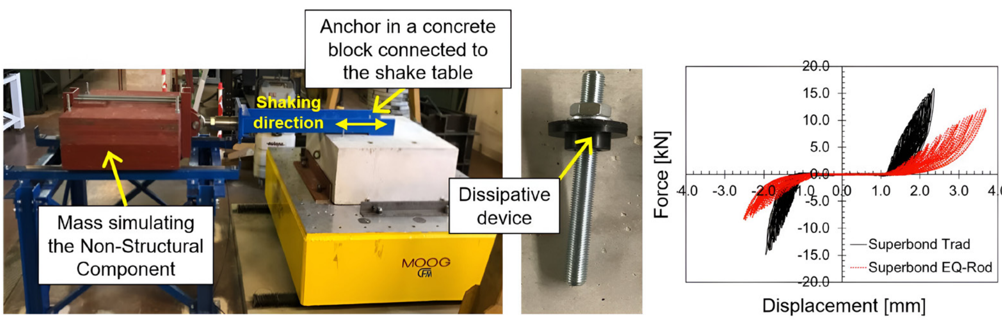


Figure 5. (a) Test set-up and EQ-Rod dissipative anchor. (b) Force-displacement curves of the traditional vs. EQ-Rod solution (e.g., for chemical / superbond anchors).

Uni-axial shake table tests were performed to assess the seismic performance of this solution, known as the EQ-Rod prototype, comparing it with traditional fasteners. As described in Ciurlanti et al.[61], the testing protocol was developed at the Structural Engineering Laboratory of the La Sapienza University of Rome, and aimed to simulate dynamic responses of fasteners under earthquakes. The shake table introduced different input motions to the anchor rod, which was installed in a concrete block fixed to the table and connected to a driving mass that simulated building contents. The experimental campaign included both sinusoidal and earthquake signals (Far Field and Near Fault earthquakes scaled according to Eurocode 8). The experiments demonstrated that the EQ-Rod solution reduce forces by 20-40% compared to traditional anchors. This improvement is attributed to its large hysteretic energy and greater displacement during most cycles, which enable effective isolation and dissipation. Overall, the solution performed better in cracked concrete than in uncracked concrete, showing greater displacement, lower frequencies and less force attraction. Despite the potential for further improvements (combining gap-filling with a tight-fit EQ-Rod dissipative system could offer the most reliable benefits), the tested prototype effectively demonstrated its efficacy in reducing the acceleration experienced by the connected non-structural components and the forces acting on the anchor.

Conclusions

Building a resilient society has become a key priority in earthquake risk reduction and management policies. This paper has presented the use of low-damage techniques as a promising solution for developing the next generation of earthquake-resilient buildings, capable of minimizing post-earthquake damage. As a result, these buildings reduce financial losses, casualties and environmental impact, while enhancing post-event building response and accelerating recovery through faster repair times. Additionally, low-damage solutions, incorporating Plug & Play connections and modular components, offer advantages from a circular economy perspective, enabling easy disassembly and waste minimization.

After reviewing low-damage technologies for structural and non-structural components, this paper has discussed recent experiments that showcased their outstanding seismic performance and reinforced their potential for implementation in modern design and construction. Although the experiments showed minimal damage under moderate-to-high intensity earthquakes (up to a 2% inter-story drift ratio), the observed damage suggests that further refinements in connection detailing are necessary for future applications. The research projects involved collaboration with various manufacturers, demonstrating the technology's applicability and promoting its broader adoption. However, the development of standardized detailing is essential to further promote this solution in new construction, and additional research is needed to support its application in retrofitting strategies.

Future Directions

Enhancing environmental sustainability

Low-damage buildings have clear benefits in terms of high performance, modularity and flexibility throughout a building's lifecycle, however, further research is needed to enhance their environmental sustainability. The use of bio-based materials is increasingly emerging, driven by advancements in sustainable development. These materials offer substantial climate mitigation potential by reducing energy demand and sequestering carbon throughout their service life. While studies demonstrate the potential of bio-based components[62,63], there is still limited experimental research on their dynamic response to earthquakes. Research efforts are needed to study their seismic damage mechanisms and explore system enhancements that would facilitate the integration of bio-based solutions into seismic construction practices. This will advance the development of low-carbon, resilient prefabrication systems, enabling multifunctional building envelopes and structural systems with minimal embodied energy. To this end, future research should focus on developing building envelopes that use local bio-sourced materials while ensuring indoor air quality and user comfort. Establishing specific requirements and performance criteria will also be crucial for incorporating low-carbon and resilience concepts into the design phases of prefabricated systems. Additionally, integrating circular economy principles into low-carbon prefabrication will help quantify the substantial environmental benefits of these new building practices.

Multi-hazard resistant technologies

In addition to the significant socio-economic losses, market disruptions and environmental damage caused by earthquakes, climate change is exacerbating the frequency and severity of weather-related events such as heat waves and flooding. These events are increasingly impacting the construction sector and the health and well-being of building occupants. This highlights the pressing need to improve societal resilience by addressing the multiple and diverse hazards that buildings may face throughout their lifespan, and by developing multi-hazard resistant integrated technologies. Current design approaches predominantly address single hazards, often neglecting or providing limited consideration for multi-hazard resilience. In contrast, holistic design approaches can lead to technologies that offer higher overall performance. For instance, integrated solutions that enhance both seismic and energy resilience have been shown to reduce the loss of resilience by 86%[64]. This leads to greater cost savings and a better return on investment, especially when seismic safety is integrated into the design of energy-efficient building envelopes[65].

In façade engineering, further research is needed to develop multi-hazard resistant components that are easy to disassemble and durable, thereby facilitating maintenance, repair and upgrades. Early design methods should guide the selection of climate-adaptive and earthquake-resistant technologies. These innovations will lead to the creation of multi-layer building solutions with extended service lives. Integrated, scalable, low-carbon modules that combine the façade system with the load-bearing structure in a modular construction format could provide a holistic solution, or serve as an exoskeleton intervention, to enhance building multi-hazard resilience in a cost-effective and sustainable manner.

Funding

The experimental project on the integrated timber-concrete building received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 730900. The research project on post-installed anchors was funded by Fischerwerke Artur Fischer GmbH & Co. KG.

Ethics Committee Approval

This work does not require an ethics committee approval.

Conflict of Interest

The authors declare no conflicts of interest.

References

1. EM-DAT, "The international disaster database, Centre for Research on the Epidemiology of Disasters," [Online]. Available: https://public.emdat.be/. Accessed: Sep 30, 2024.
2. W. Y. Kam, S. Pampanin, and K. J. Elwood, "Seismic performance of reinforced concrete buildings in the 22 February Christchurch (Lyttelton) earthquake," *Bulletin New Zealand Society and Earthquake Engineering*, vol. 44, no. 4, pp. 239–278, 2011, doi: 10.5459/bnzsee.44.4.239-278. (CC-BY license)
3. S. Taghavi and E. Miranda, "Response assessment of nonstructural building elements," Pacific Earthquake Engineering Research Center, Berkley, USA, 2003.
4. FEMA P-58-7, *Seismic performance assessment of buildings*, *Volume 7 – A guide to state-of-the-art tools for seismic design and assessment*, Applied Technology Council for the Federal Emergency Management Agency, Washington, USA, 2018.
5. M. J. N. Priestley, M. C. Calvi, and M. J. Kowalsky, *Displacement-Based Seismic Design of Structures*, IUSS Press, Pavia, IT, 2007.
6. S. Pampanin, "Reality-check and renewed challenges in earthquake engineering: Implementing low-damage structural systems – From theory to practice," *Bulletin New Zealand Society and Earthquake Engineering*, vol. 45, no. 4, pp. 137-160, 2012, doi: 10.5459/bnzsee.45.4.137-160. (CC-BY license)
7. S. Bianchi, J. Ciurlanti, and S. Pampanin, "Comparison of traditional vs low-damage structural & non-structural building systems through a cost/performance-based evaluation," *Earthquake Spectra*, pp 1-20, 2020, doi: 10.1177%2F8755293020952445.
8. J. Ciurlanti, S. Bianchi, and S. Pampanin, "Raising the bar in seismic design: Cost–benefit analysis of alternative design methodologies and earthquake-resistant technologies," *Bulletin of Earthquake Engineering*, vol. 21, no. 5, pp. 2723-2757, 2023, doi: 10.1007/s10518-023-01625-x.
9. S. Bianchi, J. Ciurlanti, M. Overend, and S. Pampanin, "Low-carbon & low-damage technologies for improving the resilience of buildings," Proceedings of the SECED 2023 Conference, 2023.
10. R. Fenwick, D. Bull, and D. Gardier, *Assessment of hollow-core floors for seismic performance*, University of Canterbury, Christchurch, NZ, 2010.
11. J. F. Stanton, W. C. Stone, and G. S. Cheok, "A hybrid reinforced precast frame for seismic regions," *PCI Journal*, vol. 42, no. 2, pp. 20–32, 1997, doi: 10.15554/pcij.03011997.20.23.
12. M. J. N. Priestley, S. Sritharan, J. R. Conley, and S. Pampanin, "Preliminary results and conclusions from the PRESSS five-story precast concrete test building," *PCI Journal*, vol. 44, no. 6, pp. 42–67, 1999, doi: 10.15554/pcij.11011999.42.67.

13. D. Marriott, S. Pampanin, D. Bull, and A. Palermo, “Dynamic testing of precast, post-tensioned rocking wall systems with alternative dissipating solutions,” *Bulletin of New Zealand Society for Earthquake Engineering*, vol. 41, no. 2, pp. 90–103, 2008, doi: 10.5459/bnzsee.41.2.90-103. (CC-BY license)
14. fib, “Seismic design of precast concrete building structures,” *International Federation for Structural Concrete*, Bulletin no. 27, pp. 254, Lausanne, CH, 2003. (© fédération internationale du béton (fib), 2003)
15. F. Sarti, A. Palermo, and S. Pampanin, “Fuse-type external replaceable dissipaters: Experimental program and numerical modeling,” *Journal of Structural Engineering*, vol. 142, no. 12, 2016, doi: 10.1061/(ASCE)ST.1943-541X.0001606.
16. A. D. Amaris, S. Pampanin, D. K. Bull, and A. J. Carr, “Development of a non-tearing floor solution for jointed precast frame systems,” Proceedings of the 2007 NZSEE Conference, Palmerston North, NZ, 2007. (CC-BY license)
17. A. D. Amaris, S. Pampanin, D. K. Bull, and A. J. Carr, “Solutions to control and minimize floor damage in precast concrete buildings under severe earthquake loading,” Proceedings of the NZ Concrete Industry Conference, Rotorua, NZ, 2008.
18. A. Palermo, S. Pampanin, A. H. Buchanan, and M. P. Newcombe, “Seismic design of multi-storey buildings using Laminated Veneer Lumber (LVL),” Proceedings of the 2005 NZSEE Conference, Wairakei, NZ, 2005.
19. G. Granello, A. Palermo, S. Pampanin, S. Pei, and J. van de Lindt, “Pres-lam buildings: State-of-the-art,” *Journal of Structural Engineering*, vol. 146, no. 6, 2020, doi: 10.1061/(ASCE)ST.1943-541X.0002603.
20. A. H. Buchanan, A. Palermo, D. M. Carradine, and S. Pampanin, “Post-tensioned timber frame buildings,” *The Structural Engineer*, vol. 89, no. 17, pp. 24-30, 2011.
21. E. Miranda, G. Mosqueda, R. Retamales, and G. Pekcan. “Performance of nonstructural components during the February 27, 2010 Chile earthquake,” *Earthquake Spectra*, vol. 28, no. S1, pp. S453-S471, 2010, doi: 10.1193%2F1.4000032.
22. A. Baird and H. Ferner, “Damage to non-structural elements in the 2016 Kaikoura earthquake,” *Bulletin of New Zealand Society and Earthquake Engineering*, vol. 50, no. 2, pp. 187-193, 2017, doi: 10.5459/bnzsee.50.2.187-193.
23. D. Perrone, G.M. Calvi, R. Nascimbene, E. C. Fischer, and G. Magliulo, “Seismic performance of non-structural elements during the 2016 Central Italy earthquake,” *Bulletin of Earthquake Engineering*, vol. 17, pp. 5655–5677, 2018, doi: 10.1007/s10518-018-0361-5.
24. G. Magenes and S. Pampanin, “Seismic response of gravity-load design frames with masonry infills,” Proceedings of the 13th World Conference on Earthquake Engineering, Vancouver, USA, 2004.

25. A. Baird, A. Palermo, and S. Pampanin, “Facade damage assessment of multi-storey buildings in the 2011 Christchurch earthquake,” *Bulletin of New Zealand Society and Earthquake Engineering*, vol. 44, no. 4, pp. 368-376, 2011, doi: 10.1002/suco.201100040. (CC-BY license)

26. C. E. Grigorian, T. S. Yang, and E. Popov, “Slotted bolted connection energy dissipators,” *Earthquake Spectra*, vol. 9, no. 3, pp. 491-504, 1993, doi: 10.1193/1.1585726.

27. K. C. Chang, Y. Y. Lin, and M. L. Lai, “Seismic analysis and design of structures with viscoelastic dampers,” *Journal of Earthquake Technology*, vol. 35, no. 4, 1998.

28. S. Sivanerupan, J. L. Wilson, E. F. Gad, and N. T. K. Lam, “Drift performance of point fixed glass facade systems,” *Advances in Structural Engineering*, vol. 17, no. 10, pp. 1481-1495, 2014, doi: 10.1260%2F1369-4332.17.10.1481.

29. S. D’Amore, S. Bianchi, J. Ciurlanti, and S. Pampanin, “Seismic assessment and finite element modeling of traditional vs innovative point fixed glass facade systems (PFGFS),” *Bulletin of Earthquake Engineering*, vol. 21, pp. 2657–2689, 2023, doi: 10.1007/s10518-023-01622-0.

30. S. Bianchi, G. Lori, V. Hayez, M. Overend, and G. Manara, “Influence of design variables on seismic performance of unitized curtain walls: A parametric experimental study,” *Glass Structures & Engineering*, vol. 9, pp. 165-184, 2024, doi: 10.1007/s40940-024-00255-2. (CC-BY license)

31. PCI, *Architectural precast concrete*, Precast/Prestressed Concrete Institute, Chicago, USA, 2007.

32. FEMA, *Reducing the risks of non-structural earthquake damage - a practical guide*. Federal Emergency Management Agency, FEMA E-74, Washington, USA, 2011.

33. J. P. Pinelli, J. I. Craig, and B. J. Goodno, “Energy-based seismic design of ductile cladding systems,” J*ournal of Structural Engineering*, vol. 121, no. 3, pp. 567-578, 1995, doi: 10.1061/(ASCE)0733-9445(1995)121:3(567).

34. A. Baird, A. Palermo, and S. Pampanin, “Controlling seismic response using passive energy dissipating cladding connections,” Proceedings of the 2013 NZSEE Conference, Wellington, NZ, 2013. (CC-BY license)

35. M. Aliaari and A. M. Memari, “Experimental evaluation of a sacrificial seismic fuse device for masonry infill walls,” *Journal of Architectural Engineering*, vol. 13, pp.111-125, 2007, doi: 10.1061/(ASCE)1076-0431(2007)13:2(111).

36. M. Mohammadi and M.R.G. Mahalleh, “A new infilled steel frame with engineering properties,” *Structures and Buildings*, vol. 165, pp. 15–25, 2012, doi: 10.1680/stbu.2012.165.1.15.

37. M. Preti, L. Migliorati, and E. Giuriani, “Experimental testing of engineered masonry infill walls for post-earthquake structural damage control,” *Bulletin of Earthquake Engineering*, vol. 13, pp. 2029–2049, 2014, doi: 10.1007/s10518-014-9701-2.

38. P. Morandi, R.R. Milanese, and G. Magenes, "Innovative solution for seismic-resistant masonry infills with sliding joints: In-plane experimental performance," *Engineering Structures*, vol. 176, pp. 719-733, 2018, doi: 10.1016/j.engstruct.2018.09.018.
39. A. S. Tasligedik and S. Pampanin, "Rocking cantilever clay brick infill wall panels: A novel low damage infill wall system," *Journal of Earthquake Engineering*, vol. 21, no. 7, pp. 1023-1049, 2016, doi: 10.1080/13632469.2016.1190797. (© Taylor & Francis Group, LLC)
40. A. S. Tasligedik, S. Pampanin, and A. Palermo, "Damage states and cyclic behaviour of drywalls infilled within RC frames," *Bulletin of New Zealand Society and Earthquake Engineering*, vol. 45, no. 2, pp. 84-94, 2012, doi: 10.5459/bnzsee.45.2.84-94. (CC-BY license)
41. R. P. Dhakal, G.A. MacRae, and K. Hogg, "Performance of ceilings in the February 2011 Christchurch earthquake," *Bulletin of New Zealand Society and Earthquake Engineering*, vol. 44, no. 4, pp. 379-389, 2011, doi: 10.5459/bnzsee.44.4.377-387. (CC-BY license)
42. A. Baird and H. Ferner, "Damage to non-structural elements in the 2016 Kaikoura earthquake," *Bulletin of the NZ Society for Earthquake Engineering*, vol. 50, no. 2, pp. 187-193, 2017, doi: 10.5459/bnzsee.50.2.187-193. (CC-BY license)
43. A. Filiatrault, et. al, "Experimental seismic fragility of steel studded gypsum partition walls and fire sprinkler piping subsystems," Proceedings of the Structures Congress, Orlando, USA, 2010.
44. G. Araya-Letelier, E. Miranda, and G. Deierlein, "Development and testing of a friction/sliding connection to improve the seismic performance of gypsum partitions," *Earthquake Spectra*, vol. 35, no. 2, pp. 653–677, 2019, doi: 10.1193/123117EQS270M.
45. C. Petrone, G. Magliulo, and G. Manfredi, "Shake table tests on standard and innovative temporary partition walls," *Earthquake Engineering and Structural Dynamics*, vol. 46, no. 10, pp. 1599-1674, 2017, doi: 10.1002/eqe.2872.
46. A. S. Tasligedik, S. Pampanin, and A. Palermo, "Low damage seismic solutions for non-structural drywall partitions," *Bulletin of Earthquake Engineering*, vol. 13, pp. 1029-1050, 2014, doi: 10.1007/s10518-014-9654-5. (© Springer Science+Business Media Dordrecht 2014)
47. S. Brandolese, L. Fiorin, and R. Scotta, "Seismic demand and capacity assessment of suspended ceiling systems," *Engineering Structures*, vol. 193, pp. 219-237, 2019, doi: 10.1016/j.engst ruct.2019.05.034.
48. K. P. Ryu and A.M. Reinhorn, "Experimental study of large area suspended ceilings," *Journal of Earthquake Engineering*, vol. 23, no. 6, pp. 1001-1032, 2017, doi: 10.1080/13632469.2017.1342294.

49. A. Pourali, R. P. Dhakal, G. A. MacRae, and A. S. Tasligedik, “Fully-floating suspended ceiling system: experimental evaluation of the effect of mass and elastic isolation,” Proceedings of the 16th WCEE, Santiago, CN, 2017. (© (2017) by Chilean Association on Seismology and Earthquake Engineering (ACHISINA) All rights reserved.)

50. Y. Lu, G. Mosqueda, Q. Han, and Y. Zhao, “Shaking table tests examining seismic response of suspended ceilings attached to large-span spatial structures,” *Journal of Structural Engineering*, vol. 144, no. 9, 2018, doi: 10.1061/(asce)st.1943-541x.0002140.

51. J. S. Lee, D. I. Jung, D. Y. Lee, and B. H. Cho, “Performance evaluation of rigid braced indirect suspended ceiling with steel panels,” *Applied Sciences*, vol. 11, no. 5, 2021, doi: 10.3390/app11051986.

52. P. Quintana Gallo, M. Moghaddasi, S. Pampanin, and K. Bergmeister, “Shake table tests of post-installed fasteners in concrete with supplemental damping,” *ACI Structural Journal*, vol. 115, no. 3, pp. 595-606, 2018, doi: 10.14359/51701297. (© American Concrete Institute)

53. S. Pampanin, et al., “Triaxial shake table testing of an integrated low-damage building system,” *Earthquake Engineering and Structural Dynamics*, vol. 52, no. 10, pp. 2983-3007, 2023, doi: 10.1002/eqe.3906.

54. S. Pampanin, D. Marriott, and A. Palermo, New Zealand Concrete Society, *PRESSS Design Handbook*, Auckland, NZ, 2010.

55. S. Pampanin, A. Palermo, and A. Buchanan, Structural Timber Innovation Company Inc., *Post-Tensioned Timber Buildings - Design Guide*, Christchurch, NZ, 2013.

56. AS/NZS, *Australian/New Zealand Standard 1170*. Standards Australia/Standards New Zealand, AZ/NZS 1170, Wellington, NZ / Sydney, AS, 2002.

57. A. Palermo and S. Pampanin, Pre-stressed beams or panels (3PT). United States Patent n. US9809979B2 (filed in 2014), Japan Patent n. JP6373975B2 (filed in 2014), Canada Patent n. CA2909402C, 2017.

58. S. Bianchi, et al., “Shake-table tests of innovative drift sensitive nonstructural elements in a low-damage structural system,” *Earthquake Engineering and Structural Dynamics*, vol. 50, no. 9, pp. 2398-2420, 2021, doi: 10.1002/eqe.3452.

59. J. Ciurlanti, S. Bianchi, and S. Pampanin, “Shake-table tests of a timber-concrete low-damage building: analytical/numerical vs. experimental results,” Proceedings of the 17th WCEE, Sendai, JP, 2021. (CC-BY license)

60. H. C. Johnston, C. P. Watson, S. Pampanin, and A. Palermo, “Shake table testing of an integrated low-damage frame building,” Proceedings of the NZSEE Conference, Auckland, NZ, 2014.

61. J. Ciurlanti, et al., “Shake table tests of concrete anchors for non-structural components including innovative and alternative anchorage detailing,” *Bulletin of Earthquake Engineering*, vol. 20, pp. 3971–3993, 2022, doi: 10.1007/s10518-022-01359-2.
62. S. Bourbia, H. Kazeoui, and R. Belarbi, “A review on recent research on bio-based building materials and their applications,” *Materials for Renewable and Sustainable Energy*, vol. 12, pp. 117–139, 2023, doi: 10.1007/s40243-023-00234-7.
63. P. Blanchet, C. Perez, and M. R. Cabral, “Wood building construction: Trends and opportunities in structural and envelope systems,” *Current Forestry Report*, vol. 10, pp. 21–38, 2024, doi: 10.1007/s40725-023-00196-z.
64. S. Bianchi, “Integrating resilience in the multi-hazard sustainable design of buildings,” *Disaster Prevention and Resilience*, vol. 2, no. 14, 2023, doi: 10.20517/dpr.2023.16.
65. S. Bianchi, J. Ciurlanti, M. Overend, and S. Pampanin, “A probabilistic-based framework for the integrated assessment of seismic and energy economic losses of buildings,” *Engineering Structures*, vol. 269, 2022, doi: 10.1016/j.engstruct.2022.114852.

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Circular Economy Principles in Disaster Recovery: A Multi-Scale Strategy for Türkiye's Earthquake Response

Birgül Çolakoğlu*

This paper examines the integration of Circular Economy (CE) principles into disaster recovery and reconstruction, focusing on Türkiye's earthquake-prone regions. Drawing on the 2023 earthquakes, it highlights the need for sustainable rebuilding strategies that address immediate needs while fostering long-term resilience. Traditional reconstruction, which is often resource-intensive and wasteful, is contrasted with circular approaches emphasizing material efficiency, recycling, circular design, energy efficiency, industrial symbiosis, and waste reduction. The study explores CE applications across three scales: macro-regional, meso-city, and micro-building.

Keywords: Circular economy, Disaster recovery, Sustainable reconstruction, Resilience, Türkiye earthquakes, Build back better

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Introduction

Earthquakes are among the most devastating natural hazards, causing significant damage to urban infrastructure, communities, and economies. The severity of these impacts depends on factors such as the earthquake's location, magnitude, and type.

Rehabilitation, reconstruction, and sustainable disaster management are essential for addressing the impacts. These activities provide the environment for transitioning from emergency relief to sustainable development of the built environment, agriculture, and social well-being.

However, conventional reconstruction approaches frequently exhaust resources and generate large amounts of waste, contributing to further environmental deterioration. By contrast, sustainable reconstruction would emphasize the efficient use of materials, recycling, and waste reduction, which helps lower the ecological footprint after a disaster. This approach focuses on rebuilding physical structures and strengthening the social fabric by building resilient communities.

In addition to environmental benefits, sustainable practices in post-disaster reconstruction prove to be more cost-effective in the long run. The United Nations Office for Disaster Risk Reduction (UNDRR) states that for every $1 invested in disaster-resilient infrastructure, $4 is saved in reconstruction costs. This statement underscores the economic rationale for investing in preventive and resilient infrastructure to mitigate future disaster expenses. Sustainable approaches stimulate local economies by incorporating long-lasting building materials, minimizing future repair expenses, cutting energy costs, and generating employment opportunities through innovative reconstruction methods. Sustainable disaster management can transform crises into opportunities by integrating circular economy (CE) principles, digital technologies, and smart city planning.

The Circular Economy (CE) offers a structured framework for implementing sustainability. According to the Ellen MacArthur Foundation, it is "an industrial economy that is restorative or regenerative by intention and design."[1] Geisdoerfer et al.[2] define it as "a regenerative system in which resource input and waste, emissions, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops." .

CE emphasizes the creation of closed-loop systems, where materials continuously circulate within the economy through recycling, upcycling, reuse, and resource regeneration. It enhances resource efficiency by fostering industrial collaboration, extending product lifespans, and transforming waste into valuable resources.

Methods

The following sections describe three circularity implementation frameworks at the regional, meso-city, and micro-building scales to help better understand the opportunities of "sustainable reconstruction." Additionally, further information about the earthquake-hit South East region of Türkiye is presented regarding the potential of applying these frameworks.

Macro-regional scale

Depending on their natural and cultural environment, industrial structure, and background, regions have specific spatial, technical, and social characteristics. They play a central role in pursuing circularity. Circular economy strategies at the macro-regional scale leverage regional strengths by emphasizing "smart specialization," which identifies competitive advantages to develop targeted circular reconstruction roadmaps[3].

Aligned with this perspective, the circular economy at the macro-regional scale emphasizes comprehensive resource management and infrastructure systems designed to strengthen regional resilience against disasters. This approach prioritizes post-reconstruction strategies at national and regional levels to rebuild the region by strengthening its competitive advantages. This, in turn, lays the groundwork for an economic and social transformation driven by innovation. Building on these principles, the key strategies for regional post-disaster reconstruction are:

Material recovery: Disaster-affected regions typically produce significant amounts of construction debris and damaged infrastructure waste. A circular economy approach at this scale emphasizes the development of a regional material recovery strategy, treating construction debris as a valuable resource for reuse and recycling. It focuses on establishing facilities that support reconstruction efforts by recovering, sorting, and recycling materials for reuse. This approach minimizes dependence on external resources and ensures that regional materials remain in circulation.

Resilient infrastructure: Regional energy reconstruction through circular strategies emphasizes integrating renewable energy sources like wind, solar, and geothermal into recovery efforts, ensuring long-term sustainability and resilience of energy systems. Regional transportation, energy, and communication networks should be rebuilt with robust, flexible materials that ensure long-term durability and enable future reuse.

Regional industrial symbiosis: The Circular Economy (CE) fosters industrial symbiosis, enabling industries to share resources, materials, and energy through interconnected networks. This approach creates mutually dependent closed-loop systems, mirroring nature's self-sustaining and regenerative processes. Post-disaster reconstruction strategies can integrate industrial symbiosis principles, replicating the cyclical material flows found in ecological systems rather than following the traditional linear economic model of resource consumption.

Meso-city scale

Cities and regions are key in transitioning to a carbon-neutral circular economy[4]. Cities are centers of human consumption of natural resources and generators of waste. The circular economy is a guiding framework for cities and regions where services (water, waste, energy, etc.) are provided, efficiently using natural resources as primary materials. Economic activities are structured to close, slow, and optimize resource cycles throughout value chains. Infrastructure solutions, such as district heating systems and smart grids, are developed to eliminate inefficient, one-way resource consumption models, promoting sustainability. Building on this concept, at the meso-city scale, circular economy principles emphasize post-disaster urban reconstruction by maximizing local resource efficiency, promoting social equity, and embedding sustainable urban development strategies. As part of this approach, the circular city should target:

- Urban waste recovery: In disaster-affected cities, establishing localized material banks can facilitate the collection, refurbishment, and redistribution of reusable materials from demolished or damaged structures. This approach minimizes reliance on externally sourced construction materials, thereby reducing transportation emissions and lowering the city's carbon footprint.
- Decentralized energy and water systems: Energy production facilities located closer to the site of energy consumption are decentralized systems. They optimize the use of renewable energy, reduce fossil fuel use, and increase eco-efficiency.
- Circular urban planning: Post-disaster reconstruction can help cities be redesigned based on circular economy principles. These principles focus on a closed loop, repeatedly reusing, repurposing, or recycling materials, minimizing resource extraction. The circular city model supports new growth and business opportunities, allowing locals to develop new strategies and create more job opportunities. It incorporates social dimensions in city planning and integrates political dimensions.
- Community-driven recovery: Local involvement and social inclusivity are important in Circular city development. Circular reconstruction approaches, including urban farming, community repair hubs, and cooperative housing initiatives, can strengthen and empower local communities.

Micro-building scale

At the micro-building scale, circular economy principles can be utilized through circular buildings. These buildings are designed and constructed to have a minimal environmental impact. The key approaches in circular building design and construction are:

- Design for Disassembly: Circular buildings utilize industrialized construction systems with modular and demountable components, enabling efficient disassembly and material reuse in the aftermath of a disaster. This design approach reduces waste by providing easy repair or replacement without generating significant waste. Circular buildings serve as material banks that reduce the need for new materials and accelerate recovery by enabling faster rebuilding with existing resources.
- Energy Efficiency and Resilience: Circular buildings incorporate sustainable energy solutions, including passive heating and cooling, natural ventilation, and on-site renewable energy sources like solar panels and wind turbines. These features reduce operational energy consumption while enhancing long-term resilience.

Integrating circular economy principles into disaster recovery at all levels, expanding from individual buildings to a larger scale, transforms rebuilding into an opportunity for sustainable development. Strategies to support recovery at the macro-regional scale include material recovery from debris, resilient infrastructure, and industrial symbiosis. The meso-city scale emphasizes urban waste recovery, decentralized energy systems, and inclusive urban planning. At the micro-building level, principles like design for disassembly, energy efficiency, and adaptive material reuse are proposed to reduce environmental impact and enhance resilience.

Integrating circular economy principles into türkiyes' earthquake disaster recovery and reconstruction

On February 6, 2023, two powerful earthquakes struck Southeastern Türkiye, registering magnitudes of 7.8 and 7.5. The disaster caused widespread destruction across 11 provinces, affecting an estimated 14.01 million people, which accounts for 16.5% of the country's population. The impacted provinces included Adana, Adıyaman, Diyarbakır, Elazığ, Gaziantep, Hatay, Kahramanmaraş, Kilis, Malatya, Osmaniye, and Şanlıurfa[5].

Beyond the devastating human toll, the economic consequences have been severe. According to the Türkiye Earthquakes Recovery and Reconstruction Assessment by the Strategy and Budget Office, the direct economic losses from the earthquakes are estimated at $34.2 billion, approximately 4% of Türkiye's

2021 GDP. Meanwhile, the Turkish Enterprise and Business Confederation has projected the total financial impact to be around $84 billion, likening the scale of destruction to that of the 1999 İzmit earthquake[6].

However, the total recovery and reconstruction costs are expected to be substantially higher, potentially twice the amount of direct damages. This increase is largely due to the additional expenses associated with rebuilding to higher standards and addressing broader recovery needs beyond the restoration of physical structures. A detailed breakdown of direct damages reveals that residential buildings account for the largest share of losses, estimated at $18 billion (53% of total damage). Non-residential structures contribute $9.7 billion (28%), while infrastructure damage is valued at approximately $6.4 billion (19%). [6] The human impact has been immense, with approximately 1.25 million people displaced and 385,000 residential units designated for demolition. The earthquake also severely affected the agricultural sector, leading to the destruction of at least 9,972 farming facilities and causing widespread damage to supporting infrastructure and systems.

Given the magnitude of these losses, the idea of 'Build Back Better' is crucial for post-disaster recovery and reconstruction. In the framework of the Circular Economy, 'Build Back Better' aims to utilize the reconstruction phase to foster more sustainable, adaptive, and resource-efficient practices[7]. This approach embodies not just the need to rebuild but also the opportunity to enhance communities' resilience to future disasters.

Building on this, circular economy principles are integrated into the 'Build Back Better' framework, which allows for the development of closed-loop systems. In these systems, damaged buildings and infrastructure materials can be recovered, reused, and recycled. This strategy not only minimizes the need for new resource extraction but also reduces waste, ensuring that rebuilding initiatives prioritize long-term resilience and environmental sustainability

Turkiye, an earthquake-prone country, faces considerable challenges due to its geographical conditions. According to the Turkish Ministry of Interior's Disaster and Emergency Management Authority (AFAD), the nation comprises 81 provinces and 922 districts, with active fault lines traversing 536 districts and 68 regions. Alarmingly, 75.80% of the total population, which amounts to 64,643,681 people, resides in these earthquake-prone areas.

In light of the devastating impact of the 2023 earthquakes in Türkiye, implementing Circular Economy principles is no longer a theoretical option but an essential strategy for fostering long-term resilience and mitigating the effects of future natural disasters. By integrating circular economy strategies across multiple levels—regional, urban, and building scales—Türkiye has the potential to reshape its reconstruction efforts into a model for sustainable development, social resilience, and economic renewal. Adopting these approaches can turn post-disaster recovery into an opportunity to rebuild stronger, allowing communities to recover more efficiently while enhancing their resilience against future challenges.

Building on this vision, Circular Economy Strategies for Regional, Urban, and Building Post-Disaster Planning emerge as a critical framework for recovery. At the regional scale, the Circular Economy offers a holistic approach to post-disaster recovery that emphasizes sustainable systems, efficient resource use, and long-term resilience. This strategy integrates Circular Urban Planning, Building Design and Construction, Water Management, Agriculture and Food Systems, Decentralized and Renewable Energy Systems, and Resource Mapping and Recovery. Each component works synergistically to establish a closed-loop system that reduces waste, conserves resources, and fosters ecological regeneration.

In the post-earthquake recovery of Southeastern Türkiye, Circular Urban Planning can ensure a resource-efficient and resilient rebuilding process. One of the key strategies is the adaptive reuse of construction debris, where materials such as concrete, steel, and bricks are sorted, processed, and repurposed instead of being sent to landfills. Establishing urban material banks in the cities of Gaziantep, Hatay, and Kahramanmaraş can facilitate the collection and redistribution of reusable building components, reducing both costs and environmental impact. Additionally, modular and prefabricated housing using recycled and locally sourced materials can enable faster reconstruction while minimizing waste. Prefabrication techniques, when combined with low-carbon materials like lightweight steel frame construction, earth-based bricks, or upcycled metal, can help rebuild homes more sustainably. Furthermore, integrating green and resilient infrastructure, such as nature-based solutions, green corridors, and flood-resistant drainage systems, can improve disaster preparedness. These strategies align with circular economy principles by closing material loops, reducing dependency on virgin resources, and creating self-sustaining urban environments.

Circular Urban Development connects resource looping, adaptation, and ecological regeneration processes to create sustainable urban systems. By embedding these principles, regions can recover not only their physical infrastructure but also regenerate ecological and social systems. Social inclusion and community participation are integral to this process, ensuring that rebuilding efforts meet local needs, foster resilience, and enhance future sustainability. Without regional strategies rooted in circular principles, disaster recovery risks perpetuating unsustainable practices and leaving communities vulnerable to future disasters.

At the urban level, circular principles ensure that cities are designed and rebuilt to be more sustainable, resource-efficient, and resilient. Circular Construction and

Building Design, Material Recovery and Reuse, Decentralized Energy Systems, Green and Blue Infrastructure, and Waste-to-Resource Systems are critical components of urban recovery.

Rebuilding energy infrastructure in Southeastern Türkiye after the earthquake requires decentralized and renewable energy solutions to ensure energy security and long-term sustainability. One effective strategy is the deployment of off-grid solar and wind energy systems, particularly solar microgrids in temporary settlements, which can provide displaced communities with reliable and clean electricity. Additionally, establishing community-owned renewable energy cooperatives can help local populations regain control over their energy needs while reducing reliance on fossil fuels. These strategies can transform cities into hubs of innovation and resilience by reducing dependency on virgin resources, promoting renewable energy systems, and turning waste into valuable resources.

Moreover, integrating these principles at the city level creates economic opportunities, such as green jobs, equitable resource access, and sustainable urban growth. Supportive governance frameworks, robust monitoring systems, and long-term policy commitments are essential for effective implementation. Without such frameworks, the potential of circular urban planning to build resilience and sustainability may remain untapped.

At the micro-scale, buildings play a pivotal role in disaster recovery. A Circular Economy approach to building design emphasizes durability, adaptability, and resource efficiency. Circular strategies include Design for Adaptability and Flexibility, Sustainable Material Selection, Energy Efficiency and Renewable Energy Integration, Circular Maintenance and Building Operations, and Post-Disaster Community Engagement. By focusing on modular designs, the reuse of materials, and the integration of renewable energy, buildings can be made more resilient to future disasters. This approach not only addresses urgent reconstruction demands but also promotes long-term sustainability. Actively involving communities in the design and rebuilding process enhances social inclusion, ensuring that the new infrastructure reflects local needs and preserves cultural identity. Without adopting circular building strategies, reconstruction efforts risk becoming short-sighted, compromising both the safety and sustainability of future generations.

Current Approaches

Turkiye's 2023 earthquake displaced 1.25 million people and destroyed South East Turkiye's natural and physical infrastructure. In response to the urgent need for housing, the government focused on rapid post-disaster housing reconstruction, rather than implementing a comprehensive development strategy that integrates regional, urban, and building-scale planning. Nevertheless, this method has raised several issues, which are pointed out below, about the region's future sustainability, building's structural integrity, and durability.

Due to a lack of disaster and post-disaster preparedness planning, ad-hoc disaster recovery and reconstruction actions were taken, avoiding solutions based on sustainability and circular economy principles. Reconstruction speed has raised concerns about the durability and quality of the new structures for long-term resilience. The environmental impact of the chosen construction materials also creates a significant problem. The emphasis on quick construction, combined with the absence of sustainability and circularity strategies, results in using neither sustainable nor recyclable materials. Also, the lack of sustainable and circular approaches in reconstruction efforts may cause the long-term durability of buildings to be overlooked, as well as the future risks associated with climate change. Community engagement is another important strategy for incorporating local community input regarding their social, cultural, and economic needs, which plays a crucial role in rehabilitating post-disaster communities. However, community engagement had been overlooked during the rapid reconstruction processes. The financial pressure of rapid reconstruction on government budgets and local administrations has raised alarms about the long-term economic sustainability of these initiatives.

Implementing solutions based on sustainability and circular economy principles in development plans at multiple scales through "smart specialization " could have enhanced the competitive advantages of the Southeast region of Türkiye, leading to faster economic and social recovery.

Conclusion

Implementing the Circular Economy across several levels-regional, city, and building, is truly the way to build back better for sustainable and resilient development in Türkiye's post-disaster recovery. These three levels present highly differing yet interdependent roles in building an adaptive and resource-efficient recovery pathway-clean pathway truly. Without this convergence, the reconstruction process will consistently revert to old conventional systems that will neither be resilient to future disasters nor sustainable for development in the long run.

The earthquake response to Türkiye was really a trial for Circular Economy applications in post-disaster recovery. However, there was no circular planning across the scales-urban, building, as well as integrated material management all the reasons of urgency and value that underpin circular resilience. The government prioritized a response enabling easy shelter for the displaced. In the wake of this, temporary housing could be positioned quickly but without considering long-term sustainable growth for the region and city development, since reconstruction did not incorporate sustainability and resilience.

A major constraint was limited technological infrastructure and the inability to apply a circular principle at the regional and building levels. It appears that circular construction in the built environment mainly pursues a vision of leveraging advanced technological tools and data-driven decision-making, which optimizes material reuse, resource efficiency, and urban regeneration. Although integrated digital systems, coherent technical knowledge, and coordination are severely lacking, this impedes the shift from linear reconstruction to circular economy models. In such cases, it is imperative to mention that different levels of regional building scale present highly complicated and multifaceted challenges in translating circular economy principles into practice. This fundamentally requires immense buy-in from decision-makers to put in place regulatory architecture, financial incentives, and enforcement frameworks that create the conditions under which circular strategies can develop at every level. Making firm policies, providing incentives to stakeholders, and developing an integrated governance approach without missing any will still continue to challenge the circular recovery from disasters.

Funding

This research received no external funding.

Ethics Committee Approval

This work does not require an ethics committee approval.

Conflict of Interest

The author declares no conflicts of interest.

References

1. Ellen MacArthur Foundation, "What is circular economy?" [Online]. Available: https://www.ellenmacarthurfoundation.org/topics/circulareconomyintroduction/overview.
2. M. Geissdoerfer, P. Savaget, N. Bocken, and E. Hultink, "The circular economy – A new sustainability paradigm?," *Journal of Cleaner Production*, vol. 143, no. 6, pp. 757–768, 2017, doi: 10.1016/j.jclepro.2016.12.048.
3. S. Vanhamäki, *Implementation of circular economy in regional strategies*, Lappeenranta-Lahti University of Technology, Lahti, Finland.
4. OECD, "The circular economy in cities and regions: Synthesis report," OECD Urban Studies, OECD publishing, Paris, 2020, doi: 10.1787/10ac6ae4-en.
5. Türkiye Earthquakes Recovery and Reconstruction Assessment, Strategy and Budget Office (SBO) of the Presidency of the Republic of Türkiye. [Online]. Available: http://www.sbb.gov.tr/turkiye-earthquakes-recovery-and-reconstruction-assessment.
6. Global Rapid Post Disaster Damage Estimation (GRADE) Report: Kahramanmaraş Earthquakes Türkiye, Global Facility for Disaster Reduction and Recovery (GFDRR), World Bank Group, 2023. [Online]. Available: https://documents.worldbank.publication/documents-reports/documentdetail/099022723021250141/p1788430aeb62f08009b2302bd4074030fb.
7. United Nations Office for Disaster Risk Reduction (UNDRR), "Words into action guidelines: Build back better in recovery, rehabilitation, and reconstruction," 2017. [Online]. Available: https://www.undrr.org/publication/words-action-guidelines-build-back-better-recovery-rehabilitation-and-reconstruction
8. The building back circular framework: Circular economy strategies for post-disaster reconstruction and recovery. [Online]. Available: https://link.springer.com/article/10.1007/s43615-024-00495-y.

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Performance of Buildings during the Feb. 6th, 2023 Kahramanmaras Earthquake Sequence

Oğuz Cem Çelik*

This paper describes observed building performances from the two major earthquakes of Mw=7.9 Pazarcik/Nurdagi and Mw=7.8 Elbistan/Ekinozu (a.k.a. the Kahramanmaras EQs) on February 6th, 2023. Many existing buildings (both made with reinforced concrete (RC) and masonry) experienced heavy damage or thousands collapsed due to many reasons. Poor material properties, irregular structural systems, architectural based issues, and weak soil properties resulting in soil liquefaction contributed to these catastrophic results. Well-known damage patterns (both individual (any one listed above) and combined (two or more damage types occurring in the same building)) that were observed in the past earthquakes are repeatedly witnessed in these recent events since the building typologies (and of course related problems) are quite similar in the existing building inventory in Turkey. It is noteworthy that a number of newly code designed buildings has also collapsed during these earthquakes. The paper begins with evolution of seismic codes in Turkey (from 1940 to date). Some changes in basic structural design parameters (e.g. base shear coefficients, zone factors, ductility issues etc.) are summarized and discussed. Today's updated design philosophy and expected performance levels are introduced. Some engineering characteristics of the measured strong ground motions are plotted and compared with the code expectations. Based on the observations in the earthquake-stricken areas in southeast Turkey, vast majority of the buildings requires immediate seismic retrofitting. Finally, a refined damage classification and potential retrofit measures are proposed for improved seismic performance. Both conventional and innovative retrofit schemes are introduced for potential rapid implementation in seismic upgrading of the big cities (including Istanbul, with a population of 16M) in Turkey.

Keywords: Seismic, Damage, Kahramanmaras, Reinforced concrete, Masonry, Retrofit

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Introduction

Turkey is known as seismically very active part of the world similar to Japan, New Zealand, China, west cost of USA, and most Mid and South American countries such as Chile, Venezuela, Peru, Guatemala, Mexico etc. To date, many devastating earthquakes occurred in the country resulting in significant figures of human and property losses. The December 27th, 1939 Great Erzincan earthquake (with a probable magnitude of M 7.9~8.1) is of special importance since the first seismic code of the country was released in 1940 following this tragic event. This code was adopted from the Italian seismic code effective at that time and basically some preliminary rules were issued for masonry buildings. Over the course of time, major work has been performed to improve the seismic code[1]. New versions of the code was released in 1949, 1953, 1962, 1968, 1975, 1998, 2007, and finally in 2018. Seismic zones, base shear coefficients, design philosophy (e.g. strength and drift based designs) have evolved with special emphasis on ductility in each version of the code. The building stock (especially, residential buildings made with reinforced concrete (RC) moment frames without ductile details), however, has grown significantly from 1950s to early 1990s in an uncontrolled way, creating problems from the perspectives of urban planning, architectural, and structural design issues. In RC residential buildings with building importance factor of I=1.0, one of the major problems was to commonly build these buildings with low concrete grades resulting from hand casting until early 1980s. In addition, moment frames with infill brick walls mostly detailed as nonductile until 1970s were used as major load bearing systems in low-rise and mid-rise building stock. RC shear walls were used rarely in some special residential projects or in government buildings having higher building importance factor (i.e. I=1.5 or so). Although, ductile detailing rules were included mainly in the 1968 code following the July 22, 1967 Adapazari (a.k.a. the Akyazi, Mudurnu EQ) M (6.8~7.2) magnitude earthquake since many RC buildings suffered damage or collapsed during this event. The 1975 code was one of the contemporary codes in the Balkan region that included RC, steel, masonry, and timber buildings but majority of the code was devoted to widely used RC framed buildings. Ductility issues were more stringent wither newer seismic hazard map suggesting larger seismic forces for the design of new buildings. Although this code was a strength-based code, interstory drift limits were defined for RC frames for the first time in the country. It should be noted that previous reconnaissance visits to earthquake-hit regions report acceptable damage in buildings well-inspected during the construction phases. On the contrary, uninspected and not-code-compliant buildings claimed many lives in the past devastating earthquakes [2,3,4,5,6,7].

Widely observed building damage and collapses are well classified in [4,5,6,8]. In brief, architectural based damage in the existing building stock was noteworthy. It has been recognized for long that designing buildings with regular structural systems is essential and structural behavior cannot be improved with advanced ways of structural analyses. This reality has been supported by the codes by imposing various levels of penalty factors for the design of architecturally irregular buildings. It has been proved many times that roughly designed (even with hand calculations) modular/regular/simpler buildings have always better behaved than irregular buildings.

The author of this paper made reconnaissance visits to earthquake stricken area over several decades. The latest February 6th, 2023 Kahramanmaras earthquake sequence with moment magnitudes of Mw=7.9 (Pazarcik/Nurdagi) and Mw=7.8 (Elbistan/Ekinozu) is believed to be the most devastating ones since 1939 [9,10,11]. This paper describes observed building performances from these two major earthquakes. Many existing buildings (both made with reinforced concrete (RC) and masonry) experienced heavy damage or thousands collapsed due to many geotechnical, architectural, and structural reasons. Earthquake source parameters played a significant role on these catastrophic events. Section 2 is dedicated to structural properties of existing building stock and their performance in the past earthquakes. Section 3 discusses response spectra obtained from strong ground motion (SGM) data and damage classification for various structural systems in the earthquake stricken areas. Also, performances of a few previously retrofitted buildings are evaluated. Some widely used retrofit schemes are summarized in Section 4. Section 5 is devoted to general evaluations with final remarks.

Properties of Existing Building Stock and Performance

Structural system alternatives

Various types of structural systems are allowed in the current Turkey Building Earthquake Code (TBEC-2018)[12]. This code has been effective in the country since January 1st, 2019 and is valid for both new design of buildings and for retrofit design of older buildings. In the previous codes before 2018, cast-in-situ RC buildings (moment frames, solid structural walls/cores, frame+shear wall dual systems or coupled shear walls), prefabricated RC buildings of several types (with and without shear walls and systems with various connection details), structural steel buildings (moment frames, braced frames (either with concentrically or eccentrically - i.e. CBFs, EBFs, or with RC shear walls/cores), masonry buildings, timber buildings were introduced as potential seismic structural systems. Note that building behavior factors (R) are proposed in these code to be 3~8 depending on the level of ductility expected for the building structural system under consideration. Basically, two levels of ductility are introduced such as nominal and high ductility systems.

Observed seismic damage in the previous earthquakes

As mentioned earlier, reinforced concrete (RC) frames have been widely used in low-rise, mid-rise, and even high-rise/tall buildings (together with shear walls or cores) in Turkey. Seismic performance of such buildings during the past earthquakes has been well explained in [2,3,4,5,6,7,8]. Many reconnaissance investigations have revealed that the existing building stock has suffered significant damage or collapses mainly from the reasons as listed below:

RC Buildings : Insufficient material quality (both for concrete and steel rebar), corrosion of reinforcement bars (common and a serious problem in older buildings), irregular load-carrying systems (both in plan layout and elevation), pounding/hammering effects of buildings in series, non-ductile reinforcement details and insufficient transverse reinforcement (i.e. lack of confinement), panel zone detailing errors (note that this is a common weakness, especially for RC buildings constructed before the 1990s), insufficient cross-section dimensions (both from the low concrete quality and higher axial load and shear force demands), short columns and beams (mainly from poor architectural design without consideration of seismic effects), insufficient lateral stiffness of flexible frame structures resulting in second-order (P-Δ) effects, soft and weak stories (in multi-story buildings accommodating open ground stories for commercial purposes), architectural detailing issues, removal of nonstructural/infill walls at ground floor, local soil conditions (soil amplification, liquefaction, etc).

Masonry Buildings: Poor material (wood, brick, stone, iron, mortar etc), irregular systems (both in plan and elevation), pounding, insufficient wall dimensions, excessive wall slenderness (in-plane and out-of-plane damage or collapses), insufficient stiffness, strength, and ductility, weak/soft stories (due to interventions) large wall and floor opening sizes, flexible diaphragms (mainly from layout openings and timber/wooden flooring), heavy domes, arches, vaults, supports regions, tie bars, and local soil conditions.

Inappropriate structural and architectural interventions have been observed both in existing substandard RC buildings and masonry buildings. These interventions (e.g. removing partition/architectural walls, random/uninspected structural alterations causing additional stresses in beams and columns etc.) have contributed to damage significantly.

Building Performance in the February 6th, 2023 Kahramanmaras EQs

General thoughts on strong ground motion records

On Feb. 6th, 2023 two devastating earthquakes measuring Mw 7.9 and 7.8 (also calculated to be 7.8, 7.7, or 7.6 in many other sources) occurred on the southwest part of East Anatolian Fault (EAF) zone located southeast Turkey. Casualties totaled more than 50.000 with additional tens of thousands got injured. Thousands of buildings (mostly substandard and some newer/code-compliant) have collapsed, leaving countless people exposed to unfair living conditions in winter for months. Twelve provinces (and their towns and villages in rural areas) with around 13.5M people (16% of the whole population of Turkey) were heavily affected [8,9,10].

To better evaluate observed heavy damage and collapses, elastic response spectra of the selected stations are illustrated in Figure 1a and 1b. Both weak and firm soil classes are considered in these graphs. The acceleration response spectra with a 5% damping ratio are plotted along with the design spectrum proposed by the latest Turkey Building Earthquake Code (TBEC), (2018)[12] for the rare design earthquake level of DD-2 (10% probability of exceedance in 50 years with an average return period of 475 years). Note that these curves are developed for various building typologies and soil classes as shown by the red shaded areas. It is seen that computed spectral accelerations are far beyond the proposed values in the current code. Other in-depth evaluations regarding these earthquake data are presented in [9]. It is shown that not only the horizontal components but also the vertical (i.e. up and down) components played a significant role in the earthquake stricken areas.

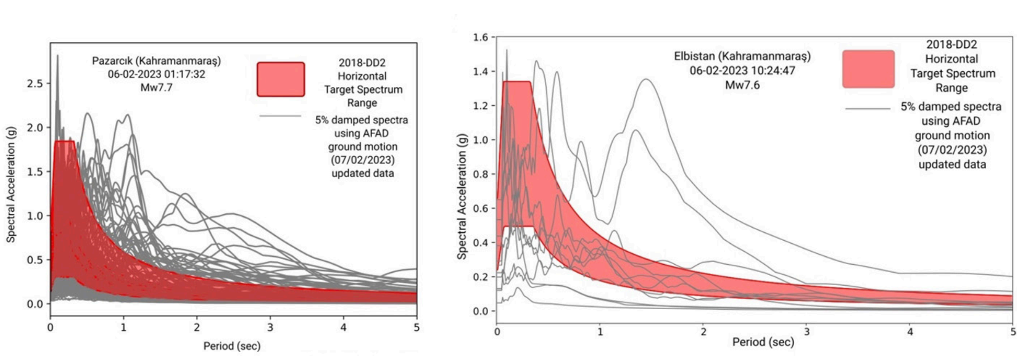

Figure 1. 5% damped spectra for strong ground motion data covering many building typologies and soil classes (DD-2) (with Kurtulus Atasever).

Damage investigation in buildings

The author of this paper made several reconnaissance trips to the earthquake hit provinces during the latest earthquakes. These visits reveal that typical building damage patterns as observed in the past few earthquakes in Turkey as explained in 2.2 are repeated with few exceptional modes of failures specific to these earthquakes. Almost every type of buildings including the historical buildings (mostly masonry) experienced excessive amount of damage in the Feb.6th, 2023 Kahramanmaras earthquake sequence. Substandard residential, school, hospital, private, government buildings were severely destroyed. Among many weaknesses, once again, low material (concrete strengths of as low as (8~10)MPa, poor masonry unit and mortar strengths) quality, architectural-based structural irregularities, nonductile systems, and soil amplifications and liquefaction problems (especially in Antioch/Hatay, Golbasi/Adiyaman) contributed to such devastation significantly. In multi-story (mid-rise and high-rise) residential buildings, due to high local accelerations, some poorly designed newer buildings collapsed from an overturning mode of failure. Casualties in such buildings were heavy. Figure 2 shows some damage types observed in RC buildings. In general, response of tunnel form residential buildings was satisfactory (for further details for this, see [9]).

Most of the older and some new RC buildings with 5~8 stories in Turkey use moment frames with solid infill walls. Especially for older buildings (before 2000), nonductile concrete frames constitute a significant percentage of the building stock and are vulnerable to seismic actions. For example, in Istanbul, 47% of the building stock has been built in between 1980~2000 while 22% and 31% have been built before 1980 and after 2000, respectively. In addition, 66% of the building stock has 1~4 stories while 32% and around 2% of the buildings possess 5~8 and 9 or more stories, respectively. Although these numbers represent Istanbul metropolitan city, there are many similarities with other provinces in Turkey. Note that some buildings with 7~8 or more stories have usually U-shaped RC shear cores to accommodate elevators (i.e. elevator shafts) around the staircase area. Since these use very small dimensions when compared to overall story area, it is hard to assume that such lightly stiffened systems could be assumed as dual frame + shear wall/core systems. In most cases, these elevator cores do not have sufficient connection to floors to provide a smooth lateral load transfer to/from the floor diaphragm.

As an unsolved historic problem of soft/weak story (B2 and B1 type irregularities as defined in TBEC-2018), short column, torsional irregularity (A1 type irregularity as defined in TBEC-2018) resulted in pronounced damage in buildings. Also, lack of balanced framing action in both orthogonal directions of building layout was another issue (mostly from architectural reasons) to cause excessive interstory drifts. Higher ground stories (usually 1, sometimes 2 stories) without infill walls and with large floor openings were architectural based issues mandated by building owners in the region.

Such designs led to unrepairable damage or in some cases collapses mainly from large ground story drifts creating additional bending moments (i.e. second order effects) that were far beyond the capacities of building columns. The situations got even worse when both axial load and shear force demand/capacity ratios in columns were almost doubled the design values in cases where concrete quality was poor.

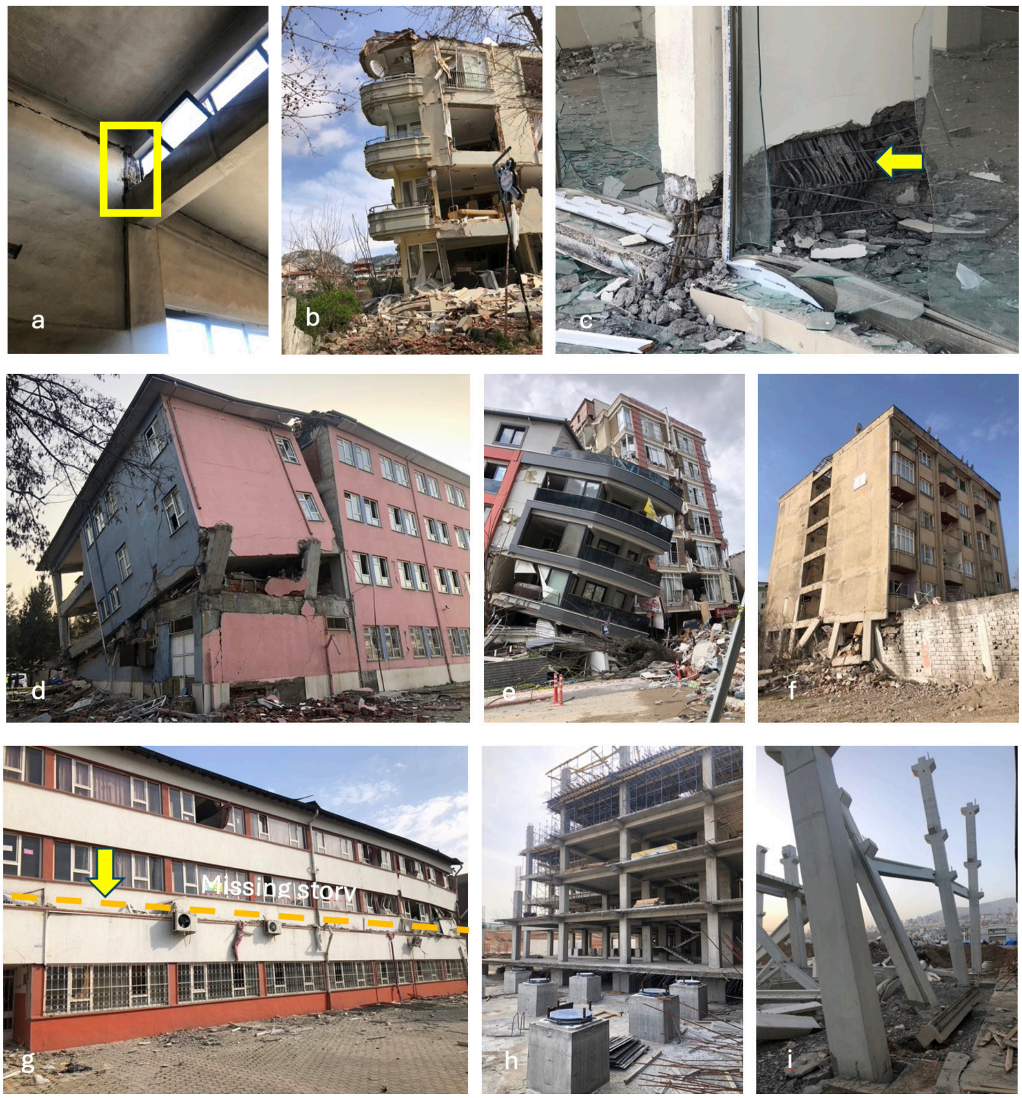

Figure 2. Structural damage to buildings a)Short column b)Flexible moment frames c)Shear wall failure (concrete crashing and rebar buckling) d)School building mid-story collapse e)Building collapse from irregularity f)Ground story collapse of sub-standard building g)Mid-story collapse in school building h)Hospital building with isolation devices (under construction) i)Totally collapsed prefabricated industrial building (under construction).

Soil based damage to buildings was mostly observed in Antioch/Hatay and Golbasi/Adiyaman. Numerous buildings were damaged mainly from liquefaction, bearing failure or excessive soil settlements[9]. Some examples are illustrated in Figure 3. Among them, Figure 3c shows a two-story prefabricated building that survived the quakes only with repairable damage. Note that these buildings were constructed as permanent housing units (a total of 228) following the May 5th, 1986 earthquake (Mw 6.1) occurred in Dogansehir-Surgu. Only a small percentage of these well-designed prefabricated buildings exist since they have been replaced with mid-rise heavy buildings. Newer buildings has experienced damage from soil as well since soil pressures during the earthquakes exceeded the bearing capacities of underlying soil layers. Using thick raft/mat foundations did not help much. Although such heavy buildings tilted significantly, structural / nonstructural damage was limited in the superstructure as expected. Similar failure patterns were observed especially in the March 13th, 1992 Erzincan and August 17th, 1999 Kocaeli (İzmit) earthquakes measuring Mw 6.8 and 7.4, respectively. Pounding in neighboring buildings (with and without significant seismic gaps) was common at Golbasi, Adiyaman. Bidirectional effects were significant as well[13].

Figure 3. Soil based building damage at Golbasi a)Pounding b)Soil failure causing tilting c)Prefabricated low-rise house with repairable damage d)Soil failure (loss of ground story) e)Soil failure (loss of ground story) f)Typical infill wall-frame damage.

Historic masonry buildings (residential, hotels, religious) experienced significant damage or collapsed. Some of the damaged buildings are depicted in Figure 4. Mostly stone masonry buildings exist in the region in addition to some traditional Turkish housing units.

Common damage types were in the form of in-plane and/or out-of-plane (or interaction of both) wall collapses, wide X or diagonal (/) cracking formations, dome collapses, vault collapses, minaret collapses (especially above the balcony), slab collapses, tie-rod failures, integrity loss in structural components etc.

Figure 4. Masonry building damage and collapses a)Collapse of church b)Partial collapse of hotel c)Governer's building d)Severe damage and collapsed parts of masonry building e)Collapse and damage of mosque f)Minaret collapse g)Church collapse h)Limited damage to traditional building with masonry and wooden components i) Excessive damage to newly restored mosque (tie-bar fracture, arch collapse from front view-roof and other interior parts collapsed).

Note that historic buildings in Antioch, Hatay, Kahramanmaras, Malatya, Adiyaman suffered serious damage mainly due to poor soil conditions as well as from local peak ground accelerations (PGAs) which were unbearable for such heavy and nonductile building stock. On the other hand, buildings with simple and regular load bearing systems behaved well (as in previous earthquakes) as expected[14,15].

Performance of retrofitted buildings

Seismic performance of buildings retrofitted prior to a devastating earthquake is worth evaluating. Such buildings (although not many) exist in the region. Generally speaking, buildings (both historic and relatively new) appropriately retrofitted prior to these earthquakes behaved satisfactory as per the design intent. However, buildings retrofitted with inappropriate methods led to severe damage or even collapses especially in registered (historic) buildings. Seismic evaluations should be carefully carried out during the restoration projects of historic masonry buildings. In most cases, soil-structure interaction should be taken into consideration and soil improvement works should be implemented when necessary. Otherwise, all work-done in the superstructure for a better seismic performance could be useless especially under such devastating events.

Figure 4. Continued j)Ground story wall collapse k)Minaret collapse and loss of integrity of body stones l)Mosque total collapse m)Excessive damage to newly restored mosque n)Interior view of mosque (collapse of dome and arches) o)Collapse of upper story and roof of school.

Potential Retrofit Measures for Existing Buildings

It is mandatory that seismically vulnerable buildings should be retrofitted as per the Chapter 15 of TBEC-2018[12]. Historical / registered buildings are exempt from this statement since the architectural and cultural values need to be protected and cannot be damaged by a potential heavy intervention during the retrofit works. There are several ways to upgrade a building for a better seismic resistance. Figure 5 shows a simplified representation of benefits of innovative seismic retrofit for continuous functionality and resilience either by period shift (e.g. seismic isolation) and added damping (e.g. seismic dampers of any kind). Note that no damage (or damage free) or limited damage is possible performances when such ways are used.

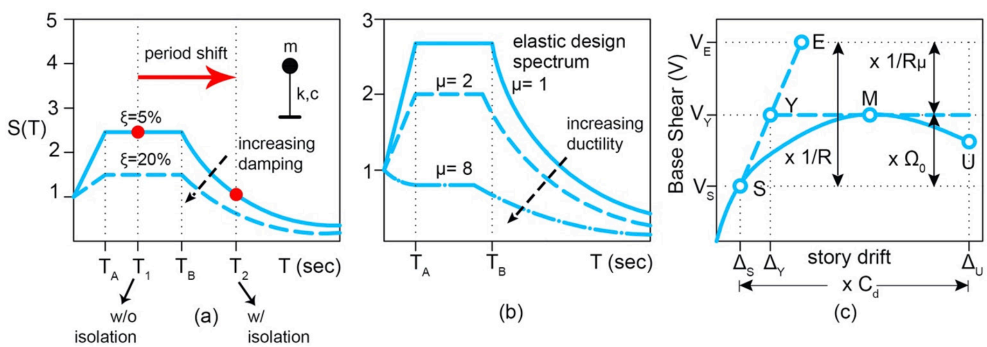

Figure 5. Potential benefits of seismic isolation and added damping on seismic retrofit a)Impact of period shift and increasing damping b)Impact of increasing ductility c) Some design parameters introduced in seismic codes.

Figure 5c shows a typical plot of base shear versus drift relation for a typical structure. In this figure, design base shear level is defined with VS while idealized bilinear response (VY is the yield strength) is represented by a dotted line following the S-Y-M path. Apparently, the S-Y-E path corresponds to elastic response while S-M-U path is the actual inelastic response. Structural behavior (a.k.a. force reduction) and overstrength factors are shown by R and Ω 0, respectively. In addition, Cd is introduced as displacement amplification factor which is also a function of structural overstrength factor, ductility, and damping ratios.

It is clear that seismic demands could be reduced by innovative techniques. However, most of the buildings in the existing building stock could not be suitable to implement such technologies and therefore other conventional methods could be a reasonable way as well (Figure 6). To increase member capacity and ductility, column jacketing, steel jacketing, G/CFRP wrapping are widely used. For enhancing lateral stiffness/rigidity, adding RC shear walls/cores in both plan directions, adding steel bracing systems with X, /, or V configurations, or a mix use of RC shear walls/cores and steel bracing systems are very good alternatives to upgrade vulnerable buildings. Note that adding RC walls/cores and steel bracing would increase seismic demands mainly due to shortening building vibration periods. Also, further retrofit works may be needed in the foundation system due to increased loads in locations where RC shear walls or steel bracing members are used[16,17,18,19]. Historical buildings have their specific rules in retrofitting such as protecting heritage value following a minimum level of intervention as per the Venice Charter for the conservation and restoration of monuments released in 1964. This document provides an international framework for the conservation and restoration (including retrofitting) of historic buildings.

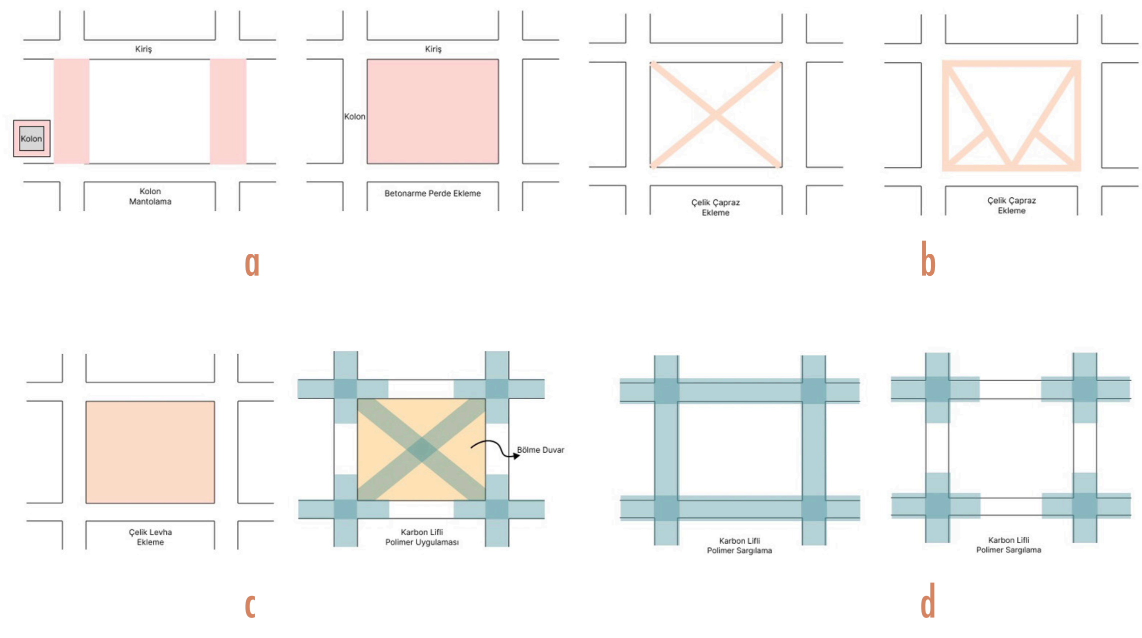

Figure 6. Potential retrofit schemes for framed buildings a)Column jacketing and adding RC shear wall b)Adding steel bracing of any configuration c)Adding thin steel plate shear wall and using infill wall as part of retrofit together with G/CFRP sheets d)Wrapping frame elements with G/CFRP(complete and partial wrapping around beam-to-column regions).

Real-life examples of some retrofit schemes are shown in Figure 7. Very critical issues in selecting seismic retrofit alternatives are usually downtime (interruption of daily activities during the post-earthquake recovery phase), possible temporary evacuation scenarios, and of course the total cost of retrofit works. Therefore, architecture friendly solutions are always sought by building owners. This demand has led to seismic retrofit designs using building façades only if the building is suitable for such interventions (e.g. Figure 7b,d).

Figure 7. Real-life retrofit examples a)Adding steel bracing (Municipality Building, Japan) b)Adding seismic damper on building façade (Japan) c)Adding steel bracing (Tsukuba University, Japan) d)Adding steel dampers on building façade (TIT, Japan) e)Adding RC shear wall, new foundation, RC jacketing and using CFRP plates as reinforcement (School building, Istanbul).

Evaluations and Final Remarks

Although the February 6th, 2023 Kahramanmaras earthquake doublet were the most powerful continental earthquakes that occurred on the same day, the existing building stock (both historic and contemporary) was not strong enough to survive during these events. There are still lessons to be learned from the performances of the buildings that survived the quakes with some damage. Weak soil conditions played an important role on this catastrophic damage distribution. Response of buildings with simple structural systems was satisfactory although excessive damage has been recorded. Proper seismic retrofit applications conducted prior to these earthquakes have proved their effectiveness by keeping the damage level at acceptable margins (at least life safety performance level). Big steps should be taken to preserve both architectural and cultural as well as the structural integrity of historical buildings. Residential buildings deserve particular attention since the aged building stock in Turkey is not ready for future devastating earthquakes with similar magnitudes. Any of the seismic retrofit measures mentioned in this work or reconstruction of the ones when deemed necessary can be taken to prepare this vulnerable stock for future earthquakes. In addition to widely accepted construction techniques, innovative structural systems such as base isolation and energy dissipation devices should also be considered as alternatives both in retrofit and reconstruction works.

Although seismically isolated government hospitals survived the earthquakes with minor or no damage, some substandard hospitals collapsed. Though some application mistakes made in isolated buildings have been explored, their performance was within still acceptable limits.

Rapid visual screening (RVS) methods are useful tools in determining seismic vulnerability of the existing building stock especially in big cities. These methods provide the user with a prioritization of the building stock based on a scoring scale. Such scoring would suggest a wise classification of buildings that need to be renewed and retrofitted. Among many, the Canadian way of RVS explained in [20] is an efficient method for such scoring as this way is quite appropriate for the existing building stock in Turkey. Scoring is based on many factors including type of structure, structural irregularities, seismicity of the region, soil conditions, floor system, building importance, building condition, non-structural items.

In addition to building weaknesses, strong ground motion features and bidirectional effects should be well investigated in future studies for better explaining widespread building damage and collapses[21, 22].

Conclusions

Overview of seismic damage to buildings is pointed out with references to observations made following the devastating Feb.6th, 2023, Kahramanmaras earthquake sequence in Turkey. Damage classifications in various types of buildings are introduced. It is seen that similar damage types have been observed as seen in the past earthquakes in Turkey. Some effective seismic retrofit schemes are proposed for the existing building stock. The following conclusions can be drawn from this work:

- Structural properties (strength, stiffness, ductility) of the existing building stock in the earthquake-stricken areas were below the existing standards. Therefore, catastrophic damage and casualties can be attributed to this sub-standard building stock.
- Newer (i.e. code-compliant) buildings experienced significant damage and some collapsed (a minor percentage). This is attributed to the large magnitudes, complex rupture process, triggering mechanism of the earthquakes. The recorded peak ground accelerations (PGAs) and calculated velocities (PGVs) were well in excess of the proposed values in TBEC-2018.
- Structural irregularities and weak soil properties have significantly contributed to this catastrophic damage and losses.
- Seismically vulnerable, non-code-compliant buildings in the existing building stock (damaged or undamaged) should be retrofitted by conventional or innovative techniques as explained in the text.
- Rapid visual screening (RVS) methods can be used for determining highly vulnerable buildings in cities with large problematic building stock [e.g. 20 among many].

Author Contributions

NA

Funding

This research received no external funding.

Ethics Committee Approval

This work does not require an ethics committee approval.

Acknowledgments

Dr. Kurtulus Atasever of MSGSU helped in preparing Figures 1 and 6. This help is sincerely acknowledged.

Conflict of Interest

The author declares no conflicts of interest.

References

1. I. Aka, F. Keskinel, F. Cili, and O. C. Celik, "Betonarme," Birsen Yayınevi, 637 pages, Istanbul (Textbook on RC Structures), 2001.
2. O.C. Celik, "Observed beam-column connection failures during 17 August 1999 Kocaeli (İzmit) and 12 November 1999 Duzce, Turkey Earthquakes, The Paramount Role of Joints into the Reliable Response of Structures-From the Classic Pinned and Rigid Joints to the Notion of Semi-rigidity," NATO Science Series II, *Mathematics, Physics and Chemistry*, Vol.4, pp.197-206, 2000.
3. O.C. Celik, "Seismic performance of buildings during the last two decades earthquakes in Turkey," Proceedings of 2013 International Van Earthquake Symposium, 23–27 October, Van (Keynote Speech), 2013.
4. H. Sesigur, O. C. Celik, F. Cili, and K. Ozgen, "Effect of structural irregularities and short columns on the seismic response of buildings during last Turkey earthquakes," Proceedings of 3rd International Conference on Earthquake Resistant Engineering Structures-ERES2001, Malaga, September 4-6, 2001, pp.83-90.
5. F. Cili, O. C. Celik, and H. Sesigur, "Architectural based damages to buildings during 17 August 1999 Kocaeli (İzmit) earthquake," Proceedings of the 3rd Japan-Turkey Workshop on Earthquake Engineering, February 21-25, İstanbul, 2000, pp.451-458.
6. F. Cili, K. Ozgen, and O. C. Celik, "Evaluation of seismic damages to RC buildings during 1992 Erzincan earthquake," Proceedings of 10th European Conference on Earthquake Engineering, Vol.1, 28 August - 2 September, 1994, pp.773-778.
7. O. C. Celik and F. Cili, "Impact of excessive story drifts on seismic response of RC buildings during last Turkey earthquakes," Proceedings of fib Symposium-Concrete Structures in Seismic Regions, Athens, May 6-9, 2003.
8. O. C. Celik, A. Bal, K. Atasever, S. Emanet, and S. Koca, "Reconnaissance investigation following the January 24th, 2020 Doganyol (Malatya) – Sivrice (Elazig) earthquake (Mw 6.7 – East Anatolian Fault Zone)," *Precast Concrete Journal* (Beton Prefabrikasyon), vol. 134, pp. 5-28, ISSN 1300-3488 (in Turkish), 2020.
9. O. C. Celik, M. B. C. Ulker, C. Gocer, S. Guntepe, O. Koz, M. M. Eyupgiller, M. Aksu, and A. Yaz, "Multidisciplinary reconnaissance investigation covering structural, geotechnical, and architectural based damage to mid-rise residential buildings following the February 6th, 2023 Kahramanmaraş, Türkiye Earthquake Doublets (Mw 7.8, Mw 7.6)," *Soil Dynamics and Earthquake Engeneering Journal*, vol. 182, 2024, doi: 10.1016/j.soildyn.2024.108738.
10. R. Okuwaki, Y. Yagi, T. Taymaz, S.P. Hicks, "Multi-scale rupture growth with alternating directions in a complex fault network during the 2023 South-Eastern Türkiye and Syria earthquake doublet," *Geophysical Research Letters*, vol. 50, pp. 1-14, 2023, doi: 10.1029/2023gl103480.

11. C. Liu, T. Lay, R. Wang , T. Taymaz, Z. Xie, X. Xiong et al., “Complex multi-fault rupture and triggering during the 2023 earthquake doublet in Southeastern Türkiye,” *Nature Communications*, vol. 14, pp. 1–14, 2023, doi: 10.1038/s41467-023-41404-5.

12. Turkey Building Earthquake Code (TBEC), Ministry of Environment, Urbanization, and Climate Change, 2018.

13. H. Sesigur, O. C. Celik, and F. Cili, “Review and evaluation of combination rules for structures under bidirectional earthquake excitations,” Proceedings of 13th World Conference on Earthquake Engineering, August 1-6, Vancouver, Canada, Paper No: 2079, 2004.

14. O. C. Celik and H. Sesigur, “Performance of historic masonry buildings during the April 6, 2009 L’Aquila Earthquake,” Proceedings of 14th European Conference on Earthquake Engineering, August 30-September 3, Ohrid, Rep. of Macedonia, 2010.

15. O. C. Celik, H. Sesigur, and F. Cili, “Importance of wood and iron tension members on seismic performance of historic masonry buildings: Three case studies from Turkey,” ATC&SEI Conference on Improving the Seismic Performance of Existing Buildings and Other Structures, 9-11 December, San Francisco, CA, USA, 2009.

16. O. C. Celik, J.W. Berman, and M. Bruneau, “Ductile design and testing of steel frames having moveable bracing infills,” Proceedings of the 5th International Conference on Behaviour of Steel Structures in Seismic Areas - STESSA 2006, 14-17 August, Yokohama, Japan, 2006, pp. 191-196.

17. O. C. Celik, H. Sesigur, and F. Cili, “Turkish experience on seismic retrofit of buildings using steel members,” National Symposium on Steel, Timber and Composite Structures, 18-19 May, Sofia, Bulgaria, 2006.

18. H. Sesigur, O. C. Celik, and F. Cili, “Repair and strengthening of ancient structures in seismic areas,” Proceedings of the First European Conference on Earthquake Engineering and Seismology, 3-8 September, Geneva, Switzerland, 2006, Paper No: 1387.

19. F. T. Cizmecioglu and O. C. Celik, “RC column and/or shear wall cross-sectional area ratios in Turkish school buildings before and after seismic retrofit,” Proceedings of Structural Faults and Repair, 10-12 June, Edinburgh, Scotland, 2008.

20. O. C. Celik, A. Ilki, C. Yalcin, and E. Yuksel, “Doğu ve Batı Avrupa kentlerinde değişik tip binaların deprem riskinin hızlı değerlendirilmesi üzerine bir deneyim,” Ulusal Deprem Mühendisliği Konferansı, 16-20 Ekim, İ.T.Ü. Süleyman Demirel Kültür Merkezi, Cilt II, s. 297-304, Maslak, 2007 (in Turkish).

21. A. Yahiaoui, O. Koz, and O. C. Celik, “Computed bi-directional combination coefficients for structures using the Feb.6th, 2023 Kahramanmaras earthquakes’ ground motion data,” Proceedings of the 3rd Crotian Conference on Earthquake Engineering (3CroCEE), 19-22 March, Split, Croatia, 2025.

22. O.Koz, S.Guntepe, and O.C.Celik, “Analysis of SGM data characteristics for better explanation of building damage during the Feb.6th, 2023 Kahramanmaras, Turkey earthquakes,” Proceedings of the 3rd Crotian Conference on Earthquake Engineering (3CroCEE), Split, 19-22 March 2025.

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Structural Lessons from Türkiye's Earthquakes: Design-Inspection-Destruction Nexus

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On February 6, 2023, a sequence of earthquakes, among which earthquakes with moment magnitudes of 7.8 and 7.5 were the strongest, struck southeastern Türkiye, leading to an unbearable catastrophe with heavy loss of life, injuries, and damage. These earthquakes were the most devastating in the history of Türkiye in terms of the loss of life and damage to structures.

Following the disaster, several recon teams were commissioned by the Turkish Ministry of Environment, Urbanization, and Climate Change to survey post-earthquake damage in the region and take immediate remedial actions. As part of one of these teams, the authors inspected many reinforced concrete buildings in the earthquake-affected area, together with experts commissioned by the Architectural Institute of Japan.

The substandard characteristics of collapsed and still-standing but damaged reinforced concrete buildings were documented during the inspections to evaluate these structures from both architectural and civil engineering points of view. A detailed analysis of the data gathered from the inspected buildings indicated the vital role of the architect in the design of earthquake-resistant buildings and the essential collaboration between engineers and architects in the face of an increasingly degrading construction industry with the sole objective of maximizing profit margins.

Furthermore, defects in the structural design of damaged and collapsed buildings are often the result of structural irregularities that stem primarily from the low quality of architectural and engineering design services. These services are the first to be sacrificed to maximize profit. Architectural plan layouts are often determined by decisions related to maximizing marketable floor area rather than spatial or structural concerns at the expense of soft/weak stories, vertical discontinuities in the structural elements, and short column formations.

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These irregularities combined with low-quality materials (i.e., low-strength concrete and plain reinforcing bars) and improper engineering inspections were observed to exacerbate the extent of structural damage and loss.

The study also discussed the impact of modifications and improvements in national building regulations after the earthquakes, while underlining the mutual responsibilities of architects and civil engineers. Given that most of the building stock of Türkiye is vulnerable to future earthquakes, some recommendations are provided. Namely, the prioritization of structural interventions (i.e., repair and/or strengthening activities) of susceptible buildings and reinforcing the regulations on the authorization of architects and civil engineers in a more sound construction inspection process.

Keywords: Earthquake reconnaissance, Türkiye earthquake, Regulation, Structural damage

Introduction

Several tectonic plates surrounding Türkiye resulted in a westward escape of the Anatolian block, thereby leading to many major earthquakes. This makes the country one of the most seismically active regions of the world. Within the last three decades, Türkiye has been hit by several earthquakes with moderate to large magnitudes, which have caused significant loss of life and property. Erzincan (1992), Dinar (1995), Ceyhan (1998), and Kocaeli and Düzce (1999) earthquakes (also known as the Marmara earthquakes) have been among the most destructive earthquakes in the last 30 years. It was reported that even after the Kocaeli earthquake, the number of accounted deaths were 18,373, while there were approximately 16,400 heavily damaged or totally collapsed buildings[1]. Furthermore, two sequential devastating earthquakes occurred on February 6, 2023, striking the southeastern part of Türkiye with Mw=7.8, followed by an Mw=7.5, approximately nine hours later at around Pazarcık and Elbistan, respectively[2]. A total of 11 provinces in the Southeastern Anatolia, Mediterranean, and Eastern Anatolia regions, home to a total of approximately 14 million people and 16.4% of the total population of Türkiye (data.tuik.gov.tr), were affected by the earthquakes. Measured spectral accelerations during the earthquakes significantly exceeded the design spectral acceleration of even DD-1 ground motion levels (2% probability of occurrence within a 50-year period) around Antakya, particularly for periods exceeding 0.6s[3]. These recent earthquakes have caused life losses exceeding 50,000, resulting in 250,000 heavily damaged or collapsed buildings[4]. In May 2024, even one year after the earthquake, nearly 700,000 people were reported to live in temporary shelters[5].

In the immediate aftermath of the February 2023 earthquakes of Türkiye, national and international response teams were mobilized, focusing on search and rescue operations, medical assistance, and provision of shelters for the displaced population[6]. In a parallel effort, a joint reconnaissance mission was organized by the Ministry of Environment, Urbanization, and Climate Change of Türkiye and Architectural Institute of Japan. The mission was carried out by highly qualified and specialized teams of engineers and architects comprised of academics from top universities of both countries as well as prestigious private companies. The reconnaissance mission consisted of classification of post-earthquake damages and the comparison of Japanese and Turkish damage assessment methods to evaluate their weaknesses and strengths regarding their predictive power of damage in comparison to documented real damage. In the scope of the present study, the observations of one of the teams of this mission, namely the authors, are discussed with a focus on the necessity of an integrated and complementary damage inspection by a multidisciplinary team consisting of both architects and structural engineers.

Specifically, this study will focus on i) observed structural deficiencies on reinforced concrete structures, ii) the role of existing regulations on architectural/structural design and inspection, and iii) the respective responsibilities and potential culpabilities of architects and structural engineers. The reconnaissance mission showed that the existing reinforced concrete building stock, particularly the buildings constructed prior to 2000s, were extremely vulnerable against the earthquakes due to the poor quality of concrete and reinforcing details. The structural irregularities such as soft/ weak story and short column formations, and vertical discontinuities stemming primarily from a profit driven construction industry at the expense of architectural and structural deficiencies, exacerbated the extent of the damage. Insufficient inspection during the construction of the buildings also played a key role on the high number of heavily damaged or collapsed buildings.

Figure 1. Some representative observed damages: (a) insufficient stirrup spacing/detailing, poor quality of concrete, lack of confinement for plastic hinge region, (b) soft & weak story formations resulting in significant lateral drift, (c) heavy corrosion in a stadium column, (d) usage of plain reinforcing bars (Images by author).

Observations on Structural Deficiencies

According to field observations, the reasons for the structural damage to reinforced concrete buildings can primarily be attributed to i) insufficient stirrup spacing/detailing, ii) usage of plain reinforcements, iii) poor concrete quality (such as apparently insufficient compressive strength and improper aggregate sizes), iv) lack of confinement around critical column regions, especially at joints, v) structural irregularities such as soft stories, weak stories, and short columns because of deficient architectural and structural design, and vi) improper rigidity distribution of the vertical structural members. Representative examples of observed damage are shown in Figure 1. Schmidt hammer readings taken from ground floor columns of 12 collapsed buildings or buildings requiring urgent demolishing indicated concrete compressive strengths of approximately 12 MPa. It should be noted that, it was evident from the construction practice and level of corrosion that most of these inspected buildings were constructed according to the provisions of Turkish seismic building code of 1975[7]. This code required at least C16 class of concrete (16 MPa of characteristic compressive strength), allowing for the use of plain reinforcing bars, where it was violated in the construction of the buildings, particularly in terms of provided lateral reinforcement spacing, hook angle, and hook length.

In many cases, improper load transfer among the structural members was clearly observed, resulting in discontinuities in the load distributions in both the horizontal and vertical planes. For one column, some columns were placed irregularly without following continuous structural gridlines. In the case of beams, some have been documented to transfer loads to other beams instead of columns. Such discontinuities and irregularities in the structural system led to deteriorating moment-frame behavior of buildings under earthquake excitation. Our observations about floor layout, both on the ground floor and on the upper floors, suggest no reason other than profit maximization by contractors and investors to be the sole reason for such irregularities. In short, such irregularities were not the result of whimsical architectural fantasy in the search for radical spatial schemes.

The resulting risk was further increased when accompanied by inadequate detailing, workmanship, and poor quality of construction materials, all of which often occurred simultaneously. Column failures were mostly due to non-ductile reinforcement detailing, insufficient lap splices, and improper interaction between the columns and the infill masonry partition walls. The tensile reinforcing bars at the bottom of the beams were observed to be inadequately anchored through the beam-column joints. Specific forms of ribbed slabs comprising shallow beams and one-way infilled joists ("asmolen" slabs in Turkish) are quite common in the inspected region. Damage was widespread in such systems because of the poor lateral stiffness and large deformation of the joists, leading to the dislodging of the hollow clay tile formwork.

In addition, floors that collapsed in the form of pancakes were one of the major reasons for most loss of life. This behavior can be attributed to the irregular and poor structural system design as well as the weak column-strong beam mechanism resulting from the lack of design quality. Examples of this collapse mechanism are shown in Figures 2 and 3.

Problems related to poor soil conditions, which were not carefully considered during structural design, were also among the reasons for the collapse of the buildings (Figure 2). Some buildings, especially those in Gölbaşı and Adıyaman, were exposed to liquefaction owing to poor soil conditions and insufficient consideration of the soil in foundation design (i.e., using a mat foundation instead of a deep foundation, as shown in Figure 2). In addition to these problems, user-induced damage during occupancy, such as the removal of one or more columns, drilling of the concrete cover severely to hang possessions or even drilling of structural elements for air duct openings, and disruption of the reinforcement joints for different purposes were observed, which potentially caused considerable damage to the structures. It is also worth mentioning that the structures determined to be non-damaged or slightly damaged (i.e., only hairline cracks in structural members) were structurally sound, not because

Figure 2. Example of soil liquefaction (Images by author).

Figure 3. Examples of (a), (b) pancake collapse (Images by author).

of the quality of the design service they received or because of the quality of manufacturing or the materials used, but primarily because of the relatively low peak ground acceleration (PGA) values that affected these structures. In other words, they were fortunate. Furthermore, we observed that the buildings in the slight damage state suffered from diagonal cracks on the nonstructural partition walls. In the lower stories of buildings, damage was concentrated to the infill masonry walls because of the higher demands in this region of the moment-frame buildings. This phenomenon can be considered as one of the disadvantages of ductility design, which enables buildings to exhibit a large amount of lateral drift, thereby increasing nonstructural damage. On the other hand, particularly in structures constructed prior to 2000, heavy corrosion damage occurred prior to earthquakes, increasing vulnerability. Corrosion may lead to earlier yielding and buckling of reinforcing bars under severe conditions, causing a reduction in the bar diameters.

All the observed and assessed buildings in the field study, as well as the majority of the building stock in the region, were typical and highly simple mixed-use residential buildings, which did not require any sophisticated architectural and structural design services. The ground floors of these buildings were allocated to shops, which required interrupted space planning, whereas the upper floors housed regular two- or three-bedroom apartments with no spatial challenge. Often, their architectural and structural designs are copied and reused and slightly adapted to their respective sites, streamlining, and economizing from the design services. The building stock, therefore, was architecturally and structurally of mediocre quality requiring no sophisticated design solutions. The observed damage, which is highly unexpected from such repeated and basic building types, is indicative of the quality of the construction and design services received by these buildings.

Regulations

Because of the earthquake risk and the magnitude of predicted casualties and economic losses under potential earthquake scenarios, many laws and regulations have been enacted in Türkiye since the 1999 Marmara earthquake. Examples include the urban transformation law and the associated regulations for identifying risky buildings, regulations regarding insurance (such as compulsory earthquake insurance), revisions made to the Turkish building earthquake code in 2007 [8] and 2018 [9], and new regulations in the building inspection system and zoning of planned areas involving changes to the authority of civil engineering and architecture professions.

Law No. 6306 on Urban Transformation (commonly known as the Urban Transformation Law) was enacted in 2012 to address the risks posed by natural disasters, particularly earthquakes. The Law aims to facilitate the identification and strengthening of buildings that are considered unsafe or at risk of collapse. Certain incentives and support such as rental assistance, law-interest loans, tax exemptions, and subsidies for demolition costs are offered to individuals whose buildings are slated for demolition because of their risk levels. These incentives and supports are designed to encourage the strengthening of risky buildings while reducing financial strain on property owners during the process. Furthermore, the Urban Transformation Law and other related regulations mandate that property owners should be protected against the economic consequences of seismic events. Consequently, compulsory earthquake insurance (coordinated by the Turkish Catastrophe Insurance Pool, DASK) was introduced in the aftermath of the 1999 Marmara earthquake as part of the efforts to mitigate the financial risks associated with earthquakes. All owners of residential buildings within municipal boundaries are required to have DASK coverage, and property owners cannot complete certain legal transactions such as buying, selling, or leasing their property. The insurance covers damage to the main structural components of buildings (e.g., walls, floors, roofs, and foundations) caused by earthquakes and related natural disasters such as landslides or tsunamis. However, it does not cover the content or personal belongings inside the property. The DASK is designed to provide financial protection to homeowners, reduce state liability, and encourage urban transformation by providing a financial safety net.

While the above regulations and laws aimed to improve the quality of the construction industry, numerous zoning amnesties issued around the same time interval had the opposite effect. These amnesties have allowed unauthorized or noncompliant buildings to be preserved, preventing urban transformation processes from achieving their intended goals. The high number of building registration certificates issued because of the 2018 zoning amnesty (Law No.

7143), along with the creation of an unregulated area, has further exacerbated challenges related to seismic resilience, given that the majority of these buildings have not received any engineering services. The data reported within the disaster reduction plan (İRAP) of İzmir can be considered an example (izmir.afad.gov.tr). According to this report, the number of issued building registration certificates due to the 2018 zoning amnesty is approximately 400,000, revealing the risk of loss in this scope.

In addition, Türkiye's struggle and test with earthquakes dates back to earlier times than the devastating 1999 earthquakes, as early as the Great Erzincan earthquake of 1939, which was a milestone itself. After a significant loss of life and property in this earthquake, the initial formal regulation on the seismic design of buildings, known as the "Türkiye Earthquake Zones Building Regulation," was issued by the Ministry of Public Works in 1940 based on an Italian code. This regulation succeeded by updates in 1953, 1961, 1968, 1975, 1998, and 2007. In the upcoming years, the regulations from 1998 and 2007 [8] have incorporated various calculation methods in detail, such as Equivalent Static Load, Modal Combination, and Time History Analysis. The Turkish Building Earthquake Code [9] was updated and implemented in 2019. One of the most significant advancements in this new regulation is the ability to determine site-specific earthquake hazards according to geographic location, shifting earthquake hazard assessments from macro-to microscale approaches.

Under the 2007 Seismic Code[8], earthquake zones were categorized into five regions, with acceleration values ranging from 0.1 g to 0.4 g. In contrast, the most current code in use mandates site-specific calculations via the "Interactive Earthquake Web Application" provided by AFAD. TBEC-2018[9] also broadened its material scope to include preengineered reinforced concrete, light steel, and wooden structures. While TSDC-2007[8] defined four building usage classes (BKS), TBEC (2018) reduced them to three classes and introduced the Earthquake Design Class (DTS), which is characterized as a function of short-period spectral acceleration (SDS), an indicator of the severity of the expected earthquake. Furthermore, TBEC-2018[9] identified four levels of earthquake ground motion, replaced the local soil groups with six local soil classes, and introduced a vertical design acceleration spectrum. It considers eight building height classes, four damage levels, and a more extensive range of concrete grades[10]. The steel reinforcement classification was changed to B420C and B500C to characterize steel with a chemical composition that is different from that of TSDC-2007[8]. The cross-sectional element damage levels are defined based on the tensile strain of the reinforcement, compressive strain of the cover/core concrete of the columns, and plastic rotations of the structural members in both TSDC-2007 and TBEC-2018. In TSDC-2007, damage regions are classified as minimum damage, moderate damage, heavy damage, and collapse regions for each structural cross-section, and the overall building performance level can be determined as Immediate Occupancy (IO), Life Safety (LS), Collapse Prevention (CP), or collapse (CO). The building of interest should at least satisfy the LS performance level for an earthquake with return period of 475 years (10% probability of exceedance in 50 years). After TBEC-2018 was released, target performance levels were updated as Uninterrupted Occupancy (IO), Limited Damage (LD), Controlled Damage (CD), and Collapse Prevention (CP) states. Furthermore, to ensure the accurate application of provisions of the design guidelines on construction sites, Law No. 4708 on building inspection was released in 2001, and as of this date, it has been implemented in 19 pilot cities, which also included most of the affected region after the February 2023 earthquakes. It should be noted that, as of the date that this article was prepared, there is no certain regulation mandating the use of shear walls in the design of a regular reinforced concrete structure in Türkiye. However, the Turkish Ministry of Environment, Urbanization, and Climate Change is known to be on the verge of releasing a notification on enforcing the usage of shear walls, which also points out that the next generation Turkish Seismic Design Code will involve such mandatories for civil engineers. The use of such long walls also has the potential to limit the architectural efficiency of buildings.

The February 2023 earthquake also necessitated revisions in the zoning laws in Türkiye with the aim of defining the boundaries of the planned areas. According to the planned area zoning regulations released by the Ministry of Environment, Urbanization, and Climate Change in 2023, closed overhangs cannot be constructed in buildings with ground plus seven or more floors, whereas the columns attached to these overhangs must be connected to each other with surrounding beams, specifically in buildings involving residences. In addition, the height of commercial ground floors cannot exceed four-and-a-half meters, short columns cannot be used, and it is mandatory to leave a gap for attached buildings, as the distance between the adjacent buildings should be at least 30 mm up to 6 m building height, while an additional 10 mm should be considered for each 3 m height increment. The modification of the planned area zoning regulation also addressed the requirements for civil engineers and architects. For civil engineers, there is no specific requirement of expertise and experience when the designed building has fewer than five floors, whereas three to seven years of experience is warranted for higher buildings. For architects designing public buildings, a minimum of five years of experience in public institutions, university departments, or professional chambers is required. Designing a minimum of four different buildings totaling a minimum of 10,000m^2 is also mandated. If an architect has a graduate degree, they are considered to have met half of these criteria. Recently, the Ministry of Environment, Urbanization, and Climate Change of Türkiye also released regulations on the Design Supervision and Control Services of Special Buildings (DTGU), which outline the conditions for advanced design methods and technologies required for the design supervision and control of special buildings. The guidelines also specify the educational requirements, professional qualifications, and experience needed for those providing these services, along with documentation processes for certification. Furthermore, the regulation established procedures and principles for the execution of these services.

All of these laws and related regulations were implemented throughout the country as of 2011. These efforts only indicate the seriousness of the authorities and experts in improving the quality of construction in the country. Observations of the authors after the recent earthquakes showed that the buildings subjected to a qualified building inspection process behaved quite well with respect to buildings built without proper inspection, strongly indicating that the new regulations and laws worked only as long as they were followed. Regardless of the advancements in such regulations, we maintain that it is even more important to establish a sound inspection system for both the design services and the construction process immune from all other factors that might hamper the quality of the construction industry. Regulations and laws are only effective if they are enforced and if they are not bent to maximize profit.

What needs to be done?

When the aftermath of past earthquakes is investigated, it is clear that the year 2000 can be considered as an important milestone in the Turkish construction industry. First, the 1975 building earthquake code was significantly revised in 1998 and was extensively applicable around the year 2000. Second, the 1999 Marmara earthquake increased the awareness of seismic resistance. Third, new regulations enforced the use of ready-mix concrete and deformed bars together with the new Building Inspection Law enacted in 2001 for 19 pilot cities (including earthquake-affected areas in the February 2023 earthquake), which was then extended to the entire country in 2011. Finally, the reinforced concrete design guidelines (TS-500) were enacted in 2000. Therefore, most earthquake master plans developed for the largest metropolises in Türkiye (i.e., İstanbul and İzmir) consider this date a key parameter for assessing the risk of the existing building stock. Recent studies indicate that approximately 70% of the existing buildings in Istanbul were constructed before the 1999 earthquake[11], indicating high risk. Similarly, Cakti et al.[12] reported that nearly 194,000 buildings (16% of all buildings) in Istanbul will experience moderate or heavy damage under a moment magnitude of 7.5 scenario earthquake. Furthermore, approximately half of the total building stock in Türkiye was constructed before 2000[13], which indicates the scale of risk in the case of an earthquake. Consequently, approximately 12 million buildings in Türkiye may be at risk based solely on their construction date, underscoring the urgent need for effective emergency management strategies.

The vulnerability of the high portion of the existing building stock in Türkiye to future earthquakes underlines the urgency of risk assessment studies. Identifying the number of risky buildings, prioritizing them, and carrying out necessary interventions are urgent issues that need to be addressed. Considering the current construction costs, demolishing and rebuilding all risky structures may not be economically feasible. This strengthens many buildings using efficient and rapid methods. Due to limited financial resources and time, priority should be given to buildings with the highest risk, which necessitates the implementation of rapid risk assessment methodologies in the first step to identify and classify the building inventory. Building inventory studies should primarily focus on densely populated settlements, thereby posing a greater risk of loss. In doing so, buildings should be divided into categories according to the seismic risk score, which is assigned using rapid seismic performance assessment methods. This performance-based and risk-oriented classification may aid in the development of reliable intervention strategies aligned with risk-mitigation purposes. The intervention strategies for buildings with the lowest score (highest risk) should be prioritized, and these buildings should be demolished and rebuilt immediately. In cases where retrofitting is a feasible solution (i.e. cost of retrofitting does not exceeding the 40-50% of the cost corresponding to demolishing and rebuilding, according to the practice in Turkish retrofitting market), retrofitting should be preferred. In risky buildings, where retrofitting is feasible, the primary goal of strengthening efforts should be to prevent the collapse of the building, thereby reducing earthquake-induced losses. Therefore, the seismic performance targets required for new buildings by current seismic design regulations should be relaxed for existing structures. For example, after strengthening, the performance level of the collapse prevention should be considered sufficient. This approach could also pave the way for strengthening riskier buildings at the same cost.

Given the fact that buildings adjacent to the city's main arteries are dangerous for logistic operations immediately after an earthquake, priority should be given to these buildings, and intervention should begin from there. Important public buildings such as hospitals, schools, municipality buildings, and police stations, which are expected to operate immediately after the earthquake, should also be analyzed in terms of their seismic safety. In residential buildings, building owners should be encouraged to strengthen their buildings while incentivizing support, such as exemptions from fees and taxes, and long-term and low-interest loans should be provided by public authorities. Urban planning should focus on urban transformation through a holistic and phased approach, from parcel-scale to larger-scale planning. Related authorities should create good examples to demonstrate pilot urban transformation areas with the aim of increasing public interest and confidence in the urban transformation process. Cultural heritage should also be assessed in terms of seismic safety. Rehabilitation and conservation of existing historical assets should be ensured through extensive inventory studies. Recent earthquakes have also necessitated qualified damage assessment teams capable of rapid and accurate damage classification. These reconnaissance teams should receive periodic training and joint certification programs with universities should be implemented. A unit should be established within each local municipality, which should issue Earthquake Resistance Certificates for new buildings, promote this process, and gradually expand it to include existing risky structures.

The necessary coordination in this manner should be conducted in collaboration with academic institutions. Deploying the existing rapid assessment techniques to all residential buildings should begin with neighborhoods previously identified as having the highest seismic risk to collect the necessary data to prioritize and implement a seismic retrofit program.

It should be noted that without extensive collaboration among civil engineers, architects, and public authorities, including non-profit professional societies and chambers, it is impossible to avoid such destructive consequences after earthquakes. Türkiye has learned immensely from these catastrophes and has made immense progress in terms of legal regulations of the construction industry and in technical advancements in the construction industry since the early earthquakes of the republic. However, our experience indicates that when these legal and technical advancements are not sought after and are at times sacrificed to maximize profit, we are bound to phase new catastrophes. As professionals in charge of the built environment, we have an ethical responsibility to demand and enforce good and sound practices even when all others are against such practices. We can do this only in solidarity, and not in isolation.

Conclusions

The recent devastating earthquakes in Türkiye underscored the responsibilities and critical need for collaboration and solidarity among civil engineers, architects, and public authorities. This collaboration and solidarity are essential for early estimation of quantitative losses following a destructive seismic event, such as the number of collapsed buildings, fatalities, homeless individuals, and direct economic losses. Such information is crucial for stakeholders, such as early responders, governments, and the insurance industry, enabling them to plan effectively and manage the recovery phase more efficiently. The main conclusions and recommendations deduced from this study are as follows:

- The large number of existing substandard and risky buildings necessitates the development of intervention strategies that specifically prioritize the extent of the risk.
- Retrofitting can be an effective, economical, fast, and sustainable solution for building earthquake-resistant buildings. This appears to be an unavoidable

choice, given that demolishing and rebuilding all risky buildings in Türkiye is impossible both economically and temporally. In addition to their efforts to integrate earthquake resistance into conceptual architectural design, architects should also play a key role in the selection of non-invasive retrofitting solutions to mitigate impacts on building functions and minimize negative impacts during construction.

- Many structural irregularities originating from architectural design have the potential to exacerbate structural damage and even the collapse of buildings. Architectural education in earthquake-prone countries should incorporate the essentials of earthquake-resistant architectural design in the curriculum. Similarly, structural engineering education needs to incorporate the teaching of basic architectural knowledge to have a sound understanding of the close interaction between space design, planning, and structural design.
- Even though the current actions taken immediately after the earthquakes in terms of laws and regulations may play a critical role in the mitigation of seismic risk, building inspection procedures should be revisited. This process should continue through periodic inspections of buildings during their occupancy.

Author Contributions

Both authors equally contributed on the conceptualism and writing/editing original draft.

Funding

This research received no external funding.

Ethical Compliance

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Data Access Statement

Research data supporting this publication are available from the NN repository located at www.NNN.org/download/.

Acknowledgments

The authors gratefully acknowledge the Ministry of Environment, Urbanization, and Climate Change, Turkish Disaster and Emergency Management Authority (AFAD), Architectural Institute of Japan (AIJ), and the Natural Disaster Insurance Institution (DASK) for their support.

Conflict of Interest

The authors declare no conflicts of interest.

References

1. E. Durukal and M. Erdik, "Physical and economic losses sustained by the industry in the 1999 Kocaeli, Turkey earthquake," *Natural Hazards*, vol. 46, pp. 153-178, 2008.
2. AFAD (Turkish Disaster and Emergency Management Authority), "Report on the February 2023 Earthquake in Türkiye," [Online]. Available: www.afad.gov.tr., Accessed: 05 Oct, 2024.
3. S. Pujol, I. Bedirhanoglu, C. Donmez, J.D. Dowgala, M. Eryilmaz-Yildirim, K. Klaboe, and E. Sonmez, "Quantitative evaluation of the damage to RC buildings caused by the 2023 southeast Turkey earthquake sequence," *Earthquake Spectra*, 2023, vol. 40, no. 1, pp. 505-530.
4. C. Tura, Y. Sahinkaya, F. Gullu, U. Demir, K. Orakcal, and A. Ilki, "Observed performance of a RC wall-frame building during the February 2023 Türkiye earthquake and performance improvement using FRPs," Proceedings of the 11th International Conference on Fiber-Reinforced Polymer (FRP) Composites in Civil Engineering (CICE 2023), Rio de Janeiro, Brazil, July 23-26, 2023.
5. [Online]. Available: https://www.aljazeera.com/news/2024/2/5/a-year-on-from-turkeys-quake-disaster-the-trauma-haunts-survivors. Accessed: Oct 5, 2024.
6. UN OCHA (United Nations Office for the Coordination of Humanitarian Affairs), *Türkiye earthquake situation report*, [Online]. Available: www.unocha.org, Accessed: Oct 5, 2024.
7. TSDC, *Turkish earthquake design code*, Turkish Republic the Ministry of Public Works and Settlement. Ankara, Türkiye, 1975.
8. TSDC, *Turkish earthquake design code*, Turkish Republic the Ministry of Public Works and Settlement. Ankara, Türkiye, 2007.
9. TBEC, *Turkish building earthquake code*. General Directorate for Foundations, Ankara, Türkiye, 2018.
10. M. Raouffard, T. Asai, S. Tajiri, K. Sugimoto, K. Kusunoki, F. Dogan, U. Yazgan, U. Demir, and T. Cinar, "A detailed damage survey on reinforced concrete buildıngs in 2023 Turkiye earthquake," Proceedings of 18th World Conference on Earthquake Engineering, (WCEE 2024), Milano, Italy, 2024.
11. H. H. Aydogdu, C. Demir, T. Kahraman, and A. Ilki, "Evaluation of rapid seismic safety assessment methods on a substandard reinforced concrete building stock in Istanbul," *Structures*, vol. 56, p. 104962, 2023.
12. E. Cakti, E. Safak, U. Hancilar, and K. Sesetyan, "Updating probable earthquake loss estimates for Istanbul province," Technical Report prepared for Istanbul Metropolitan Municipality, 2019.
13. [Online]. Available: https://nip.tuik.gov.tr/?value=BinaIstatistikleri, Accessed: Nov 20, 2024.

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Integrating Dynamic Seismic Simulation in Architectural Design: A Parametric Approach for Tall Buildings with Outer Diagrids

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This paper presents a comprehensive computational workflow to generate, evaluate, and compare different outer diagrid designs for tall buildings, focusing on their structural efficiency under various load conditions, including seismic actions. Such diagrid systems not only enhance both structural resilience and architectural flexibility but also provide primary resistance to lateral loads, allowing for smaller internal core structures. Despite their advantages, widely used architectural design software, such as Grasshopper®, offer limited support for the seismic simulations essential for such complex structures. To address this limitation, a novel integration of the Alpaca4d plug-in, based on OpenSees software, is developed to facilitate seismic simulations for architects and engineers.

The methodology generates a diverse dataset of tall buildings by varying critical design parameters, including the geometries of the top and bottom floors, floor heights, and vertical transformations such as tapering or twisting. From over 61,200 theoretical combinations, the Latin hypercube sampling technique is adopted to select 1000 models to ensure a representative diversity. Each model is subject to cross-section optimisation based on Eurocode load combinations, incorporating both permanent and live loads according to code specifications. Dynamic analyses are then performed under seven ground motions selected from the PEER NGA-West2 database, to capture structural responses under realistic conditions.

The computational workflow generates key outputs, including inter-storey drifts, base reaction forces and moments, and acceleration distributions, recorded at critical nodes and elements to optimise data collection and computational efficiency. These outputs provide a detailed understanding of the seismic performance of each model and serve as the basis for

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further structural/materials optimization. By leveraging these results, the workflow will support in the future early decision-making in structural and architectural design, also in view of the progresses in the artificial intelligence field. Overall, this approach offers a streamlined and adaptable method for systematically evaluating and optimising the seismic design of tall buildings for architectural design.

Keywords: Computational design, Tall buildings, Architectural form generation, Seismic simulations, Design exploration, Early-stage design

Introduction

The successful design of tall buildings increasingly relies on integrating architectural creativity with structural functionality[1]. Early design decisions have a profound impact on resource utilization, financial outcomes, and the ultimate form and functionality of a building[2,3]. Performance-driven design approaches emphasize the need for collaboration between architects and engineers from the beginning, enabling innovative solutions that balance aesthetics, structural efficiency, and sustainability.

Tall buildings present unique design challenges due to their complex structural and functional requirements. Architects often prioritise visually striking forms, which may clash with structural efficiency and safety requirements. To address these conflicting priorities, early-stage collaboration between architects and engineers is essential to develop designs that harmonize architectural vision and structural performance. Traditional sequential design processes, where architects lead the design and engineers support structural requirements, often lead to inefficiencies and major deviations from the original concepts[4,5]. This highlights the need for integrated design workflows that align aesthetic and structural goals from the outset.

Design of tall buildings is a case that underscores the benefits of integrating architectural and structural considerations from the start. Unlike intuition-based design approaches, this method employs quantitative assessments to guide early design decisions. Metrics such as lateral displacement, total weight, and stiffness are essential for assessing the efficiency and feasibility of proposed designs. Structural stiffness, in particular, is a critical parameter in tall building design, as it directly influences lateral stability and material utilisation. The integration of such performance metrics within a multi-objective optimisation framework has facilitated a shift toward structurally-informed design philosophies, wherein structural requirements drive rather than constrain creative exploration[6].

Among the various structural systems developed for tall buildings, outer diagrid structures have gained significant attention due to their ability to harmonize architectural flexibility with structural efficiency[7]. The diagrid typology, characterized by an external skeleton composed of diagonal elements, is uniquely suited to resist horizontal forces such as seismic and wind loads. By doing so, it reduces or strategically complements internal core structures, such as shear walls, enabling lighter and more open architectural forms. Moreover, the geometric clarity of diagrid structures often contributes to their aesthetic appeal, blending strength with elegance[8].

The benefits of diagrid systems have been validated by experimental and analytical studies. Recent experimental tests on diagrid systems have underscored the suitability of this typology for tall buildings: studies have explored the failure probabilities under cyclic displacement-controlled loading that simulate seismic actions providing insights into stiffness reductions and other performance metrics[9]. Analytical research has further explored the relationship between lateral deformation and stiffness, particularly for polygonal plans with 3 to 12 sides connected by vertical diagrids. These findings highlight the effectiveness of diagrids in tall building design but also reveal a gap in existing methodologies[10].

Parametric architectural design, whether directed by human or powered by artificial intelligence, has emerged as a significant area of interest[11,12,13]. The goal is to exploit both the automated generation of diverse building forms and the integration of extensive outputs via artificial intelligence or optimisation tools[14,15,13]. This approach necessitates the streamlined production of extensive design databases to support the generation of innovative solutions[12,13,15]. Parametric tools further enhance collaboration by providing real-time feedback on structural performance, enabling iterative refinement of architectural concepts.

This research emphasizes the schematic (conceptual) design phase, recognizing its pivotal role in the overall design process. Choosing the optimal design option during this phase sets the foundation for subsequent development stages. The significance of initial design decisions is paramount, as they greatly influence the project's ultimate form, functionality, and financial feasibility. If not carefully considered, these decisions can lead to suboptimal outcomes[16]. Construction costs, which represent a substantial portion of the project budget, are profoundly affected by early design choices[17]; therefore, a proactive approach in the initial stages can yield substantial cost savings and more efficient structural solutions[18], including structural configurations, vertical transportation systems, and mechanical installations[19,20]. Moreover, proactive design reduces downstream engineering challenges, streamlining the transition from conceptual models to practical implementation.

The use of Computer-Aided Architectural Design (CAAD) technologies, particularly those utilizing data-driven and parametric methodologies, can significantly speed up the ability to explore and evaluate design alternatives at the outset. It allows designers to rapidly assess a diverse range of design solutions while addressing various aspects[19,21,22]. Advanced computational workflows enable simultaneous evaluation of structural, aesthetic, and environmental performance, fostering a more holistic approach to tall building design. By going beyond traditional constraints, designers can broaden their creative horizons perform more diverse, design exploration[23]. Therefore, the integration of CAAD methodologies significantly enhances rapid exploration and performance-driven form-finding strategies[19, 24].

Existing works have studied the effects of alternative architectural choices made in the early design phase, e.g. in terms of tall building geometry, on the seismic response through numerical simulation, including the generation and the enrichment of a database explored by artificial intelligence tools[14,15,24]. These studies were carried out by means of a simplified approach, i.e. exploiting a statically equivalent seismic loading and a limited option of architectural forms[25]. In contrast, a computational workflow is presented here to assess the seismic behaviour of tall buildings with outer diagrids, using spectrum-compatible real accelerograms extracted from the PEER NGA-West2 database in dynamic seismic simulation. This workflow improves existing methodologies by incorporating realistic ground motion data and enabling the systematic evaluation of diverse configurations under varying seismic conditions. The workflow allows for a variety of architectural forms, thereby broadening the design space available to designers.

To do this, we use Alpaca4d, a Grasshopper plugin built upon OpenSees. As an open-source and Python-based tool, Alpaca4d includes custom enhancements for performing time history simulations, making it particularly useful given the complexities associated with open finite element (FE) tools, which often lack user-friendly interfaces. This accessibility makes dynamic seismic simulation more

Table 1. List of software and plugins used in this study, including their descriptions, versions, and dates.

Software or Plugin name	Description	Version	Release Date
Rhinoceros®	A commercial 3D computer graphics and computer-aided design application used for modelling, rendering, and analysing complex shapes and surfaces.	7.37.24107.15001	16-04-2024
Grasshopper	A visual programming language and environment integrated with Rhinoceros, used for parametric design and algorithmic modelling.	Build 1.0.0007	16-04-2024
Alpaca4D	A Grasshopper plugin developed on top of OpenSees, enabling the analysis of beam, shell, and brick elements through static, modal, and ground motion analysis.	0.7.1	19-11-2024
Karamba	An interactive, parametric engineering tool within Grasshopper for finite element analysis on complex structures.	2.2.0.17	07-10-2022
Colibri	A plugin for Grasshopper that facilitates design space exploration and optimisation by managing and visualizing large sets of design alternatives.	2.2.0	30-11-2022
OpenSeesPy	A Python library for performing finite element analysis using the OpenSees framework, allowing for advanced simulations of structural and geotechnical systems.	3.5.0	11-05-2023

feasible for architects and engineers, facilitating the creation of a database of alternative architectural forms. Furthermore, this integration empowers designers to incorporate structural insights directly into the design process, bridging the gap between architectural vision and structural feasibility. All of the software (and plug-ins) used, including their descriptions, versions, and dates, are listed in Table 1.

The approach offers valuable insights into the structural performance of diverse architectural forms and provides a time-efficient alternative to conventional FE simulations, which are typically more labour-intensive for tall buildings in practice. This paper outlines the essential features of the workflow and its efficacy for early-stage design exploration. The goal is to help designers in an early-design phase pursue a multi-objective search for a “good” choice that integrates not only aesthetics, mechanical behaviour, and, in future developments, economic cost, but also sustainability[26]. Furthermore, the findings emphasize the importance of considering lateral load considerations, particularly seismic actions, into tall building designs. These results can be extended to include other research areas, such as wind load analysis, and fluid-structure interaction[27].

Methodology

The successful design of tall buildings relies on the seamless integration of architectural creativity and structural functionality, particularly when addressing the complex demands of seismic performance. To meet these challenges, this study presents a computational workflow designed to systematically explore diverse architectural and structural configurations. This workflow ensures that critical performance criteria are addressed from the earliest design stages, streamlining the evaluation and optimization of tall building designs. The following main steps outline the methodology, serving as a foundation for the detailed analyses presented in this work.

- Generation of the model geometry. This step includes: i) a Latin hypercube sampling (LHS) strategy[28-29] to define a manageable number of cases for the computational resources at hand; ii) usage of the design parametric tools to provide an architectural form, first as a solid model, next as a discretized set of nodes and elements; iii) pre-dimension phase to initialise the element cross-sections to the correct sizes. This step is described in Section "Definition of the tall building geometry", see below.
- Definition of the seismic loads according to suitable earthquake databases, as shown in "Definition of the dynamic loading", see below.
- Setting of required output variables according to architectural, structural, environmental, economic priorities. In this work, as shown in "Sampled response output", see below, the emphasis is on architectural and structural variables, but ongoing research is already considering also the other ones.
- Exploitation of the database. The output can be either inspected directly by generating some figures of merit according to (possibly weighted) quantities of interest, including artificial intelligence algorithms[14-15], or used to surrogate alternative architectural forms (ongoing research). This step is exemplified in "Exploitation of building database", see below.

Definition of the tall building geometry (parametric model)

The development of a parametric model for tall buildings is critical to integrate architectural and structural considerations into the seismic design. This section outlines the creation of a comprehensive database of tall building geometries, focusing on the outer diagrid structure. By leveraging parametric design tools, the study explores a wide range of architectural forms and their structural performance under seismic actions. The methodology incorporates key design parameters and employs advanced sampling and computational techniques, to ensure an efficient yet thorough exploration of the design space.

Overview of the parametric model

The goal is to develop a comprehensive database of tall buildings geometries with outer diagrids, evaluated under a range of seismic loading conditions to assess their structural performance and inform design optimisation. This database provides detailed structural performance metrics for a variety of loading conditions, focusing particularly on seismic responses.

This section elaborates on constructing a parametric model that enables the automatic generation of tall building models, including both architectural and structural components, using Grasshopper. Ten parameters were used to describe the architectural form of a tall building, based on geometric and architectural form choices; these variables are listed and detailed in Table 2, where also their names, descriptions, and value ranges are shown (Figure 3, Stage A). The choices made are summarised in the following.

- Top and bottom geometry and orientation. The geometry of the top plan is independent of the geometry of the bottom plan, and both are assumed to be polygons with a number of sides between 3 and 12. The top and bottom plans can be aligned along one of their corners or along one of their edges (Figure 3, Stage A.1).
- Number of stories and floor height. The building can have a number of floors between 40 and 60 with an increasing step of 4 floors in between. The distance h_{floor} between floors is set to be 3.5, 4.0 or 4.5m.
- Vertical transformation rule: tapering or twisting or curvilinear transition. These options control the form of the building along its vertical development, and some examples of the variety achieved by way of the morphing parameters are shown in Figure 1 (in the same picture, the relevant values of design parameters are also included). While tapering allows to connect the top and bottom plan via straight lines, twisting and curvilinear transformations modify the form via smooth curves. Additional details for the transformation rules here adopted can be found in[28] (Figure 3, Stage A.2).

Parametric model generation and sampling strategy

The theoretical design space includes 61,200 combinations, offering a diverse range of architectural forms. This number is computed by multiplying the number of possible values for each design variable. For instance, the design variable n_{top} has 10 possible values, and similarly, n_{bot} also has 10 possible values. To effectively exploit available computational resources and manage complexity, 1000 models were chosen in the design space according to a LHS rule, a technique derived from the concept of a 'Latin square' in combinatorial mathematics. A Latin square is an $n \times n$ matrix populated with n distinct elements , such that each element appears exactly once in each row and column[30]. More importantly, this method ensures diversity without bias in the dataset, particularly avoiding an overrepresentation

Table 2. Design variables and description for the parametric model of tall buildings.

Design Variable	Symbol	Description	Ranges
Edge count of top plan geometry	n_{top}	Number of edges in the top plan geometry	[3,4,...,12]
Edge count of bottom plan geometry	n_{bot}	Number of edges in the bottom plan geometry	[3,4,...,12]
Orientation of top and bottom plans	θ_{rel}	Relative positioning of top and bottom plans (corner to corner =0, corner to edge =1)	[0,1]
Total floor count	n_{floor}	Total number of floors in the structure	[40,44,48,...,60]
Floor-to-floor height	h_{floor}	Height between consecutive floors (meters)	[3.5,4,4.5]
Method of vertical transformation	t_{vert}	Method of connecting top and bottom plans (tapered/twisted/curvilinear)	[0,1,2]
Tapering intensity	i_{taper}	Area scale factor of top plan compared to bottom plan	[50%,60%,...,90%, 100%]
Twisting intensity	i_{twist}	Rotation angle of the top plan (degrees)	[30,45,60,75,90]
Position parameter for curvilinear control floor	p_{curv}	Position parameter for curvilinearity	[0.25,0.5,0.75]
Intensity parameter for curvilinear control floor	i_{curv}	Intensity parameter for curvilinearity	[0.85,1.15]

of extremes in buildings highs or discrepancies in the number of edges between top/bottom plans. Each individual tall building model generation in Grasshopper requires approximately 1 minute on average, while each FE simulation takes around 30 minutes on a regular workstation, depending on the number of floors. Furthermore, the storage requirement for each FE simulation is approximately 1.2 GB. Although in this work the use of a Linux cluster and parallelization have significantly reduced the computational time, it is still infeasible to generate and simulate all 61,200 models in the design space due to the extensive time and storage demands. Therefore, the aforementioned sampling technique has been employed to select 1000 representative samples that adequately capture the characteristics of the entire design space.

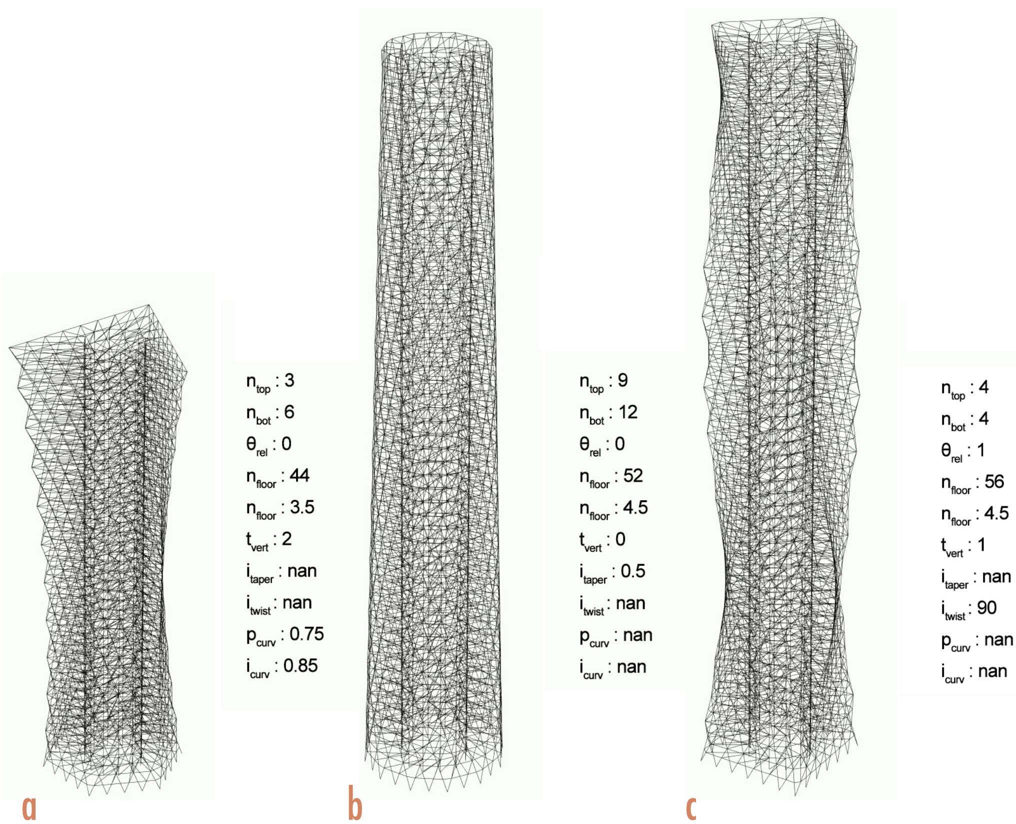

Figure 1. Examples of tall building models with different vertical transformations: (a) curvilinear, (b) tapered, and (c) twisted forms.

Diagrid integration and structural features

Once the architectural models are generated, the diagrid pattern is mapped onto the building façade by dividing the perimeter of all floor plans (Figure 3, Stage B.1). This process generates a grid of points, and polylines are then created to connect selected nodes following a specific pattern, forming the diagrid structure. Each diagrid module spans four floors. The structural components of an exemplary tall building model are highlighted in Figure 2. This figure depicts the diagrid diagonals, horizontal members, core columns, beams, bracing, and radial floor beams.

The workflow related to the model generation is detailed in Figure 3: the flowchart outlines several steps utilizing a combination of software tools. The procedure begins with a graphical parametric design script implemented in Grasshopper; which employs simulation plug-ins such as Colibri and Alpaca4d[29]. The former plug-in has been used to produce, for every case, the architectural and structural model files, a file collecting the seismic data useful for post-processing, an image of the building model with its generative information stored in a CSV file. The latter plug-in has been enhanced to support dynamic simulations by introducing features such as uniform excitation at the basement of the structure along the horizontal direction, representing a prescribed earthquake.

Efficient workflow management is crucial, especially considering the need to leverage high-performance computing capabilities. While workflow management should be independent of the software choice, the Python version of OpenSees facilitates easy integration with Grasshopper, enabling efficient automation of

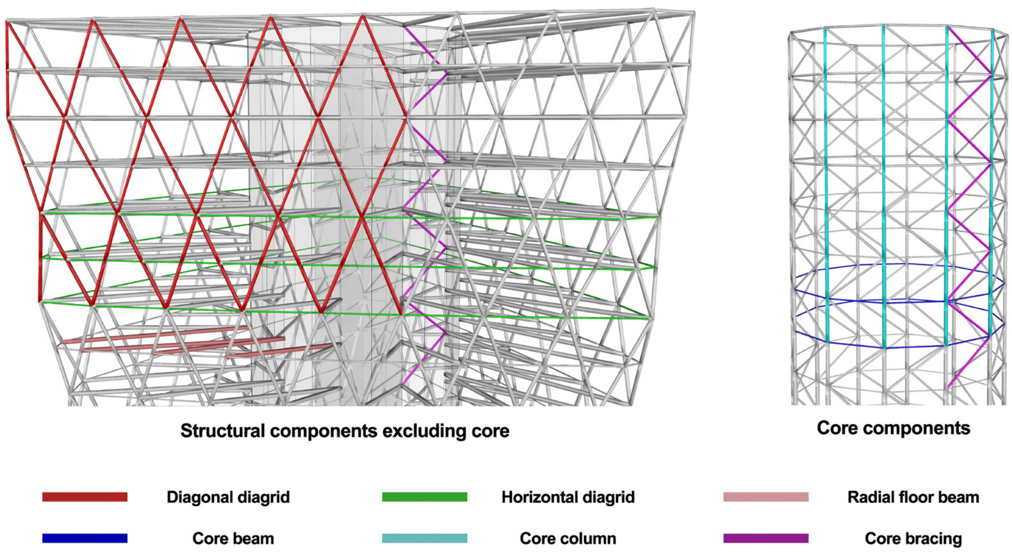

Figure 2. Design variables and description for the parametric model of tall buildings.

FE simulation files. Additionally, it supports parallelization of simulations on Linux clusters, further enhancing automation and computational efficiency. Therefore, OpenSeesPy, a Python-based scripting language designed to operate OpenSees—a well-known earthquake engineering software[31]—has been selected as the programming standard. OpenSeesPy excels in its robustness and offers flexibility for future expansion to nonlinear material behaviour or alternative analysis methods, such as modal analysis. Below is a summary of the file organisation approach:

- folders, labelled 1 to 1000 containing a Python script for Linux cluster execution, have been created (Figure 3, Stages D and E);
- four CSV files useful for the post-processing phase are included in each folder;
- an image file containing a picture of each model (1 to 1000) is also generated;
- another CSV file containing the list of the design variables corresponding to each model together with additional information inferable from the geometry only has been also produced.

Moreover, the buildings present a core connected through radial beams to the outer diagrids: the ratio between the core and the floor areas varies with height, ranging from just under 20% at lower levels to just over 20% at higher levels. All structural elements are assumed to be made of construction steel, while the floor slabs are modelled through rigid diaphragms.

The dynamic seismic simulation starts with a pre-dimensioning phase where static loads are applied as distributed loads on the beams of each floor. These include the dead weight of structural elements and other floor-specific loads like permanent or live loads for the office function, ranging from 7.5 kN/m^2 to 14.5 kN/m^2 for dead loads and assumed 2.5 kN/m^2 for live loads, without reduction in height. Eurocode load combinations are considered for this phase, incorporating a simplified seismic action with a statically equivalent method detailed in the reference[14].

This phase employs a cross-section optimiser from the Karamba, plug-in within Grasshopper, utilizing a database of over 2000 sections that vary every four floors. The optimizer aims to find the best solution by limiting horizontal displacement to h/500 of the building height and maintaining a utilisation factor of 95%, which represents the ratio between the maximum computed stress and the design stress in the structural members (Figure 3, Stage B.2).

This detailed procedure facilitates the creation of more realistic tubular sections for the outer diagrids, core columns, bracing, and both horizontal and radial beams, serving as a starting point for the construction of the building database that will undergo subsequent dynamic seismic simulation. Figure 4 illustrates a sample tall building model featuring dimensioned tubular sections for the outer diagrids. It clearly identifies different floor groups, denoted by colour gradients that indicates the diameter of the cross sections: blue signifies smaller diameters, red indicates larger diameters, and green represents values in between. A total

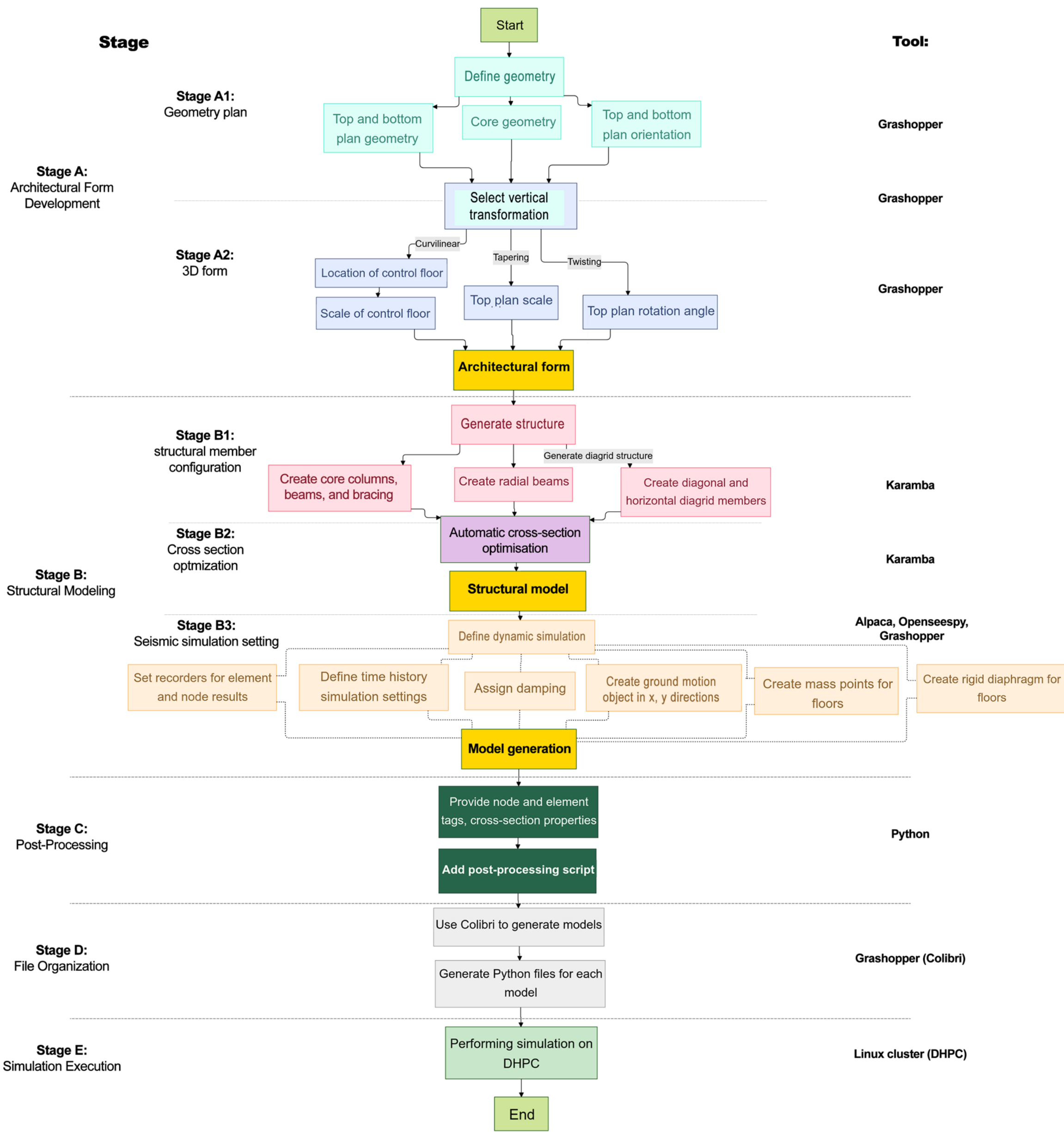

Figure 3. Detailed workflow for the generation of the building database.

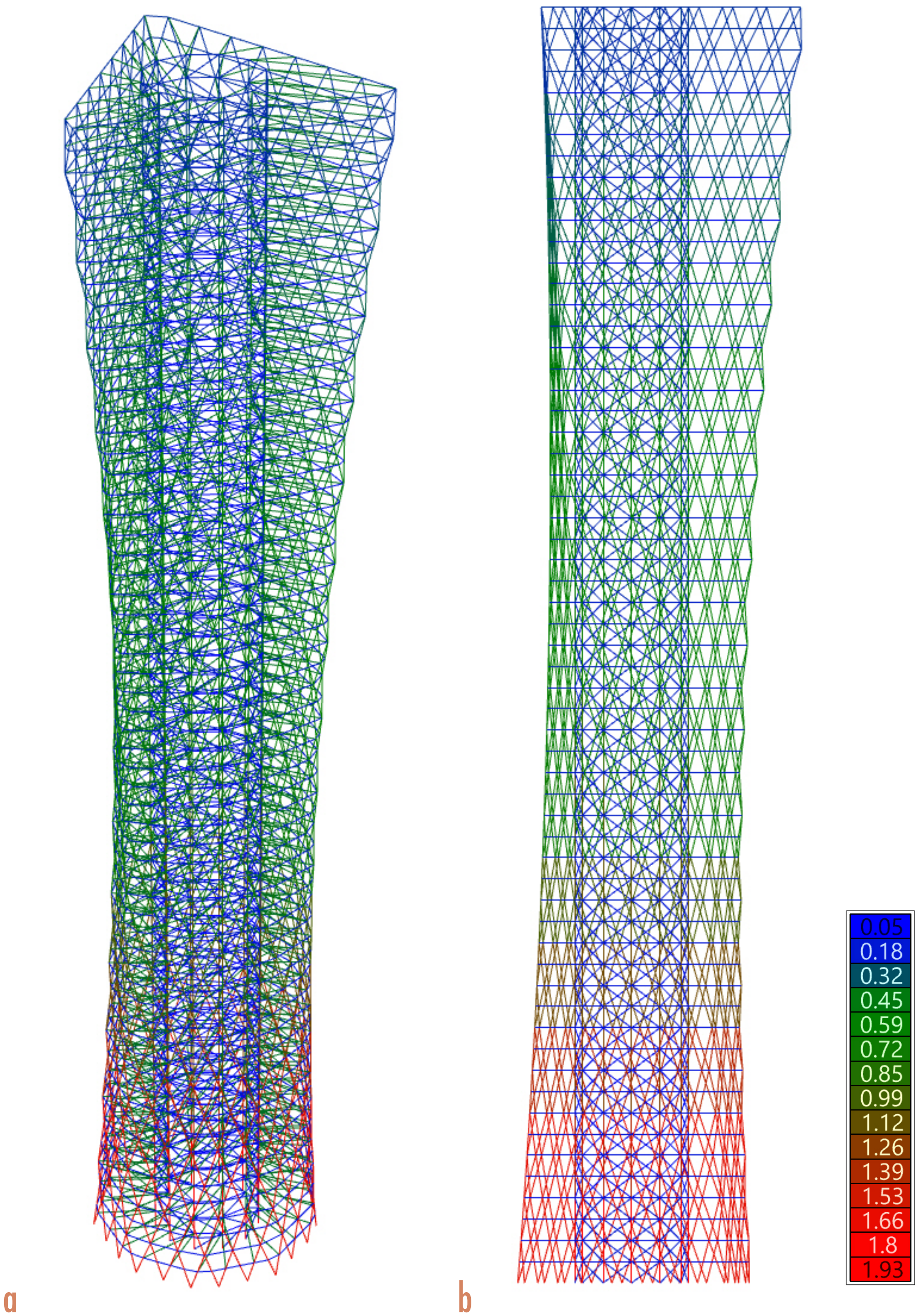

Figure 4. Example of a tall building subjected to the automated cross-section optimisation; (a) perspective, and (b) side view. The legend shows the diameter of the tubular cross section in meters.

of 65 unique cross-sections have been assigned throughout the model, ensuring an optimised distribution of material and structural efficiency tailored to the load-bearing requirements of the building.

Definition of the dynamic loading

The PEER NGA-West2 seismic database[32] has been selected to define seven different ground motions. At variance with other commonly used seismic databases, which are typically limited to periods of 4 s, it considers design spectra based on periods of up to 10 s, which are necessary to correctly define seismic inputs for tall buildings which tend to have fundamental vibration periods higher than common buildings or infrastructure (Figure 3, Stage B.3).

To ensure meaningful comparison between alternative architectural forms, the selection of seismic events has primarily focused on moderate earthquakes. Should the inclusion of more severe earthquakes be necessary due to the geo-location of the building site, the results must be interpreted with caution, as they may necessitate accounting for nonlinear constitutive behaviours in the analyses.

Figure 5 displays the seven selected motions relative to the design spectrum. A critical aspect of the seismic simulation for tall buildings in OpenSees is the integration of ground motion data into the analysis workflow. Thus, a uniform excitation at all nodes restrained to the ground, both in X- and Y-directions, has been added as a parametric design capability in Alpaca4d. For the sake of simplicity and assuming moderate excitations, the Z-vertical excitation has not been considered in this work, but it can easily be included in a future development. For the transient analysis, a Rayleigh damping with a 5% damping ratio is adopted in relation to the fundamental modes, adhering to the methodology outlined in [33]. In this study, the first ten vibration modes of each tall building model are identified and documented in a separate file. These fundamental modes include the expected cantilever-like behaviour dominated by bending along the height of the building, purely torsional modes, and also coupled bending torsional modes.

Sampled response output

Collecting data for all nodes and elements at every time step is both impractical and computationally intensive. Therefore, strategic decisions are required before initiating the analyses to determine which nodes and elements are critical for capturing the required output, and what data should be recorded during the transient analysis. In this study, OpenSeesPy's output commands are utilized as tools to store specific response data of interest, such as displacements, accelerations, and forces, during the simulation. The utilization of structural members, defined as the ratio of computed stress or force to design capacity, is calculated for key elements like diagrids, core columns, and bracing. This aids in

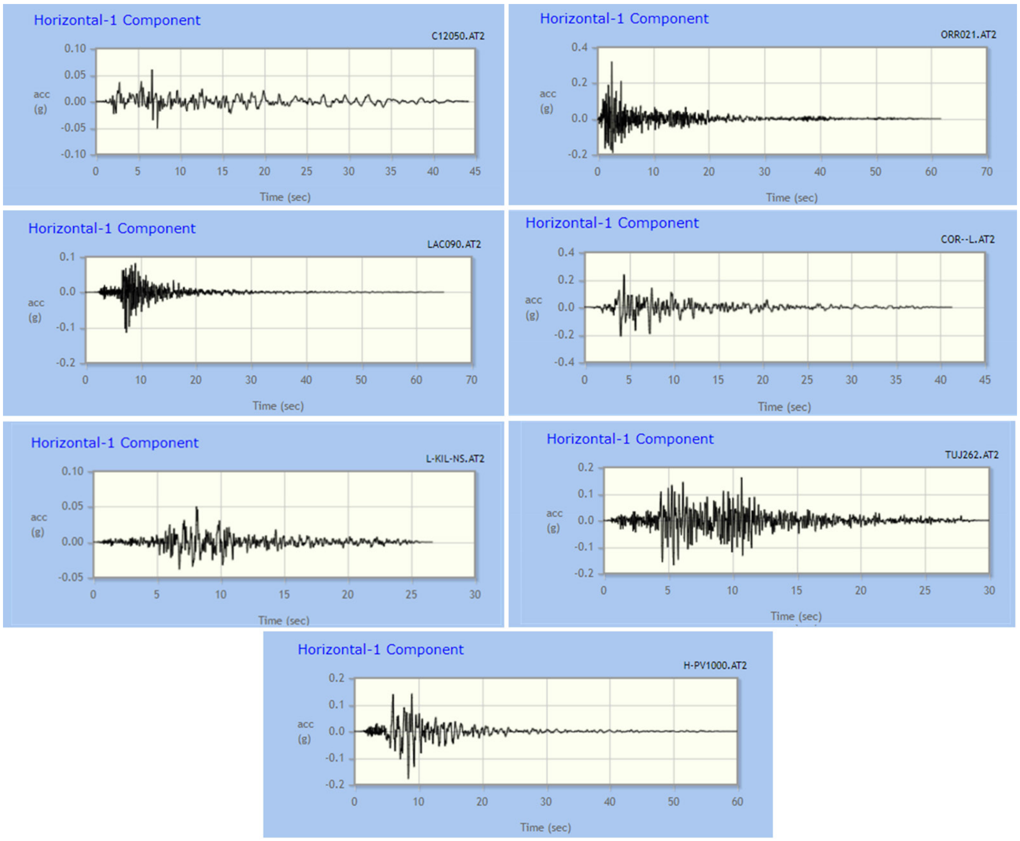

Figure 5. Selected ground motions (unscaled) used in dynamic seismic simulations.

identifying overstressed or underutilized components, optimizing cross-sections, and enhancing design efficiency during post-processing, while providing insights into load distribution for early-stage optimization.

The total number of nodes present in each model depends significantly on the building's design variables, particularly the number of stories, which ranges from 40 to 60. While a typical model with 50 floors has around 10,000 nodes, this number varies, increasing for taller buildings and decreasing for shorter ones. For instance, a model with 40 floors may have approximately 8000 nodes, while a model with 60 floors may exceed 12,000 nodes. This variability reflects the parametric nature of the models and the range of design configurations considered.

Out of this total amount, the following nodes are deemed relevant for characterizing the earthquake response: the core and outer diagrid restrained nodes, the centroid node at each floor, and the corner nodes at each floor. These nodes have been selected based on their ability to represent the dynamic behaviour of the building effectively, while minimizing computational effort. The core and outer diagrid restrained nodes are critical for capturing the structural behaviour at the building supports, where maximum reaction forces and moments occur due to seismic excitation. The centroid nodes at each floor reliably represent the average translational displacement and acceleration for the entire floor, aiding in the computation of inter-storey drift and other floor-specific metrics. The corner nodes at each floor, chosen for their maximum distance from one another, ensure the dynamic response is captured across the full extent of the floor, accounting for potential torsional effects and lateral deformations that may vary across the floor geometry.

The selection of these nodes was validated through empirical testing on a sample tall building model. This process involved conducting preliminary simulations on a single tall building with a representative design configuration (e.g. 50 floors, curvilinear transformation, and mid-range tapering). During these tests, the dynamic response was recorded for all nodes and compared against the results obtained from the reduced set of selected nodes. The comparison showed minimal discrepancies (within 5%) for key structural metrics such as inter-storey drift, floor acceleration, and reaction forces, confirming the efficacy of the node selection approach.

The data recorded for these selected nodes include the three components of the translational displacements plus three components of the translational acceleration for each time step. Reaction forces (including moments) are also added for the restrained nodes at the base of the building. Other quantities of interest, such as the inter-storey drift, are computed during the post-processing phase based on these recorded outputs (Figure 3, Stage C).

For the structural elements, a similar selection process balances meaningfulness and computational effort. The core support columns, bracing elements, diagrid diagonal elements at the supports, and diagrid diagonal and horizontal members corresponding to the corner nodes are included in the output files. To capture the full structural response, OpenSeesPy's output commands are used to store data at each end of the selected elements. Specifically, by assuming x as the axis of the beam element, the following response data are recorded: the axial force N; the two components of the shear force Vy and Vz; three components of the moment (two components, My and Mz, for the bending moment and one component Mx for the torque). All the variables are computed and stored in correspondence of each end of the considered element.

Structural analysis via high performance computing

The analysis duration is set to 30 s for all cases, with a time step of 10 ms set for writing the output variables. Both duration and time step are aimed at limiting the computational burden and are deemed suitable given the D5-95 duration of all ground motions used, which is always below this limit. The time step number is therefore set to 3000, and an implicit Newmark time integration method has been adopted. The UmfPack solver, known for its efficiency in factorizing large, sparse matrices, is employed to enhance computational speed and accuracy in handling the complex structural systems modelled in this study.

Each of the 1000 models defined in the pre-processing must be subjected to the seven ground motions obtained from the PEER NGA-West2 seismic database, amounting to a total of 7000 three-dimensional analyses. For this task, the Delft Blue supercomputer was utilized, featuring 218 computing nodes each with 48 cores 2 x Intel Xeon E5-6248R and 192 GB RAM (out of 338 total cores with alternative hardware architecture). The computations were executed on CPU cores using a job array organisation of the scheduler.

Following the solver phase, a post-processing phase is conducted on the same cluster, using Python libraries such as VFO and Opsvis to facilitate visualisation of node and element recorders. This step has been necessary for navigating the extensive data collected and involves a strategic organisation of file names, locations and other properties, automated through Python scripts and GhPython components within Grasshopper.

In the post-processing phase, inter-storey drift, normal and shear stresses, von Mises stresses, total base shear forces, and bending moments were computed for each building model and stored in designated folders.

Exploitation of the building database

Several analyses can be conducted using the resulting database. Here, to pinpoint the models of interest for designers, a specific ground motion is assumed, and models are assessed based on their performance in this context. Further investigations incorporating artificial intelligence tools to analyse the database are in progress, including proper consideration of a larger suite of earthquakes, see e.g. [28]. Models with the lowest response values for specific structural metrics are summarized in Table 3. Furthermore, all selected models are visually depicted in Figure 6, allowing a comparative analysis of their unique geometric and structural characteristics.

Model #63 (Figure 6a) outperforms others with the smallest average normalised response, achieving the best index value (0 for the best and 1 for the worst) determined by aggregating the relative positions across all considered responses. This model presents a curvilinear design with the minimum number of floors (40) and a floor-to-floor height of 3.5m, featuring a six-sided polygon at the top plan and a three-sided polygon at the bottom plan. Model #115 (Figure 6b), in contrast, demonstrates the best torsional response but with a relatively low absolute value: it is a tapered model without a change in plan area between the top and bottom, maintaining equal area at both ends. Model #302 (Figure 6c) achieves the lowest overall acceleration and is also a curvilinear model. In this way, each model listed in the table represents the best-performing design in terms of a specific seismic response. While in some cases, such as the mentioned model #63 above, the outcome confirms the designers' intuition, in other cases, such as for model #531 (Figure 6d), which has the lowest von Mises stress in the observed elements, the output leads to unexpected results. Model #531 is a building with a significant height and an interesting curvilinear form, but, evidently, it also features a well-distributed diagrid system, efficiently distributing the workload among each member. Model #725 (Figure 6f) presents the lowest mass/weight, only 6290 tons, and it is very regular, but its (relatively) low height is comparable with other cases, such as #63 or #641 (Figure 6e); so, also this case shows that the automated procedure can offer interesting insights to designers.

Table 3. Features and response values for the top-performing models among a total of 1000 considered tall building models.

Model ID	Minimized response	Overall max acceleration (m/s^2)	Overall max drift (mm)	Overall max von Mises stress (MPa)	Overall max torque (N·m)	Total max base shear force (kN)	Total mass of steel (ton)	Average normalised response
63	Average normalised response	2.219	1.670	141.55	0.000028	826,420	12,400	0.153
115	Overall max torque	2.271	1.730	108.11	0.000022	1,326,200	24,100	0.236
302	Overall max acceleration	1.528	2.357	161.45	0.000144	2,128,200	44,300	0.438
531	Overall max von Mises stress	1.570	2.310	78.80	0.000114	1,123,900	27,100	0.235
641	Overall max drift	2.339	1.571	152.62	0.000042	971,570	13,500	0.188
725	Total mass of steel	2.937	3.120	120.75	0.000113	656,000	6290	0.360
841	Total max base shear force	2.847	2.946	123.54	0.000180	623,850	9830	0.380

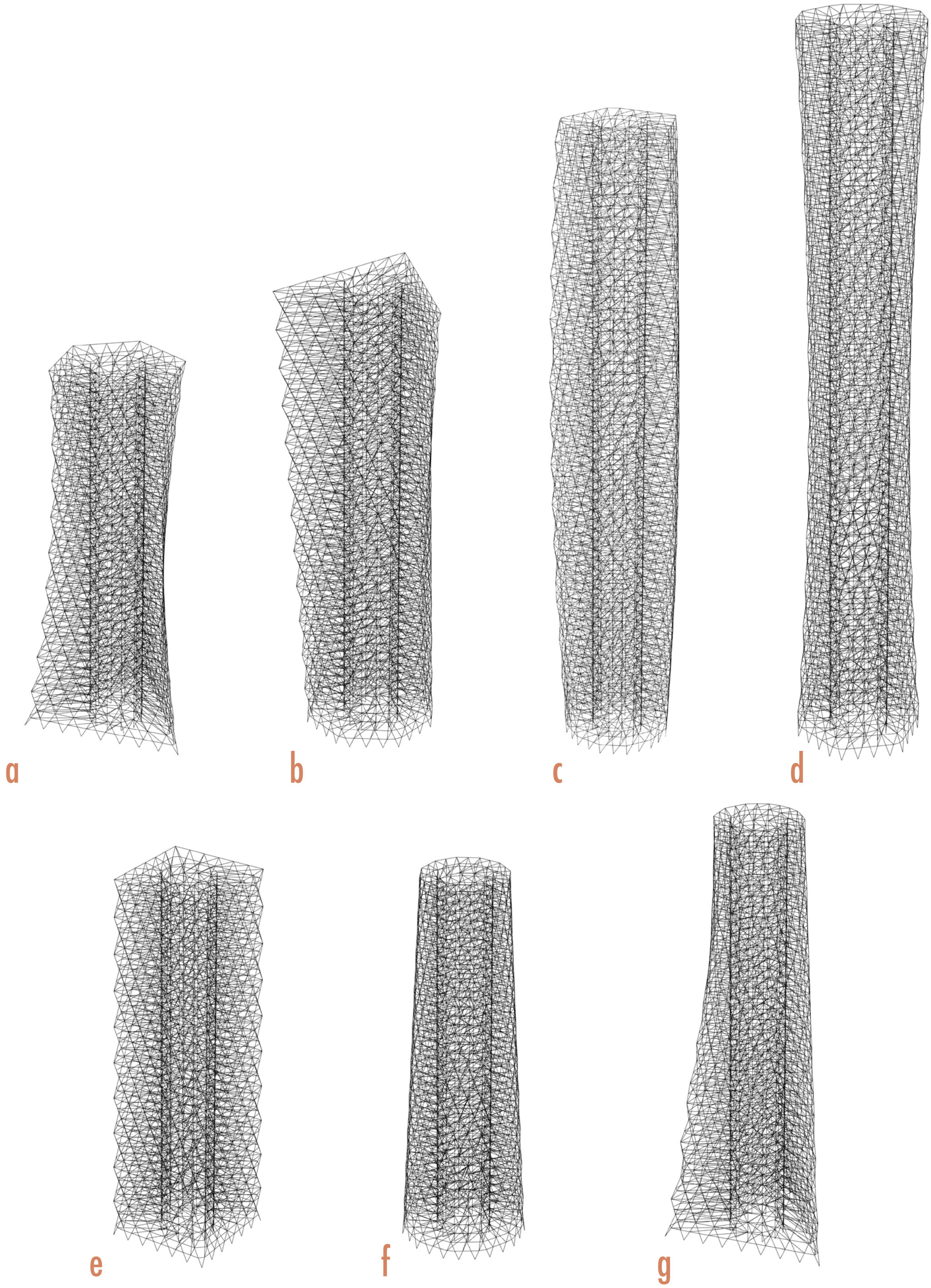

Figure 6. Visualisation of the best performing models, displaying the minimum value for specific responses outlined in Table 2: (a) model 63, (b) model 115, (c) model 302, (d) model 531, (e) model 641, (f) model 725, and (g) model 841.

Model #841 (Figure 6g) exhibits the lowest base shear force due to its minimum number of floors and tapered form, with a maximum of tapering amount of 50%. Model #725 demonstrates a comparable base shear force, featuring the same number of floors (40) and tapering; however, its top and bottom plan geometries differ from those of Model #841. Additionally, it is important to note that Model #63 also comprises 40 stories, but since it is not tapered, its base shear force is greater than that of the two aforementioned models.

Conclusion

A computational workflow has been developed to assist designers in the early stages of designing tall buildings with outer diagrid structures. This method facilitates the exploration of diverse architectural forms by providing a parametric design platform that allows systematic variation of key geometric parameters such as: number of polygonal sides for the top and bottom floors; inter-storey heights; total number of stories; vertical transformations (tapering, twisting, or curvilinear adjustments) throughout the height of the building. By defining these parameters as inputs within the parametric model, a broad spectrum of building forms can be automatically generated and analysed, offering an intuitive approach for evaluating design alternatives.

An automated process has been created to generate simulation files utilizing Grasshopper and Python, with enhancements in the Alpaca4D plug-in built on OpenSees software. This enables dynamic seismic simulations of tall buildings with outer diagrids. This workflow includes both pre- and post-processing stages, that allow raw simulation data, such as node and element outputs, to be transformed into meaningful structural indices such as inter-storey drift, base shear, and other critical metrics.

For this study, 1000 simulation files, each representing a unique building configuration, have been generated and run across seven different ground motion records, resulting in 7000 simulations. To efficiently handle this computational demand, the analyses were run on the Delft Blue Linux high-performance cluster, allowing parallel processing, and storage of all time-history results.

One of the primary motivations for building this database is its potential for training surrogate models, which could provide a rapid and computationally efficient alternative to detailed finite element simulations. This capability highlights the database value as a foundational resource for machine learning applications in architectural and structural design. Such a surrogate model, incorporating structural, economic, and environmental response parameters, can facilitate informed decision-making in the early design stages of tall buildings. Additionally, the database offers an opportunity for interactive visualization, enabling designers to explore design options dynamically and intuitively. This feature can represent an exciting direction for future development as it allows users to examine how design variations impact structural performance metrics, providing a more user-friendly and iterative approach to design exploration. Moreover, while the issue is not discussed here, the database could also be augmented a posteriori through several techniques[15,25]. However, it should be noted that the surrogate model cannot extend its predictions outside the parameter design space with which it was built, and therefore the choice of parameters cannot be underestimated.

As this research integrates 91 diverse response variables, including structural, economic and environmental factors, the resulting surrogate model provides a foundation for improving decision-making during the conceptual design stage. Future research could also prioritize the development of interactive visualization systems that allow the database to be leveraged as a design exploration tool, promoting a more hands-on approach to optimizing tall building designs. Furthermore, future work could extend this database with additional design features and responses while incorporating generative AI algorithms to identify high-performing designs within the parameter space. These algorithms can enable automated design generation and optimisation, significantly enhancing the exploration of innovative structural and architectural configurations.

Author Contributions

Original concept and methodology, original draft: P.K., A.G.; software and investigation—: P.K.; computational resources: C.A., M.T. Writing and editing: all authors. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Ethics Committee Approval

This work does not require an ethics committee approval.

Conflict of Interest

The authors declare no conflicts of interest.

Ethical Compliance: All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Data Access Statement: Research data supporting this publication are available from the corresponding author.

References

1. C. M. Herr, "Creativity in cross-disciplinary collaborations between architects and structural engineers in China," Proceedings of IASS Annual Symposia, vol. 2018, no. 4, pp. 1-8, International Association for Shell and Spatial Structures (IASS), July 2018.
2. R. Hyde, "Computer-aided architectural design and the design process," *Architectural Science Review*, vol. 59, no. 4, pp. 255-256, July 2016, doi: 10.1080/00038628.2016.1194516.
3. H. Sun, H. V. Burton, and H. Huang, "Machine learning applications for building structural design and performance assessment: State-of-the-art review," *Journal of Building Engineering*, vol. 33, p. 101816, 2021, doi: 10.1016/j.jobe.2020.101816.
4. M. Elnimeiri and B. S. Taranath, Tall Buildings and Urban Habitat, Council on Tall Buildings and Urban Habitat (CTBUH), 2012.
5. B. S. Taranath, *Tall building design: Steel, concrete, and composite systems*, CRC Press, 2016, doi: 10.1201/9781315374468
6. L. L. Beghini, A. Beghini, N. Katz, W. F. Baker, and G. H. Paulino, "Connecting architecture and engineering through structural topology optimization," *Engineering Structures*, vol. 59, pp. 716-726, 2014, doi: 10.1016/j.engstruct.2013.10.032.
7. K. S. Moon, "Sustainable structural engineering strategies for tall buildings," *The Structural Design of Tall and Special Buildings*, vol. 17, no. 5, pp. 895-914, 2008, doi: 10.1002/tal.475.
8. M. Ali and K. Moon, "Advances in structural systems for tall buildings: Emerging developments for contemporary urban giants," *Buildings*, vol. 8, no. 8, pp. 104, 2018, doi: 10.3390/buildings8080104.
9. C. Liu et al., "Study on flexural stiffness of diagrid non-stiffened node based on four-spring assemblage model," *Engineering Structures*, vol. 198, p. 109500, 2019, doi: 10.1016/j. engstruct.2019.109500.
10. D. Fang and C. Liu, "Mechanical characteristics and deformation calculation of steel diagrid structures in high-rise buildings," *Journal of Building Engineering*, vol. 42, p. 103062, 2021, doi: 10.1016/j.jobe.2021.103062.
11. C. Preisinger, "Linking Structure and Parametric Geometry," *Architectural Design*, vol. 83, 2013, doi: 10.1002/ad.1564.
12. L.M. Mueller et al., "Data and Parameterization Requirements for 3D Generative Deep Learning Models," Proceedings of 42nd eCAADe Conference, Nicosia, Cyprus, 9-13 September, pp. 615-624, 2024.
13. M. Turrin et al., "Design explorations of performance driven geometry in architectural design using parametric modeling and genetic algorithms," *Advanced Engineering Informatics*, vol. 25, no. 4, pp. 656–675, 2011, doi: 10.1016/j.aei.2011.07.009.

14. P. Kazemi et al., “Classification of the structural behavior of tall buildings with a diagrid structure: A machine learning-based approach,” *Algorithms*, vol. 15, no. 10, p. 349, 2022, doi: 10.3390/a15100349.
15. P. Kazemi et al., “Machine learning techniques for diagrid building design: Architectural-structural correlations with feature selection and data augmentation,” *Journal of Building Engineering*, vol. 86, p. 108766, 2024, doi: 10.1016/j.jobe.2024.108766.
16. H. Zheng, V. Moosavi, and M. Akbarzadeh, “Machine learning assisted evaluations in structural design and construction,” *Automation in Construction*, vol. 119, p. 103346, 2020, doi: 10.1016/j.autcon.2020.103346.
17. N. Brown and C. Mueller, “Early-stage integration of architectural and structural performance in a parametric multi-objective design tool,” 3rd Annual Conference on Structures and Architecture, Guimarães, Portugal, 27-29 July 2016.
18. A. S. Ramdasi and S. N. Tande, “Lateral load analysis of high rise structures,” *International Journal of Engineering Science and Technology*, vol. 6, no. 6, pp. 268, June 2014.
19. Z. Yu, H. Dai, and Z. Shi, “Structural form-finding of bending components in buildings by using parametric tools and principal stress lines,” *Frontiers of Architectural Research*, vol. 10, pp. 1-11, 2021. doi: 10.1016/j.foar.2021.11.004.
20. N. C. Brown and C. T. Mueller, “Design variable analysis and generation for performance-based parametric modeling in architecture,” *International Journal of Architectural Computing*, vol. 17, no. 1, pp. 36-52, Mar. 2019. doi: 10.1177/1478077118799491.
21. A. Bidgoli and P. Veloso, “DeepCloud. The application of a data-driven, generative model in design,” ACADIA // 2018: Recalibration. On imprecision and infidelity. Proceedings of the 38th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA), Mexico City, Mexico, 18-20 Oct. 2018, pp. 176–185, doi: 10.52842/conf.acadia.2018.176.
22. S. B. Abdalla, M. Rashid, and D. R. Ara, “Plausibility of CAAD in conceptual design: Challenges in architectural engineering for early-stage digital design tools,” *Journal of Architectural Engineering*, vol. 27, no. 2, pp. 04021004, Jun. 2021. doi: 10.1061/(ASCE)AE.1943-5568.0000457.
23. K. Saldana Ochoa, P. O. Ohlbrock, P. D’Acunto, and V. Moosavi, “Beyond typologies, beyond optimization: Exploring novel structural forms at the interface of human and machine intelligence,” *International Journal of Architectural Computing*, vol. 19, no. 3, pp. 466-490, 2021, doi: 10.1177/1478077120943062.
24. B. Ekici, Z. T. Kazanasmaz, M. Turrin, M. F. Tasgetiren, and I. S. Sariyildiz, “Multi-zone optimisation of high-rise buildings using artificial intelligence for

sustainable metropolises. Part 1: Background, methodology, setup, and machine learning results," *Solar Energy*, vol. 224, pp. 373-389, 2021, doi: 10.1016/j.solener.2021.05.083.

25. P. Kazemi et al., "Artificial intelligence-powered computational strategies in selecting and augmenting data for early design of tall buildings with outer diagrids," *Buildings*, vol. 14, no. 4, p. 1118, 2024, doi: 10.3390/buildings14041118.
26. D. Fang et al., "Reducing embodied carbon in structural systems: A review of early-stage design strategies," *Journal of Building Engineering*, vol. 76, p. 107054, 2023, doi: 10.1016/j.jobe.2023.107054.
27. E. Estrado et al., "Optimization of complex-geometry high-rise buildings based on wind load analysis," *Simulation*, vol. 99, no. 11, pp. 1133-1146, 2023, doi: 10.1177/00375497221109577.
28. P. Kazemi et al., "Deep learning approach to structural performance prediction of tall buildings in seismic areas," Proceedings of the IASS 2024 Symposium Redefining the Art of Structural Design, August 26-30, Zurich, Switzerland, 2024.
29. "Alpaca4d - OpenSees wrapper for Grasshopper," [Online]. Available: https://alpaca4d.gitbook.io/docs, Accessed: Oct 30, 2024.
30. R. Sheikholeslami and S. Razavi, "Progressive latin hypercube sampling: An efficient approach for robust sampling-based analysis of environmental models," *Environmental Modelling & Software*, vol. 93, pp. 109-126, 2017, doi: 10.1016/j.envsoft.2017.03.010.
31. F. McKenna et al., "Nonlinear finite-element analysis software architecture using object composition," *Journal of Computing in Civil Engineering*, vol. 24, pp. 95–107, 2010, doi: 10.1061/(ASCE)CP.1943-5487.0000002.
32. E. Seyhan et al., "NGA-West2 site database," *Earthquake Spectra*, vol. 30, no. 3, pp. 1007-1024, 2014, doi: 10.1193/062913EQS180M.
33. J. Hall, "Problems encountered from the use (or misuse) of Rayleigh damping," *Earthquake Engineering & Structural Dynamics*, vol. 35, pp. 525-545, 2006, doi:10.1002/eqe.541.

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Part III

CORE 2023 Student Projects

Computation for Earthquake Resilience and Recovery

Introduction

This part of the book features a selection of student projects developed during the CORE Studio: Computation for Earthquake Resilience and Recovery. The CORE Studio was taught at the Building Technology MSc program at the Faculty of Architecture and the Built Environment at Delft University of Technology between 2022 and 2025. These projects were created in the Fall 2023–2024 semester, and they represent a culmination of ten weeks of full-time work focused on applying computational thinking and programming to seismic resilience challenges in the built environment.

The CORE Studio - “COmputational REpertoire for Architectural Design and Engineering” - was designed as an educational program to integrate computational skills into architectural design and engineering processes. It introduced students to algorithmic thinking, visual and text-based programming (primarily through Grasshopper and Python), machine learning, and the application of these methods in context-specific design challenges. The studio focused specifically on leveraging computation as both a specialist skill and a transversal interdisciplinary competence.

The projects included here cover a broad range of topics, from risk assessment of structures and site-specific hazard modeling to emergency shelter design, decision-support tools, and satellite-based disaster evaluation. Each group approached their topic through data-driven methods and developed custom computational tools or workflows to support their design goals.

It is important to note that these are student projects developed in an academic setting, primarily targeting specific learning objectives. While they demonstrate strong initiative, creativity, and technical effort, the outputs may not be accurate in all details or ready for real-world deployment. The students voluntarily contributed to preparing the project materials for inclusion in this publication, and their work reflects both their personal interest and commitment to exploring the role of computation in addressing complex challenges related to seismic resilience.

These ten projects illustrate how interdisciplinary education in computation can empower future professionals to think critically and respond creatively to emerging challenges in the built environment.

Large Scale Risk Assement of Hydraulic Structures in Earthquake-Prone Regions

Bryan Zwakkenberg, Daan Weerdesteijn, Bob Post

The earthquakes that struck Turkey on February 6, 2023 caused widespread damage - not only to buildings but also infrastructure, including dams. In at least one occasion, cracks appeared in a dam, prompting the controlled release of the stored water. While dams are built to withstand earthquakes, their age and the increasing magnitude of earthquakes might cause a dam to fail. Therefore, this research aims to flag potentially dangerous dams through computational calculations based on recent structural codes, and support preparedness by generating a flood map in the event of a dam failure, enabling stakeholders to take preventive measures.

To achieve this, the project is divided into three phases: (i) the first phase combines geographic (e.g. dam locations and tectonic plate locations) data with historical earthquake data to find potentially hazardous regions, (ii) the second phase involves creating an structural model to flag hazardous dams and assign damage scenario's, and (iii) the third phase is a flood map visualization upon dam failure.

The outcome of these phases is the identification of a region which is more likely to have disastrous effects if a dam fails. This is due to the higher concentration of dams in the area, or its proximity to tectonic plates and a greater history of seismic activity. The analysis indicates that there is no direct danger of failing dams – but, if such a failure were to occur, the flood map provides a reasonable estimate of the potential path and extent of the water flow.

Keywords: Hydraulic structures, Earthquakes, Structural analysis, Flood map, Preparedness

Introduction

After the severe earthquake of February 6, 2023 in Turkey, significant cracks were reported in the dam 'Sultan Suyu' after which water had to be released as a precaution. This earthquake served as a wake-up call for several stakeholders to evaluate the risk of existing structures, also hydraulic structures such as dams. Turkey has many large important dams that provide electricity or are vital for water management across the country. Questions were raised on the safety of other dams in the region and the consequences of releasing water after some dams were severely damaged by earthquakes.

Dams are vital structures and are built to endure earthquakes, but many existing dams are old and therefore much less stiff. As dams age, the concrete slowly degrades allowing for cracks to form. When the already slightly damaged dams are exposed to an earthquake, the dams can fail having disastrous consequences. Moreover, earthquake design regulations have been frequently reassessed and updated over the past decade. These two factors highlight the need for a thorough reevaluation of the existing inventory of dams. The failure of a dam can have catastrophic effect on the environment and can lead to complete towns being washed away, major power loss in the country and valuable farmland becoming inhabitable, underscoring the critical importance of this issue.

It is therefore essential to begin reevaluations and conduct simulations based on updated conditions and the latest structural codes. Achieving this requires detailed information, which is both costly and time-consuming. A fast and user-friendly computational tool (Figure 1) that can identify potentially hazardous dams and visualize the associated flood risks would help prioritize the reevaluation process, enabling civil engineers to focus on the highest-risk areas first. This tool can be used to visualize the environmental impact, thus helping governments implement proper mitigation measures nearby settlements, farm lands or the dams themselves.

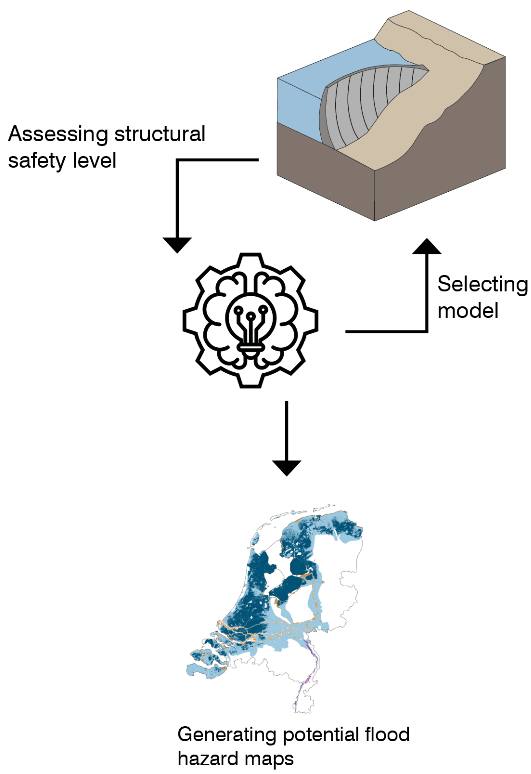


Figure 1. Computational tool.

Method

The research plan to develop this tool is divided into three phases:

- Phase 1: Creating a map with Python[1] by manipulating existing data and filtering for a potential region for the case study.
- Phase 2: Creating a structural model able to flag and assign damage scenarios, thereby assessing the level of risk a dam poses to the surrounding environment. This is done by importing the manipulated data of Phase 1 into a Grasshopper environmen[2] to create unique geometries and loads for each dam in the region. Afterwards, the earthquakes are simulated by a response spectrum analysis in Sofistik software[3] which is baked into Grasshopper to assign a hazard index for each dam.
- Phase 3: With this hazard index, the consequences of potential threatening dams can be further explored by a Python algorithm that visualises the possible flooded area if failure occurs or if water has to be released. This information can help governments or other institutions to map the risks and take proper mitigation measures.

The final outcome is to develop a code that generates maps and identifies potential areas from Phase 1, incorporates the structural model with hazard classification from Phase 2, and creates a flood algorithm to visualize potential flood zones from Phase 3 (Figure 2). Together, these phases will form the complete computational tool.

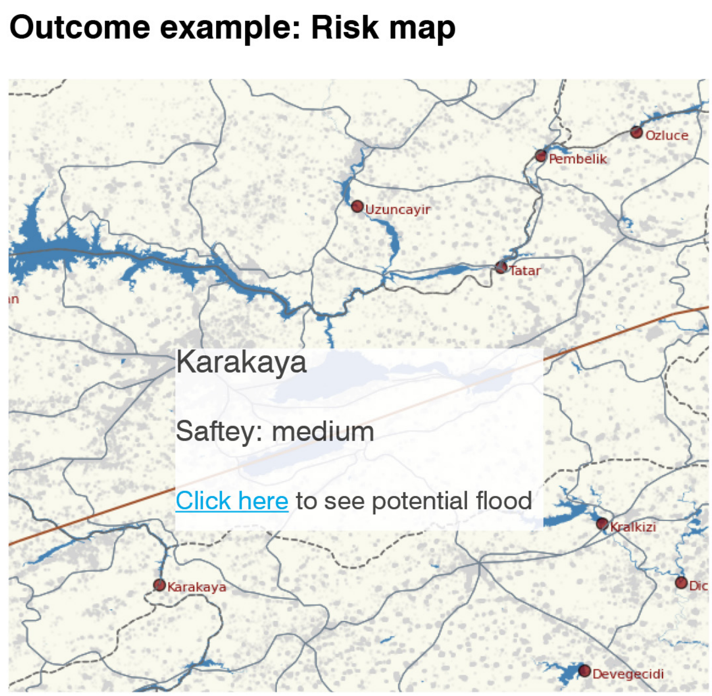


Figure 2. Risk map outcome example.

Figure 3 illustrates the general workflow for this project, divided into the three phases previously discussed, along with the software intended for each part. The icons provide an overview of the workflow for Phases 1 through 3. The software is color-coded as follows: Orange represents Python, Green represents Grasshopper, Blue represents Sofistik.

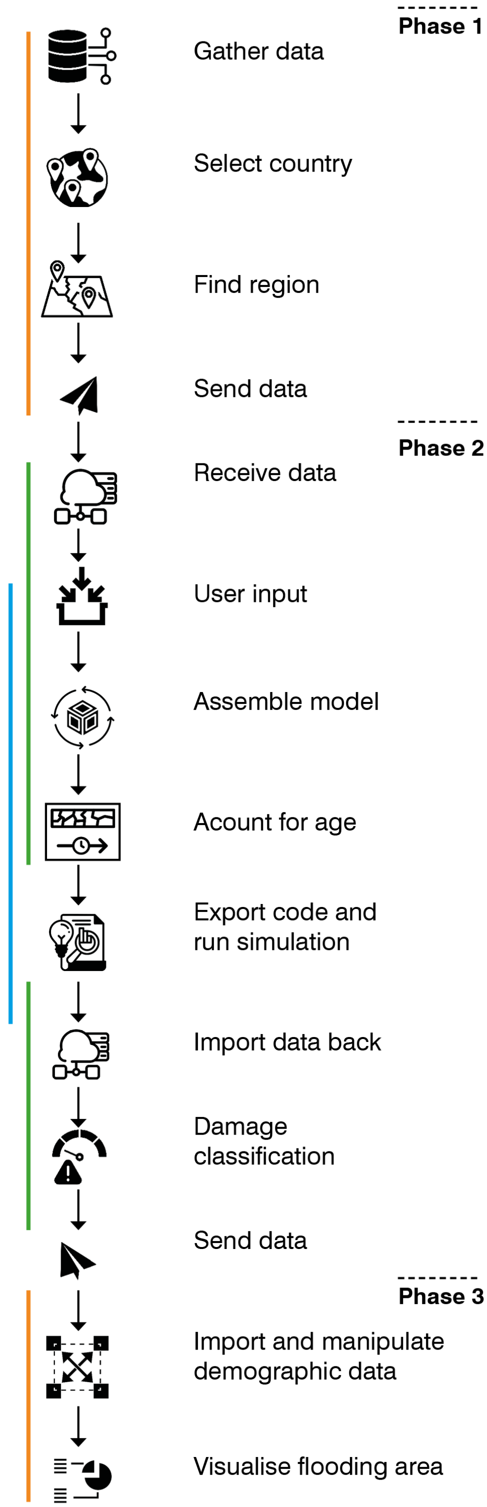


Figure 3. Workflow of the project phases.

Results

To select a suitable case study (dam) for this project, Phase 1 utilizes a self-developed Python script that maps Turkey, including fault lines, historical earthquakes (with their magnitudes), and the locations of all dams. This map provides valuable data to identify areas with a higher historical frequency of stronger earthquakes, as well as regions with a greater concentration of dams (Figure 4).

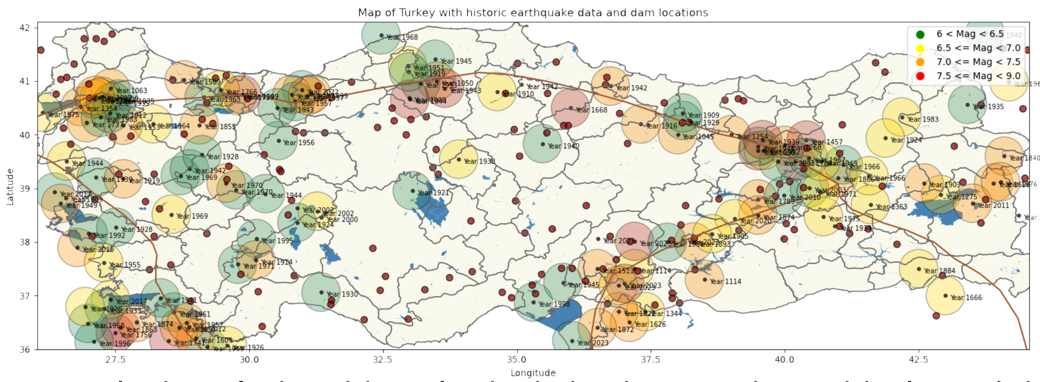


Figure 4. Plotted map of Turkey with historical earthquake data above Magnitude 6.0 and dam locations (red dots).

The main outcome of Phase 2 is a hazard map that provides, for each dam, a corresponding ‘scenario’, ‘hazard index’, and ‘PGA’ value (Figure 5).

- Scenario: In case of an earthquake, six scenarios describe the damage levels of a dam resulting from this earthquake. With 1 being ‘no damage’ and 6 being ‘complete dam failure’.
- Hazard Index: The hazard index is a resulting value of multiplying the scenario factor by the probability of each scenario to occur, with the scenario factors being:
  - Scenario 1 – factor 0
  - Scenario 2 – factor 1
  - Scenario 3 - factor 7
  - Scenario 4 – factor 20
  - Scenario 5 – factor 50
  - Scenario 6 – factor 100
- PGA: Peak Ground Acceleration value

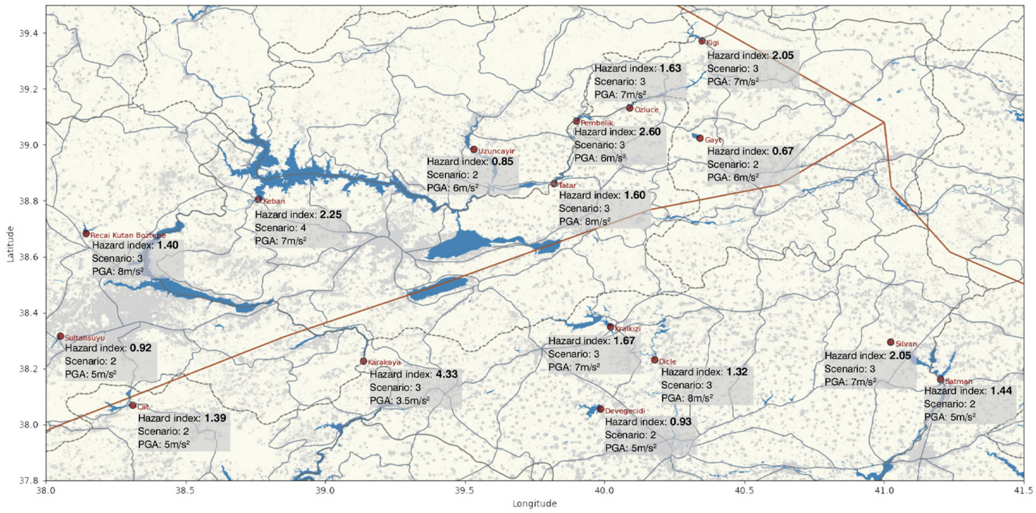


Figure 5. Final hazard map of all the 16 dams in the case study area.

To create this map, a 2D structural calculation method for earth and gravity dams was integrated into a computational workflow within Sofistik, using Grasshopper. The results were then exported to an Excel file and combined within Python to generate the final map.

In the third and final phase, the main result is a flood map that can be generated for each dam in Turkey (with the potential to scale globally, though this is currently limited by time and computing power constraints). The map displays the dam location (indicated by a red dot) and the flood area in the event of a dam failure, with darker blue representing lower-lying areas that would experience more severe flooding.

To generate the map of Figure 6, elevation data (.tif files) were used to determine the elevation of each pixel in a 3600 by 3600 pixel grid. The dam coordinates were then adjusted to align with the coordinate system of this grid to plot the dam location and determine its elevation. This process ultimately helps identify which pixels would flood and which would remain unaffected in the event of a dam failure.

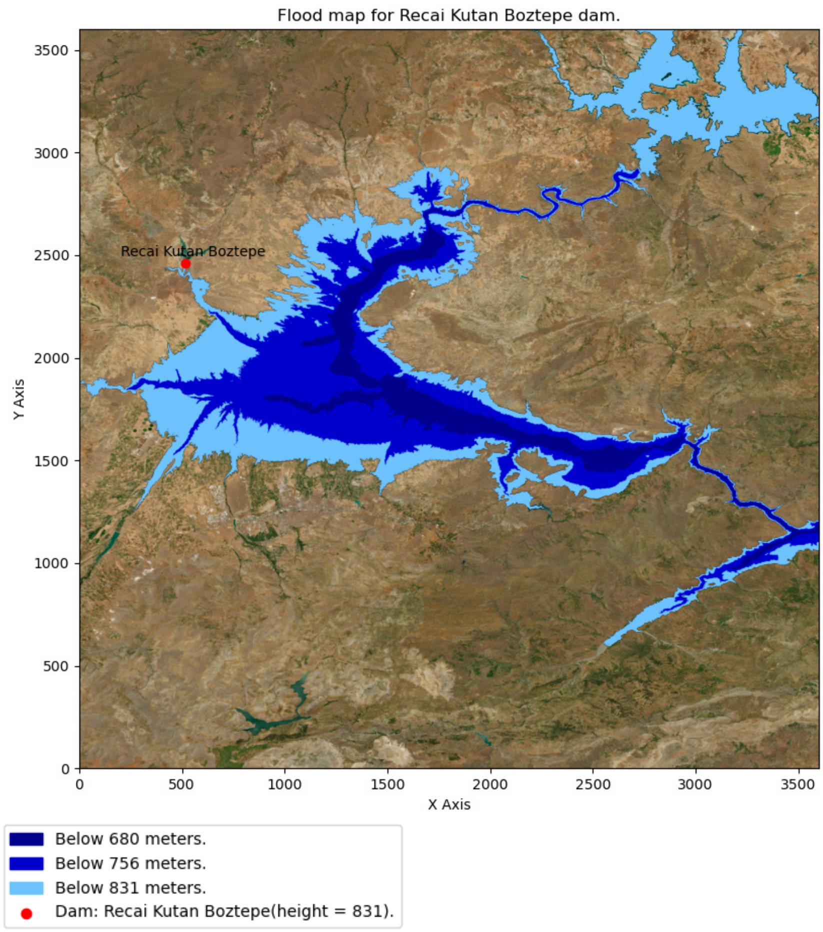


Figure 6. Flood map for the Recai Kutan Boztepe dam.

Conclusions

This research aims to identify potentially hazardous dams through computational analysis based on structural codes and generate a flood map to assist in disaster preparedness. As a result, the developed code enables to determine a region which is more likely to have disastrous effects if a dam fails, both because of more dams in this region and proximity to tectonic plates - thus more history of earthquakes. The results indicate that, based on the conducted calculations (2D simulations), there is no immediate danger of dam failure in Turkey. However, should a dam fail, relevant stakeholders can use the flood map to assess the water's behavior in the affected region and take preventive measures. This could include creating safe zones for evacuation and avoiding the placement of critical infrastructure in areas likely to experience severe flooding.

The main limitations encountered in developing this project were time and computing power. With more time, the dam calculations could have been improved by transitioning from 2D to 3D simulations, which could potentially require additional computing resources. Also, the flood map could be scaled to include dams worldwide, accessible through a dropdown menu in the Graphical User Interface. Users would first select a country, followed by a list of all the dams in that country. Currently, the tool only includes a list of dams in Turkey. However, achieving this would require significantly more time to download and organize the necessary maps and dam data—and possibly more computing power, given the large size of these maps.

References

1. Python Software Foundation. Available: http://www.python.org.
2. R. McNeel et al., "Rhinoceros 3D, Version 6.0," Robert McNeel & Associates, Seattle, WA, 2010.
3. SOFiSTiK Software. Available: https://www.sofistik.com.

Seismosolve

Aron Bakker, Zahra Khoshnevis

This study presents SeismoSolve, a comprehensive approach to enhancing seismic resilience in mid and high-rise buildings, with a focus on Antakya, Turkey, following its devastating earthquake in 2023. This study seeks to incorporate seismic bracing strategies during the early design phase of buildings, enhancing interdisciplinary collaboration among designers, engineers and contractors. By integrating computational design and structural analysis, SeismoSolve aims to streamline the development of seismic bracing systems that control building vibrations during earthquakes. This study emphasizes the role of vertical seismic dampers in strengthening structural integrity. SeismoSolve utilizes mainly digital simulations to define seismic forces acting on frame structures. These structures are parametrically designed and subjected to seismic forces using Grasshopper scripting, along with the Karamba3D and Alpaca4D plugins, to analyze the effectiveness of bracing systems. The project is complemented by machine learning algorithms to predict structural performance based on various input parameters, such as building height, grid configuration and material properties. Physical model testing was conducted to validate theoretical assumptions, showcasing the importance of balancing flexibility and stiffness in bracing systems. Despite challenges, the project achieved significant insights into seismic bracing optimization, offering a pathway toward more efficient and safer earthquake-resistant structures. Future research directions include expanding simulation variables, transitioning toward more sophisticated computational platforms, and enhancing integration with digital fabrication techniques to facilitate the construction of earthquake-resilient buildings.

Keywords: Seismic bracing, Generative design, Machine learning, Seismic resilience, Integrated design

Introduction

The growing frequency and severity of earthquakes around the world underscore the urgent need for developing resilient building structures, particularly in regions prone to seismic activity. Antakya's recent catastrophic earthquake in 2023, which resulted in the collapse or severe damage of a significant portion of its buildings, highlighted the critical importance of integrating advanced seismic resilience measures in urban development. This study introduces SeismoSolve, an innovative approach to enhancing earthquake resistance in mid and high-rise buildings through the implementation of effective seismic bracing systems. By leveraging advanced computational tools like Grasshopper[1] scripting for generative and parametric design, Karamba3D[2] and Alpaca4D[3] plugins for static and dynamic analysis, alongside machine learning techniques, SeismoSolve enables the design and simulation of efficient seismic bracing systems that can be rapidly implemented in earthquake-prone areas. The project explores the balance between flexibility and stiffness in building structures, aiming to mitigate earthquake impacts while ensuring structural safety. Through a combination of theoretical analysis, physical model testing, and data-driven optimization, SeismoSolve presents a comprehensive framework for improving seismic resilience, offering valuable insights for architects, engineers and urban planners in their efforts to design safer, earthquake-resistant buildings.

Method

The SeismoSolve project employs a multidisciplinary approach to enhance seismic resilience in mid-rise buildings through computational design, physical testing and machine learning. The workflow consists of several key stages, as indicated in Figure 1.

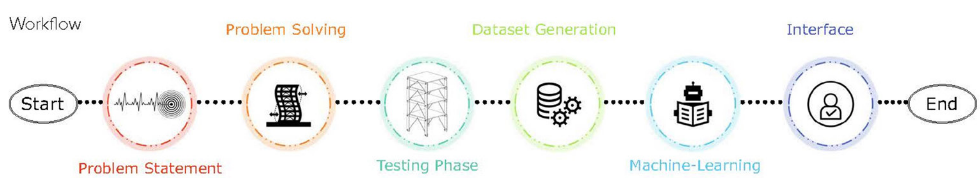


Figure 1. *SeismoSolve* overall approach.

- *Computational Analysis*: The study began by parametrically designing frame (beam-and-column) structures using Grasshopper scripting. These structures, with various parameter combinations, served as inputs for Karamba3D[2] and Alpaca4D[3]—two advanced simulation tools used to model the structural behavior of mid-rise buildings under seismic forces. These tools allowed the creation of various bracing configurations, testing their effectiveness under simulated earthquake conditions. Parameters such as building height, grid combinations, bracing geometry and material properties were adjusted to analyze their impact on seismic performance.

- *Physical Model Testing*: A physical model of the building structure was constructed to validate the computational simulations. The model included elastic bracing systems, pinned connections and varying storey heights to replicate realistic earthquake scenarios. It was subjected to shake table tests representing seismic forces from different regions, such as Groningen, San Francisco, and Kobe, to observe how the bracing system responded to these dynamic loads.
- *Machine Learning Integration*: Data from the simulations and physical tests were then used to train a K-Nearest Neighbors (KNN) machine learning classifier. This model was developed to predict the effectiveness of different bracing configurations based on various input parameters. The machine learning model was validated through confusion matrices and learning curves, achieving a 92% accuracy in predicting the optimal bracing setup for seismic resilience.
- *Design Iteration and Optimization*: The insights gained from both the simulations and machine learning models were used to refine the bracing designs. The optimization process was carried out using Python scripts to adjust variables such as bracing geometry, component and material properties, ensuring an effective and efficient seismic bracing solution.
- *Interface Development*: Finally, an interface was created using Grasshopper's Hops component and Tkinter module of Python[4], enabling real-time interaction with the SeismoSolve system. This allowed designers to input building parameters and receive immediate feedback on the seismic effectiveness of their designs, facilitating iterative improvements.

This comprehensive workflow enabled the development of a seismic bracing solution that balances structural flexibility and stiffness, offering an effective means of enhancing earthquake resilience in mid-rise buildings.

Results

The SeismoSolve project yielded significant insights into the design and optimization of seismic bracing systems for mid-rise buildings. The combination of computational simulations, physical testing and machine learning produced the following key results:

- *Effectiveness of Bracing Configurations*: The computational simulations using Karamba3D[2] and Alpaca4D[3] demonstrated that various seismic-bracing configurations, such as inverted-V and cross-bracing, significantly improved the seismic resilience of structures (Figure 2). These configurations allowed controlled movement within the building, reducing seismic forces on columns and beams while maintaining structural integrity.

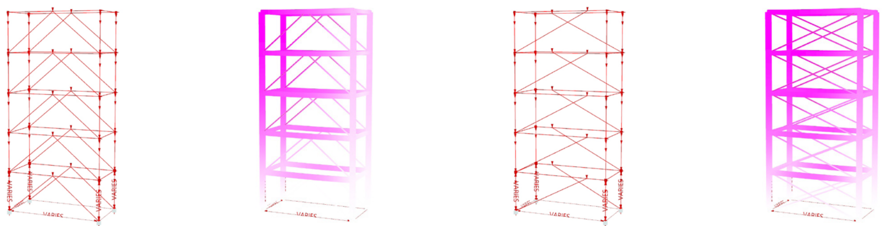


Figure 2. Bracing system configurations (inverted-V and cross-bracing).

- *Validation through Physical Testing*: Shake table tests confirmed the theoretical assumptions, showing that the elastic bracing system absorbed seismic forces effectively. The model demonstrated resilience against simulated earthquakes from different regions, including Groningen, San Francisco and Kobe earthquakes, verifying the computational model's accuracy. The experiment revealed the importance of introducing a balance between flexibility and stiffness, as overly flexible bracing led to excessive displacement, indicating potential internal damage in real-world scenarios (Figure 3).

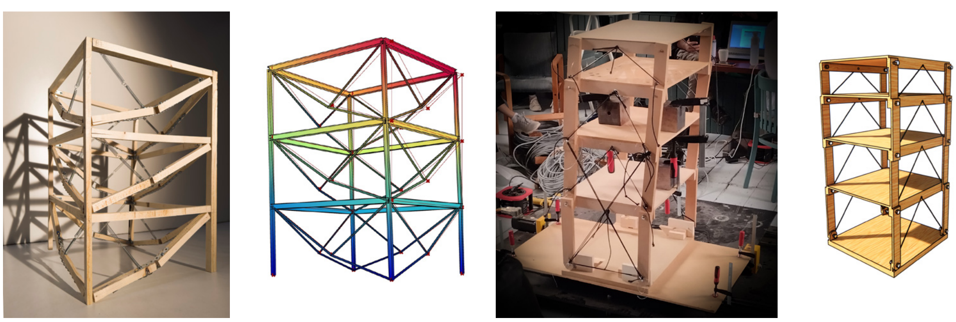


Figure 3. Prototypes tested on the shake-table.

- *Machine Learning Prediction Accuracy*: The K-Nearest Neighbors (KNN) machine learning model achieved a prediction accuracy of 92% in identifying the effectiveness of various bracing configurations. The model was particularly effective in distinguishing between suitable and unsuitable bracing designs, with accuracy rates of 94% for ineffective (False) predictions and 83% for effective (True) predictions. This outcome underscores the model's reliability in predicting optimal bracing configurations for different building parameters.

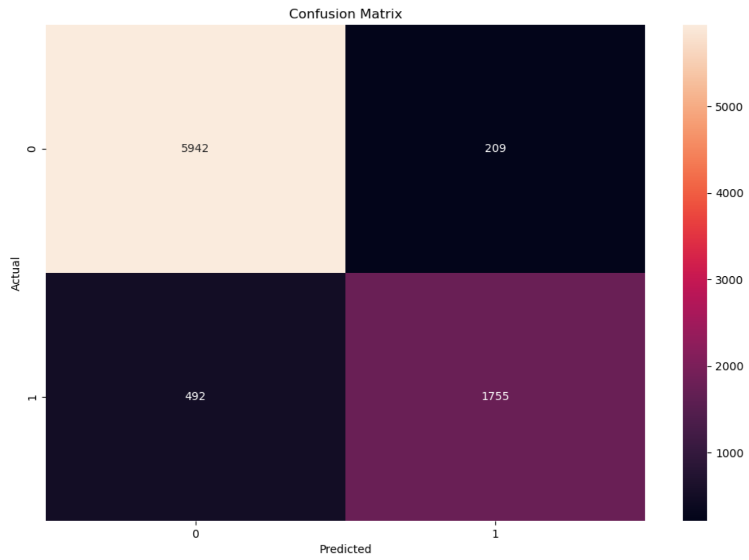


Figure 4. Confusion matrix obtained for the KNN model.

- *Optimization and Workflow Efficiency*: The integration of machine learning and computational simulations enabled rapid optimization of seismic bracing designs. The use of the optimization script allowed for fine-tuning of variables such as spring rates, grid combinations, and bracing geometry, resulting in more efficient and robust designs. The final optimized model demonstrated enhanced stiffness, reduced displacement and improved seismic resilience.
- *User Interface and Application*: The development of the interactive design interface allowed real-time feedback on seismic performance, enabling iterative design improvements. Designers could input building parameters, such as storey height, grid configuration and material properties, and receive immediate predictions on the bracing system's effectiveness, streamlining the overall design process.

Overall, the results indicate that the SeismoSolve system offers a comprehensive and accurate approach to enhancing seismic resilience in mid-rise buildings, providing valuable tools for architects, engineers and urban planners to design safer, earthquake-resistant structures.

Conclusions

This study introduced *SeismoSolve*, an integrated framework that enhances seismic resilience in buildings by combining computational design, physical testing and machine learning. Applied to the context of Antakya's 2023 earthquake, the system demonstrated its potential to improve structural performance through optimized bracing configurations. Parametric modeling and dynamic simulation tools effectively identified and tested bracing strategies such as inverted-V and cross-bracing, while shake-table experiments validated these configurations under real-world seismic scenarios.

The machine learning component proved highly accurate in predicting the effectiveness of various bracing designs, enabling data-driven decision-making early in the design process. Optimization algorithms further refined these designs, achieving a balance between flexibility and stiffness, which is essential for minimizing seismic impact. The development of an interactive design interface also provided a practical application for real-time performance evaluation, encouraging more collaborative and iterative workflows among architects and engineers.

Overall, *SeismoSolve* offers a forward-looking approach to seismic design, providing valuable tools for creating safer, more resilient buildings in earthquake-prone regions. Looking ahead, future work will focus on extending *SeismoSolve*'s applicability to more complex structures, incorporating advanced machine learning models and integrating real-time seismic data for context-specific design recommendations.

References

1. R. McNeel et al., "Rhinoceros 3D, Version 6.0," Robert McNeel & Associates, Seattle, WA, 2010.
2. C. Preisinger, "Linking Structure and Parametric Geometry, " *Architectural Design*, vol. 83, pp. 110-113, 2013, doi: 10.1002/ad.1564.
3. "Alpaca4d – OpenSees wrapper for Grasshopper," Available: https://alpaca4d.gitbook.io/ docs.
4. Python Software Foundation. Available: http://www.python.org.

Computational Shear Wall Generator for Seismic-Resilient Housing Typologies in Antakya

Georgia Kougioumoutzi, Feras Alsagaaf, Sareh Yousefi

To support the design of seismic-resilient housing, a computational evolutionary algorithm-based workflow is developed to automate seismic calculations and generate optimal shear wall layouts for high-rise residential typologies with a central courtyard (Hayat) in Antakya, Türkiye. The method allows users to optimise diverse shear wall layouts for user-selected housing typologies. The digital tool performs seismic engineering calculations and offers several design solutions that minimize the distance between the centre of stiffness and the centre of mass. A user interface is developed in Rhino/Grasshopper program to displays the best design options. The project demonstrates the possibility of streamlining the process of designing cost-effective and safe shear wall designs, allowing architects and engineers to align their priorities for seismic-resilient design and architectural spatial requirements to reach a consensus during the early design phase.

Keywords: Seismic resilience, Vernacular housing, Shear walls, Evolutionary algorithms, Generative design

Introduction

The 2023 earthquake that hit North Syria and Türkiye resulted in massive destruction and according to Türkiye's Disaster and Emergency Management Authority, casualties rose to 50,783 and at least 15.73 million people and 4 million buildings were affected. Poor construction methods and structural frames drastically increased the collapse rate in the area. The economic impact of these events ranged from $20 to 100 bn.

As a common strategy to improve the capacity of buildings to resist lateral loads without undergoing significant failure and damage, shear walls are used to provide strength and stiffness but also ductility to dissipate seismic energy and protect other structural members from inelasticity. In tall buildings, shear wall placement is a crucial aspect of seismic design to resist lateral forces during earthquakes, which can be a complex process due to conflicting requirements from architects, engineers and clients.

This study focuses on developing a graphical user interface to assist in designing earthquake-resilient buildings by analysing, controlling and suggesting different shear wall configurations, reducing lateral displacement and drift and preventing damage to the structural elements during seismic activities. The study specifically addresses new housing typologies in the Antakya region, Turkey.

Method

The overall approach involves applying computational methods to generate seismic-resilient housing typologies based on vernacular elements. The housing typology is generated by defining a set of parameters for its size and configuration, the seismic load calculation is computationally verified, and several design options are generated based on user inputs (Figure 1).

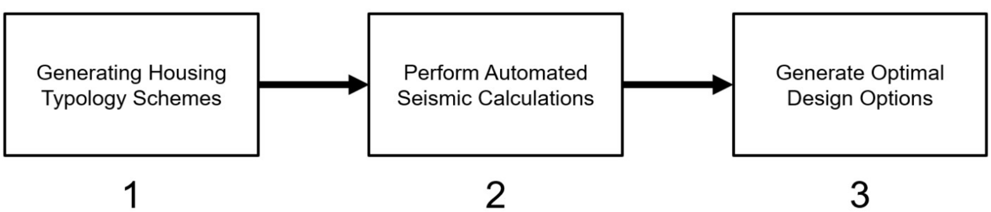


Figure 1. Overall research method addressing (1) computational generation of housing typologies, (2) automated seismic calculations, and (3) generation of optimal design options.

Defining housing typology

The spatial organisation in housing units in Antakya marks the importance of two determining elements around which the other spaces are formed (Figure 2). Courtyard, also known as 'Hayat' in the region, is an important multifunctional space that has existed in the vernacular architecture of the region since Roman rule. Another important space is the 'sofa' which translates as a transitional space that connects the rooms or the interior to the courtyard. In the modern high-rise buildings in Antakya, the concept of a courtyard is no longer a dominant factor in spatial organisation, but if included in new buildings it has the potential to add quality to the living experience of the occupants.

The spatial organisation for the proposed housing typologies considers seismic risk mitigation by symmetrical layouts, and includes other elements such as circulation paths and daylight.

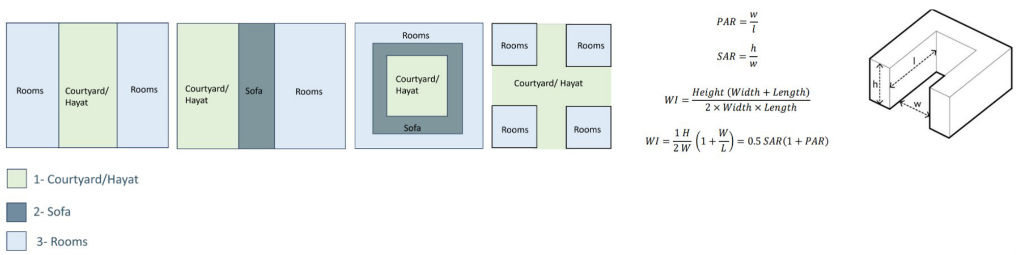


Figure 2. Types of housing typologies computationally generated, with varying sizes and courtyard enclosures.

Calculating the seismic load

Shear walls are vital when designing an earthquake-resistant building. These vertical components, often constructed of reinforced concrete, are intended to withstand lateral stresses induced by seismic or wind occurrences. European seismic codes specify requirements for shear wall design, emphasising material strength, reinforcing features, and load distribution.

In earthquake-prone areas, building design should prioritise regularity to improve structural stability. Eurocodes give specific guidelines for architects and civil engineers. First, the height of a structure should not be more than four times its foundation length. Furthermore, holes in shear walls can reduce their ability to resist lateral forces. Avoiding soft stories is critical for minimising excessive deformation, furthermore splitting the structure into rectangular pieces with expansion joints can further minimise seismic risk. Finally, symmetrical positioning of shear walls results in a more equal distribution of seismic forces, reducing torsional effects (Figure 3).

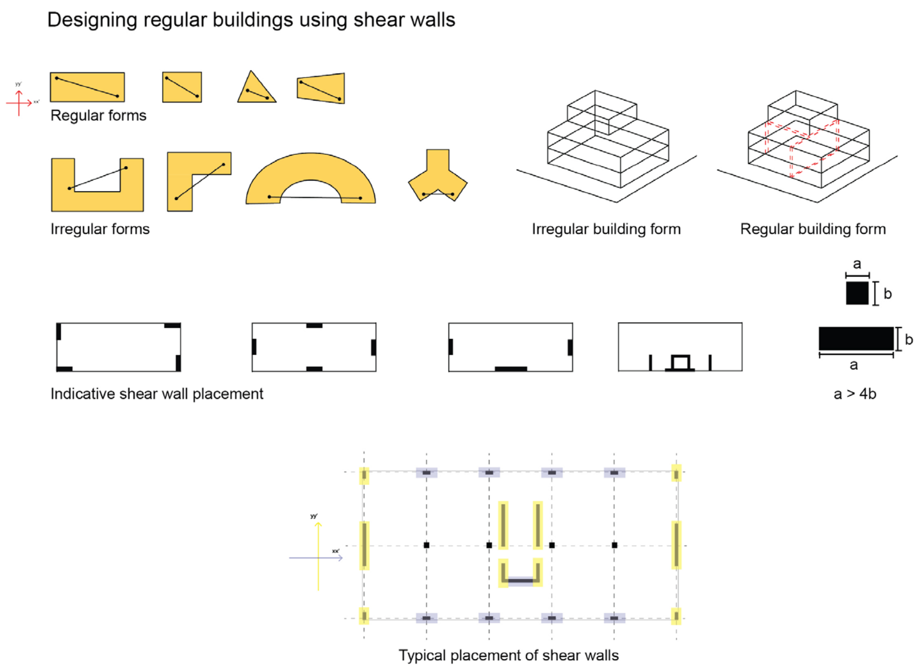


Figure 3. Regular and Irregular building configurations.

Concrete shear walls are the most commonly used earthquake resilient elements. On the technical aspect, shear walls should withstand approximately 65 percent of seismic forces applied on a building. These walls are normally rectangular in shape, with a length at least four times that of the depth, to ensure adequate stiffness and strength to withstand lateral stresses. Eurocode encourages symmetry and regularity in shear wall location. A symmetrical configuration is recommended because it may achieve uniform stiffness and strength over the whole structure, reducing the possibility of torsional impacts during seismic occurrences. A torsional check ensures that the centre of mass (CoM) and the centre of stiffness (CoS) are close together, leading to more economical construction. The engineer has to bring those two points closer so that the building does not twist and fail. The closer CoM and the CoS are, the cheaper the construction of the building will be.

To calculate the minimum shear wall length in a building, the seismic design force was computed following the linear static approach as explained in the Eurocode 8. This enabled the calculation of the area of the shear walls in each direction.

Generating optimal design options

The positioning of shear wall elements can affect other design criteria of the building design, especially the spatial design by introducing constraints (i.e. the shear wall interrupting open space and circulation paths). A less optimal shear wall layout configuration could increase the cost of reinforcement and in general increase structural material cost.

The user receives minimum shear wall length needed to satisfy seismic design criteria based on the calculations. The user specifies the count of wall segments typical size combinations. For example, the total shear wall length needed in one direction is 14 meters, the user can decide to divide by the target number of walls. The evolutionary algorithm randomly places shear walls along the column grid and tests against its objective function, which aims to minimize the distance between CoS to CoM and provide around 10-12 different optimal design options for considerations using a generation size of 12 running for 5 generations.

Results

The developed computational tool is designed to enhance the seismic resilience of new housing units in Antakya, Turkey, using shear walls as the primary lateral support system. Key findings include the successful integration of traditional hayat typologies—vernacular features of Antakya—into a flexible smart grid system that adapts to different building plots. Additionally, the project highlights the potential of using Python[1] and Grasshopper[2] to calculate seismic forces for multiple buildings in real-time, providing optimal shear wall sizes and configurations for cost-effective solutions, demonstrating possibilities for the implementation of software tools that can support early design decision-making in the field of architecture and engineering.

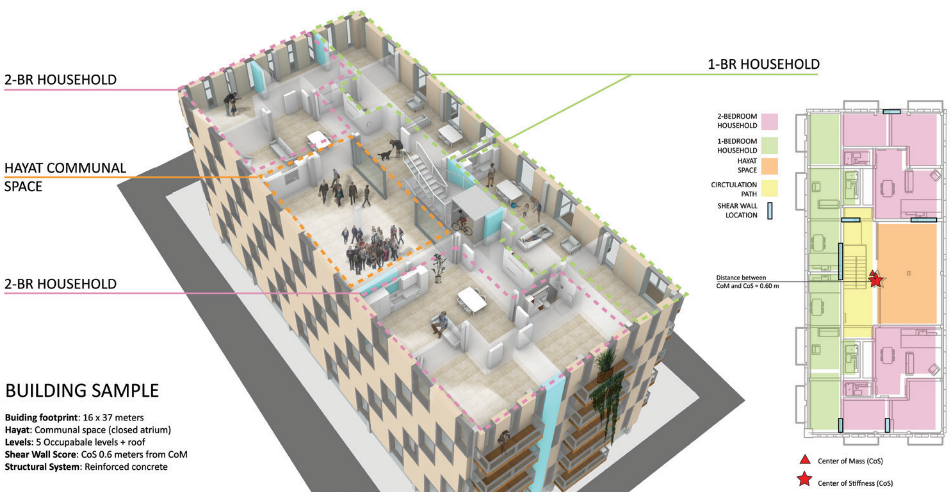


Figure 4. A housing sample generated using the Grasshopper script with optimal shear wall locations highlighted in cyan.

Conclusions

This study introduces a computational tool aimed at enhancing the seismic resilience of buildings by employing shear walls as the primary lateral support system. The tool optimises shear wall placement for seismic-resilient housing typologies in Antakya, with the traditional courtyard (hayat) as an important spatial feature. The workflow leverages a smart column grid to generate adaptable floor plans and various column-to-column spans while automating key seismic engineering calculations, such as shear wall length, centre of mass and stiffness, and torsional effects. Users can adjust wall elements and use a genetic algorithm to find optimal shear wall placements that minimise the distance between centres of stiffness and mass while optimising the cost. The tool provides the best 12 design options with fitness scores and indicates the most cost-effective and safer options.

This workflow allows architects to envision housing typologies in seismic resilient design to better contribute to post-earthquake recovery efforts. By integrating engineering data early in the design phase, it simplifies the creation of seismic-compliant buildings through automation, making it easier to explore different design options and improve earthquake safety.

A current limitation is that the tool uses a grid structure with one-dimensional parameters for each side of the building. Existing buildings or those with alternative grid systems require the creation of a new script. Existing structures with a suitable one-dimensional grid can still utilise the tool, but the building's frequency must be entered manually. Moreover, the building's structural material has a considerable impact on its overall frequency. If the building had been composed of steel or wood frames, the findings would be different, necessitating changes to the computational method.

For future research, a point-based algorithm could be developed to provide a wider range of design alternatives. Furthermore, incorporating a user interface that allows for the specific arrangement of structural elements inside the floor plan might considerably improve the design process. For example, if the user specifies the position and size of two shear walls, the algorithm will automatically find the best placement of the remaining shear walls across the floor plan to maintain torsional stability.

References

1. Python Software Foundation. Available: http://www.python.org.
2. R. McNeel et al., "Rhinoceros 3D, Version 6.0," Robert McNeel & Associates, Seattle, WA, 2010.

Holistic Site-Specific Hazard Assessment: An Attempt to Predict Directionality of Seismic Impacts for Smarter Planning

Anna Konstantopoulou, Lara Neuhaus

This project addresses the challenge of site-specific earthquake hazard assessment, particularly the difficulty of predicting both the likelihood and directional impact of seismic events. Using the Probabilistic Seismic Hazard Analysis (PSHA) method, the project aimed to create an accessible tool for evaluating earthquake risks at specific sites. The objectives included estimating earthquake probabilities and severity, as well as predicting the main earthquake direction during an event.

The methodology combined PSHA with experimental analysis of historical seismic data, processed using Python. A statistical regression was applied to identify the most likely direction of seismic wave propagation. Based on this, initial recommendations for orientation were proposed to enhance earthquake resilience of buildings.

The research results indicate that integrating directional predictions into hazard assessments could significantly improve site-specific earthquake preparedness. This project lays the groundwork for more advanced models of directional ground motion predictions. While the current model provides only basic guidelines for building orientation, future work could refine these recommendations by incorporating more complex factors such as building shape, eccentricity and construction methods based on the predicted directions of highest seismic motion.

Keywords: Probabilistic seismic hazard analysis, Ground motion prediction, Directionality, Statistical regression

Introduction

Seismic activity poses a significant risk to infrastructure in earthquake-prone regions, often leading to catastrophic damage and loss of life. Despite advancements in building codes and construction techniques, recent events, such as the February 2023 earthquakes in Turkey and Syria, have shown that even modern structures can fail under severe seismic conditions. One critical gap in current earthquake-resistant design practices is the lack of site-specific hazard assessments that account for the unique seismic characteristics of a location. Traditional approaches often rely on general seismic codes that may not fully capture local hazard variations or the directional impact of seismic waves.

This research addresses the challenge of improving the accessibility of site-specific seismic hazard assessments. Specifically, its aim is to enhance Probabilistic Seismic Hazard Analysis (PSHA) by incorporating predictions of the primary direction of peak ground acceleration (PGA) during an earthquake. Directional predictions could play a crucial role in building orientation and design, ultimately contributing to safer, more resilient structures.

The main objectives of this work are: first, to develop an easy-to-use tool for PSHA that can be applied to specific sites, and second, to experimentally predict the primary direction of seismic impact using historical data. By achieving these goals, this research seeks to bridge the gap between general seismic design practices and the unique conditions of individual sites.

Method

The research approach combines a standard PSHA with an experimental method to predict the directional impact of seismic waves. The goal was to develop a site-specific tool for assessing earthquake risks that is not only accurate but also easy to use, particularly for urban planners and designers.

The research process consisted of the following key points (Figure 1)

- Data Collection: The tool is built upon two primary data sources: the European Fault Source Model (EFSM20)[1] and the European Strong Motion Database (ESM)[2]. These datasets provide detailed information about fault lines and historical ground motion records for the selected site.
- Tool Development: Python[3] was used to develop the tool, integrating the OpenQuake and ObsPy libraries. OpenQuake[4] handles the core PSHA computations, while ObsPy processes seismic waveforms and historical data to assist in the directional prediction of the PGA.
- Directional Prediction: Using historical seismic event data, the most probable direction of PGA was extrapolated. One approach involved comparing the

recorded PGAs in three coordinate directions of the closes seismic station to the chosen site. In the end, a statistical regression method was used to identify graphically the most affected orientation of seismic waves.

- Outputs: The output for the PSHA is the PGA with a probability of exceedance (POE) of 10% and 2% in 50 years, as well as the angle (from the east axis) in which direction this PGA will most likely occur and a confidence marker derived from the deviation of results.
- Verification: The results of the hazard assessment are compared with the European Seismic Hazard Model (ESHM13/20)[5] to ensure consistency with established hazard models.

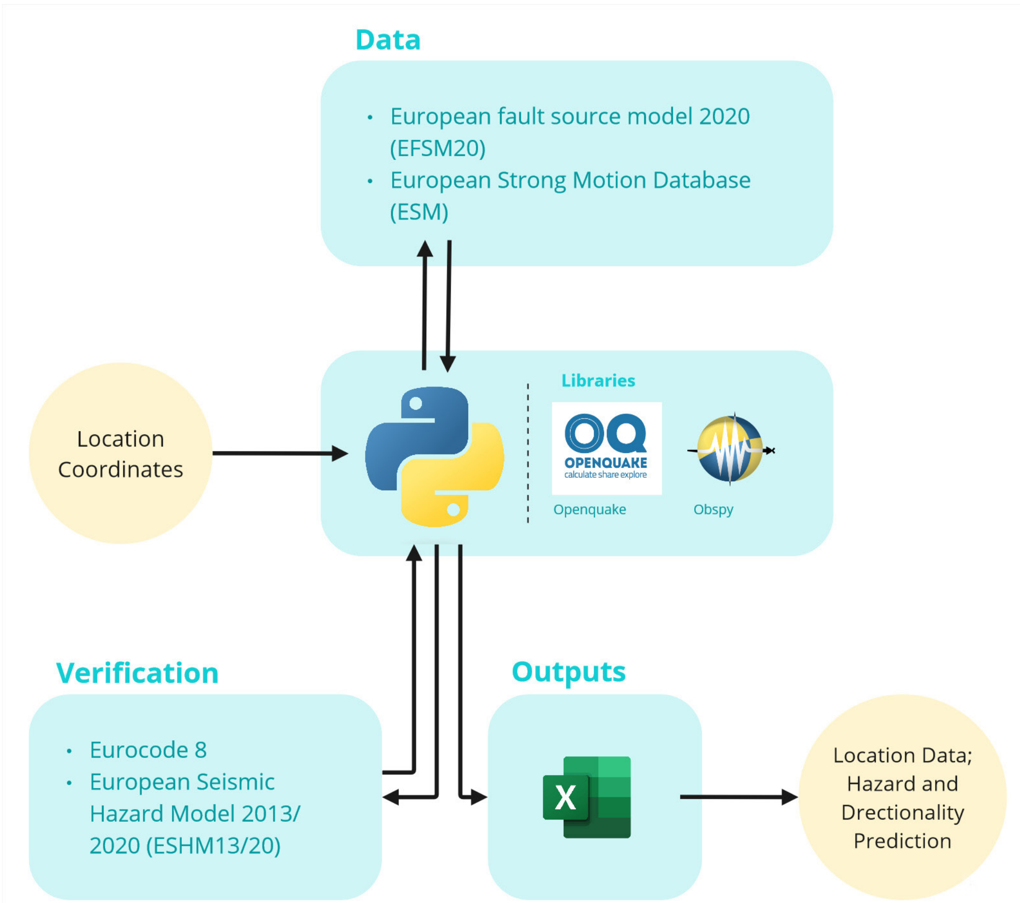


Figure 1. Research approach.

Results

The study achieved two main objectives: (i) the creation of a reliable, easy-to-use PSHA-based hazard assessment tool and (ii) the experimental prediction of seismic wave directionality at specific sites.

Seismic Hazard Assessment

For the location-based hazard assessment, the input is the location of the project site. With that information, data from the nearest seismic stations is collected, as well as data of known crustal fault lines in close proximity and data on historic seismic events. An appropriate ground motion prediction equation (GMPE) is then selected to calculate the risk for the specific site (Figures 2a and 2b).

Figures 2c and 2d present the PGA maps for two typically used scenarios: 10% and 2% POE in 50 years. These maps allow stakeholders to visualize the earthquake risk levels and plan accordingly for different hazard thresholds.

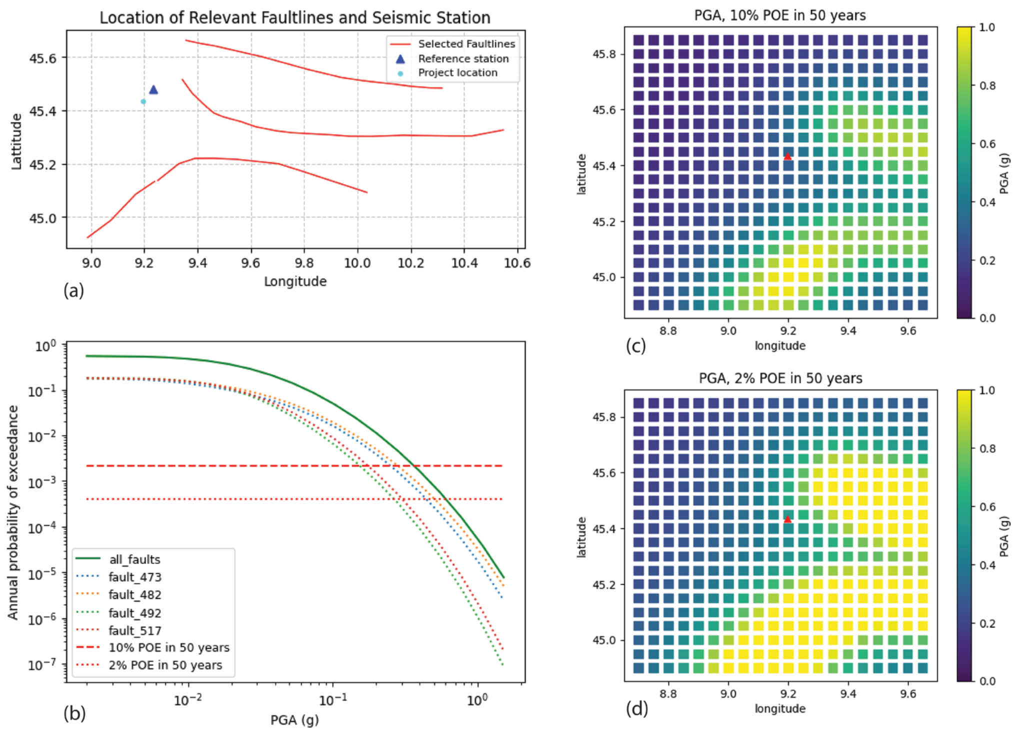


Figure 2. Overview of PSHA results for exemplary site in Italy: (a) location of fault lines and seismic station, (b) hazard curve, PGA maps for 10% (c) and 2% (d) probability of exceedance in 50 years.

Directionality prediction

To predict the primary direction of seismic impact, statistical methods were explored and a weighted linear regression was chosen to describe the acceleration of recorded events, limited to the horizontal plane.

Figure 3a illustrates the acceleration rates of one seismic event plotted on a North-East plane, with a regression line marking the most prominent direction. Figure 3b shows the combination of multiple events. In Figure 3c, the overall regression line for all events combined is shown. Figure 3d shows the angular variance of the lines for each relevant event, indicating whether a strong directional causality exists (narrow bundle) or if the accelerations are distributed randomly (wide bundle). This angle is used as a confidence marker for design recommendations.

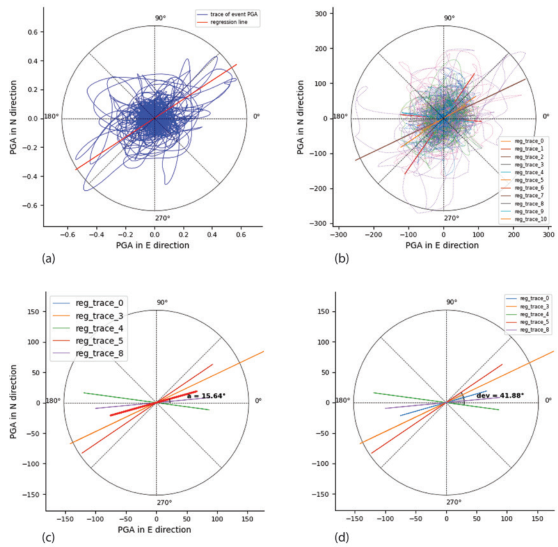


Figure 3. Analysis of historic seismic events for directionality in the acceleration: (a) one event; (b) multiple events, (c) regression line for all events, (d) angular variance.

Results could be used to support initial building design, e.g. building construction could be reinforced in the more affected directions or the layout could be planned for optimal structural response (Figure 4). If the spread of results is very wide, no prediction of direction can be made.

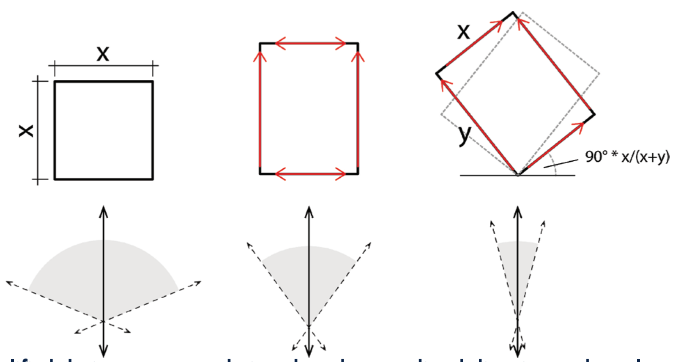


Figure 4. Simplified design recommendations based on predicted direction and result confidence level.

Conclusions

The most significant takeaway from this study is the successful development of a user-friendly site-specific hazard assessment tool based on the Probabilistic Seismic Hazard Analysis method. The tool predicts the likelihood of earthquake events, also providing experimental insights into the primary direction of seismic wave propagation.

However, the study has several limitations. First, the directional prediction model is based on historical data and statistical extrapolation, which make it reliant on good data coverage. The accuracy of directional predictions is hard to verify, since directionality is usually not considered in earthquake safe design.

In conclusion, a tool for probabilistic seismic hazard analysis for specific locations was successfully set up and options of predicting dominant directionality of seismic impacts have been explored experimentally. In the future, further research is needed to refine the model and validate the applicability for building recommendations.

References

1. R. Basili et al., “The European Fault-Source Model 2020 (EFSM20): geologic input data for the European Seismic Hazard Model 2020,” *Natural Hazards and Earth System Sciences*, vol. 24, n. 11, pp. 3945–3976, doi:10.5194/nhess-24-3945-2024.
2. L. Luzi, G. Lanzano, C. Felicetta, M. C. D’Amico, E. Russo, S. Sgobba, F. Pacor, and ORFEUS Working Group 5, “Engineering Strong Motion Database (ESM) (Version 2.0),” Istituto Nazionale di Geofisica e Vulcanologia (INGV), 2020, doi: 10.13127/ESM.2.
3. Python Software Foundation. Available: http://www.python.org.
4. V. Silva et al., “Development of the OpenQuake engine, the Global Earthquake Model’s open-source software for seismic risk assessment,” *Natural Hazards*, vol. 72, pp. 1409-1427, 2014, doi:10.1007/s11069-013-0618-x.
5. J. Woessner, L. Danciu, D. Giardini, and the SHARE consortium, “The 2013 European Seismic Hazard Model: key components and results,” *Bulletin of Earthquake Engineering*, 2015, doi:10.1007/s10518-015-9795-1.

Find Your Shelter: An Information-Driven Framework to Increase Efficiency in Site-Specific Shelter Decision-Making Process

Maartje Damen, Dimitra Mountaki, Sasipa Vichitkraivin

Natural disasters often create a housing crisis, with time constraints pushing for rapid shelter solutions. This research addresses inefficiencies in the shelter decision-making process following earthquakes, focusing on speeding up shelter provision while ensuring the selection is tailored to specific site conditions. The study aims to develop a decision support tool that leverages existing shelter knowledge to reduce the time between the event and shelter allocation. Methodologically, the framework uses data analysis and computation tools to assess location, shelter types and foundation requirements, integrating climate, population and soil data. The results show that the tool can optimize shelter selection, making the process more responsive and adaptable to local needs. These findings offer substantial improvements for post-disaster shelter allocation strategies, reducing response times and enhancing decision quality.

Keywords: Post-disaster sheltering, Decision support tool, Structural analysis, Earthquake response, Emergency housing

Introduction

Natural disasters, such as earthquakes, create immediate and overwhelming demands for shelter, exacerbating housing shortages and negatively affecting the quality of life. The Türkiye earthquakes in 2023 highlighted the inefficiency of current shelter decision-making processes, where finding suitable shelter locations and types proved challenging in a time-critical environment. The aftermath of such disasters demonstrates that every moment counts, but the complexity of site-specific conditions (e.g., urban density, infrastructure damage, and resource limitations) often delays relief efforts. This research addresses the problem by proposing a framework that streamlines shelter allocation decisions. Specifically, the project seeks to reduce the time between financial resource allocation and shelter deployment, improve the accessibility and usability of existing shelter knowledge, and assist in selecting shelter designs that not only meet structural resilience standards but also improve comfort and cultural appropriateness for the displaced population. By integrating available data sources and leveraging computational tools, the research aims to enhance the speed and quality of post-disaster sheltering decisions.

Method

The overall approach of this research focuses on creating a decision support tool that combines multiple datasets to recommend optimal shelter solutions based on site-specific conditions (Figure 1). The methodology is divided into three key phases: data collection, analysis and presentation. In the data collection phase, relevant data such as location-related factors (climate, population density, land elevation, soil type), shelter-related data (technical specifications, expected lifespan, cost, assembly requirements), and structural foundation data were gathered. These datasets were sourced from platforms like OpenStreetMap[1], population datasets, and climate APIs. In the analysis phase, the collected data was processed to assess the suitability of shelters for specific locations, considering factors like foundation needs, climate compatibility and cost-efficiency. A key aspect of the analysis was determining the interaction between shelters and local terrain conditions, especially for structural integrity. Finally, in the presentation phase, an interactive user interface was developed to allow users to input their location and requirements, and the tool would then suggest suitable shelter options. The entire process is visually supported by a flowchart to aid comprehension and streamline decision-making for the user (Figure 2).

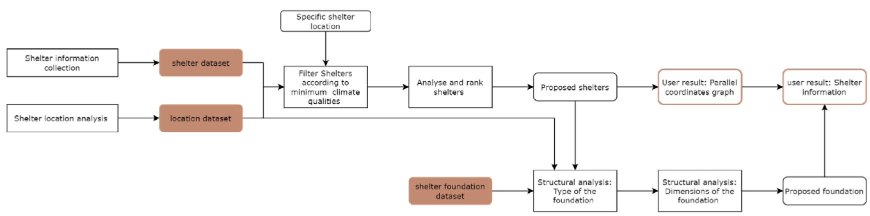


Figure 1. Overall research approach.

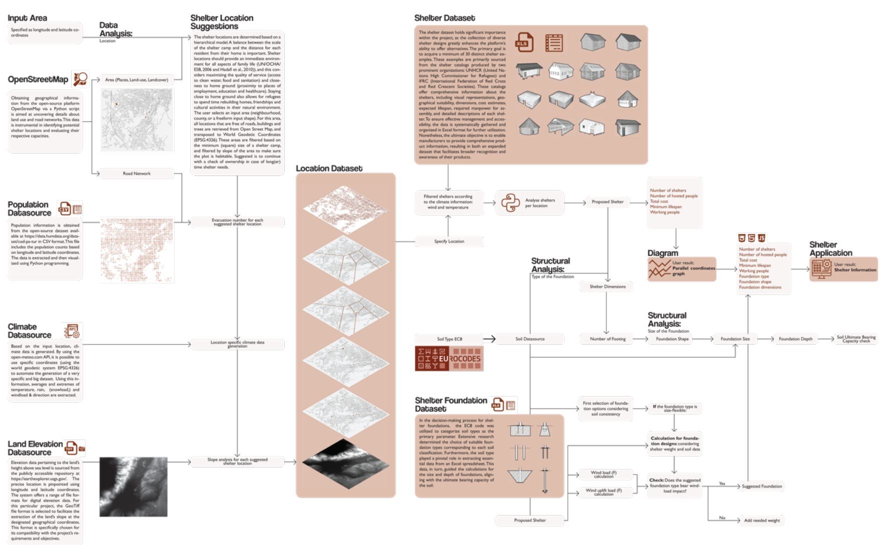
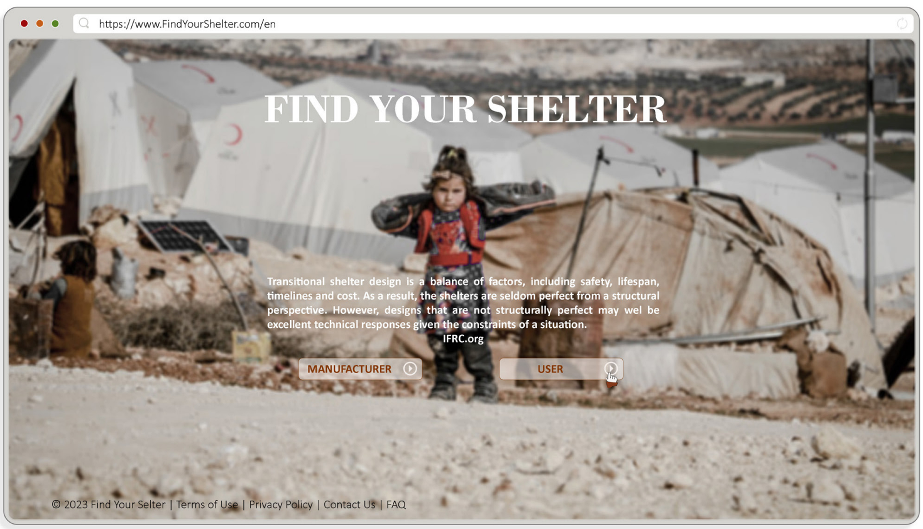


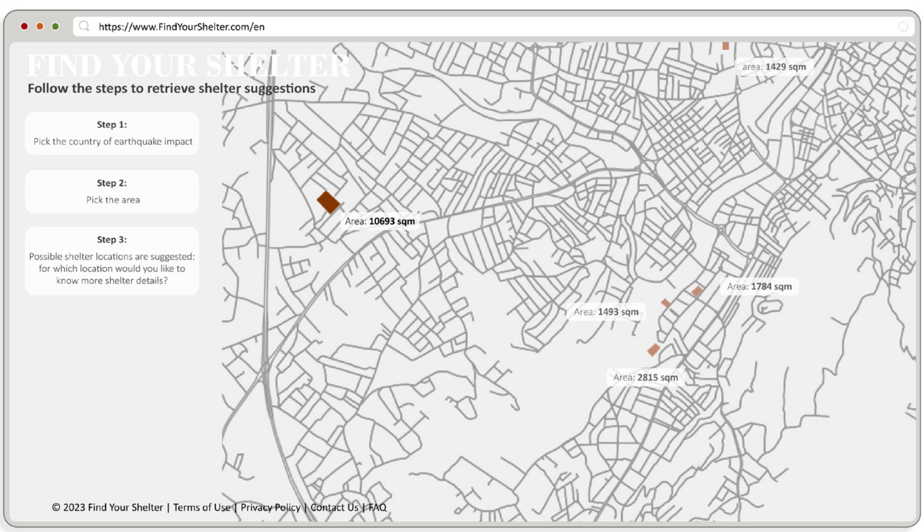
Figure 2. Computational workflow.

Results

The findings of this research reveal that the decision support tool (Figure 3) significantly enhances the efficiency of post-disaster shelter allocation. One of the primary outcomes is the reduction in decision-making time due to the integration of real-time data with pre-existing shelter knowledge. By combining climate, population and soil data, the tool enables tailored shelter recommendations that meet specific local conditions, ensuring better comfort and safety for occupants. The structural analysis of shelter foundations is another key finding, which highlights how different soil types impact shelter stability and the need for appropriate foundations in each context. These results demonstrate that the tool not only speeds up shelter selection but also contributes to the longevity and sustainability of the shelters deployed. The tool's capacity to analyze various site conditions and match them with shelter types ensures that emergency housing solutions are more resilient and better suited to both immediate and long-term needs.



(a)



(b)

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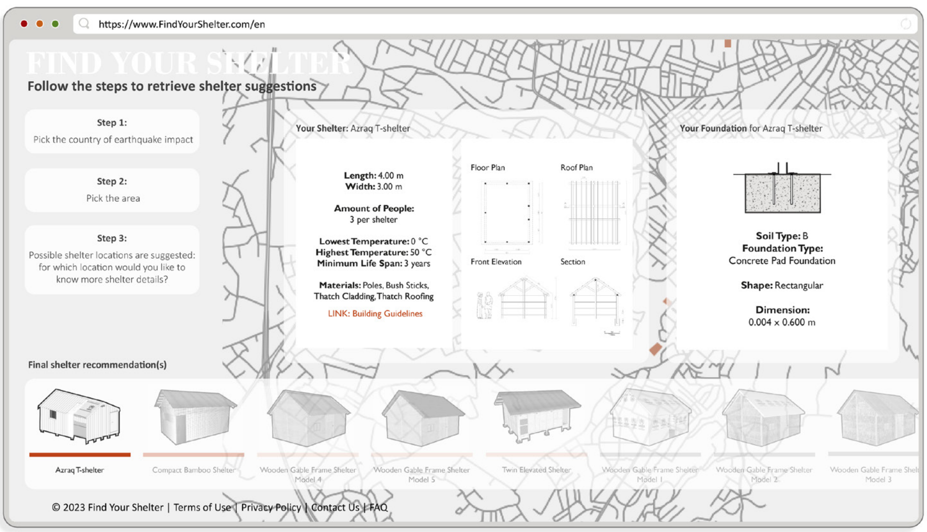


(d)

Figure 3. The final website visualization: (a) first page, (b) zoom-in area map, (c) analysis, (d) shelter details.

Conclusions

The most important takeaway from this study is the development of a practical tool that optimizes shelter allocation processes after a disaster. The research underscores the importance of integrating data from multiple sources to improve the quality of shelter decisions, especially under the pressure of time. By focusing on local site conditions, the tool ensures that the shelters selected provide structural stability, cultural appropriateness, and long-term sustainability. However, a key limitation of the tool is its current reliance on data from specific regions, such as Türkiye. Future research could focus on expanding the tool's applicability to a broader range of geographic locations and incorporating additional types of natural disasters, like floods or hurricanes. Despite this limitation, the tool represents a significant advancement in post-disaster response efforts, providing a robust framework for faster, more informed shelter decisions.

References

1. OpenStreetMap contributors, "OpenStreetMap," OpenStreetMap Foundation. Available: openstreetmap.org.

Project RED: Rapid Estimation of Disaster Consequences

Ramya Kumaraswamy, Sofia Markson

The earthquake that struck the Turkey–Syria border region in February 2023 exposed a critical gap in the speed of disaster response. Despite technological advancements, the extraction and analysis of satellite imagery still delayed search and rescue operations by more than 24 hours. Project RED is a simulation-based tool developed to shorten the time required to assess post-earthquake structural damage. It integrates seismic design codes with a national GIS database of building archetypes and real-time ground motion acceleration data to rapidly identify high-risk structures.

The tool uses a combination of Multi-Degree-of-Freedom and simplified Single-Degree-of-Freedom models to simulate how buildings respond to seismic forces. Key outcomes of the project include the generation of risk zone maps, acceleration response spectra and deformation profiles to support emergency planning. Project RED demonstrates that immediate structural risk assessments are feasible even before satellite data becomes available, significantly reducing the response lag. Open-sourcing the GIS database could further enhance accessibility and foster collaboration in disaster preparedness.

Keywords: Earthquake, Simulation tool, Loss assessment, Response strategy, Disaster management

Introduction

Project RED or “Rapid Estimation of Disaster Consequences” is a simulation tool designed to enhance the efficiency of response teams in post-disaster management following earthquakes. The tool leverages a comprehensive database of building archetypes and real-time earthquake acceleration data. It operates in alignment with seismic design codes, with a strong emphasis on structures that possess sufficient deformation capacity to withstand intense ground shaking.

By evaluating key parameters such as inter-storey drift limits for both serviceability and ultimate limit states, the simulation identifies buildings at severe risk or those near collapse. With its user-friendly interface, Project RED allows users to select earthquake magnitudes from a historical database, input archetype analysis data, and specify the analysis location. This process generates a variety of visual outputs, including acceleration time series, deformation response spectra, vibration patterns and risk maps.

However, Project RED currently faces limitations related to the development of country-specific databases and building-specific parameters. These databases are still conceptual and limited in scope. To overcome this, Project RED aims to build its own database using a dedicated structural analysis tool capable of accommodating the most common archetypes found in Turkey.

The proposed approach is centred on generating a seismic response map, with a focus on seismic design principles and structural assessment to understand how dynamic systems respond to earthquakes. Structural analysis led to the development of Grasshopper–Karamba3D scripts, enabling realistic assessment within a Multi-Degree-of-Freedom (MDOF) environment. Although seismic evaluation often requires simplifying structures into Single-Degree-of-Freedom (SDOF) systems, the approach yielded valuable insights.

Three key variables - natural frequency, participation factor and vibration shape were identified to inform tool development. By solving the governing equation of motion for SDOF structures, the tool delivers high-precision estimations of potential structural damage.

Method

The methodology follows a simulation-based, performance-driven design strategy integrating structural dynamics and real-time ground motion data. Key steps in the research include:

- **Database Structuring:** Collection and classification of building archetypes commonly found in Turkey.
- **Seismic Input Integration:** Application of real-time earthquake acceleration data. In this program, historical data were used to train the model.
- **Structural Modelling:** Use of Karamba3D[1] in Grasshopper[2] for dynamic structural simulation of the archetypes found in Turkey.
- **Damage Estimation:** Analysis based on SDOF response systems solving governing motion equations.
- **Risk Mapping:** Generation of visual outputs - risk zones, response spectra and deformation profiles. The simulation run until a popup window displays the output results. In this window, the “Neighbourhood Map” and “Risk Response Map” can be viewed. Additionally, the “Open Outputs Folder” button can be accessed to open the outputs folder in the same working directory, where intermediate results are stored.

Results

The simulation was tested using historical earthquake data. Key findings include:

- **Reduced Time-to-Insight:** Structural risks were visualized within 15–20 minutes after inputting seismic data - significantly faster than traditional satellite-based methods.
- **Key Variables Identified:** Natural frequency, participation factor and vibration shape - as critical parameters influencing structural collapse.
- **Visual Outputs**:
  1. **Acceleration Time Series** (Figure 1, top left) displays ground acceleration data for the selected ground motion event.
  2. **Deformation Response Spectra** (Figure 1, top right) illustrates the buildings’ response to specified seismic activity, showcasing data alignment with SeismoSignal software.
  3. **Modal Shapes** (Figure 1, bottom left) graphs show the fundamental mode of vibration or the governing pattern of displacement that the archetypes undergo during the seismic event.
  4. **Peak Displacements** (Figure 1, bottom right) graphs illustrate the maximum displacement encountered by each floor within a given archetype during a selected ground motion event.

5. **Neighborhood Map** (Figure 2, top) is a visual representation of various types of archetype buildings in a specified neighborhood. In the current simulation program, they are randomly assigned to the existing building footprints. The Neighbourhood Map provides a visual representation of an imaginary neigbourhood populated by various building archetypes. Please note that in the current simulation, we can simulate only 9 different building archetypes. The map randomly assigns these archetypes to existing building footprints, offering a graphical depiction of the imaginary neighborhood's diversity.

6. **Risk Response Map** (Figure 2, bottom) is a visual representation of danger spots within a neighborhood that has been subjected to severe damage or collapse due to the earthquake. The Risk Response Map visually portrays earthquake-affected archetypes within the specified neighborhood. Fatality risk assessment adheres to Turkish and international design codes, specifying Inter-Story Drift standards: 0.016 times the story height for Serviceablitity Limit State (SLS) and 0.025 times the story height for Ultimate Limit State (ULS). Non-compliance indicates a significant risk of structural damage or collapse, respectively.

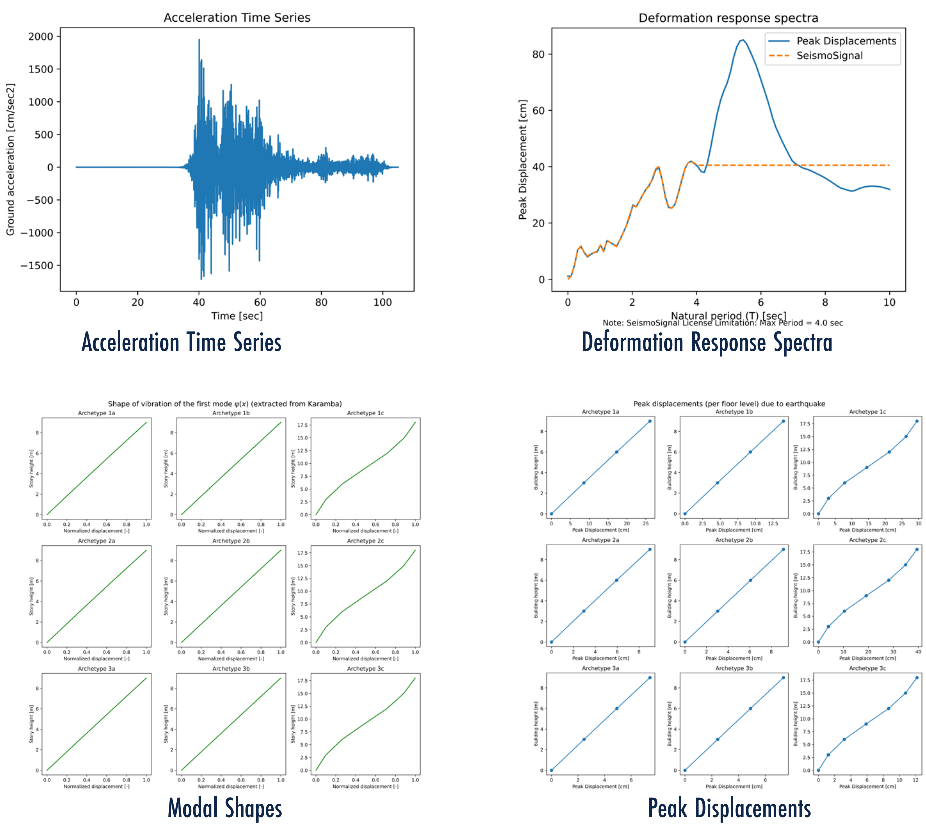
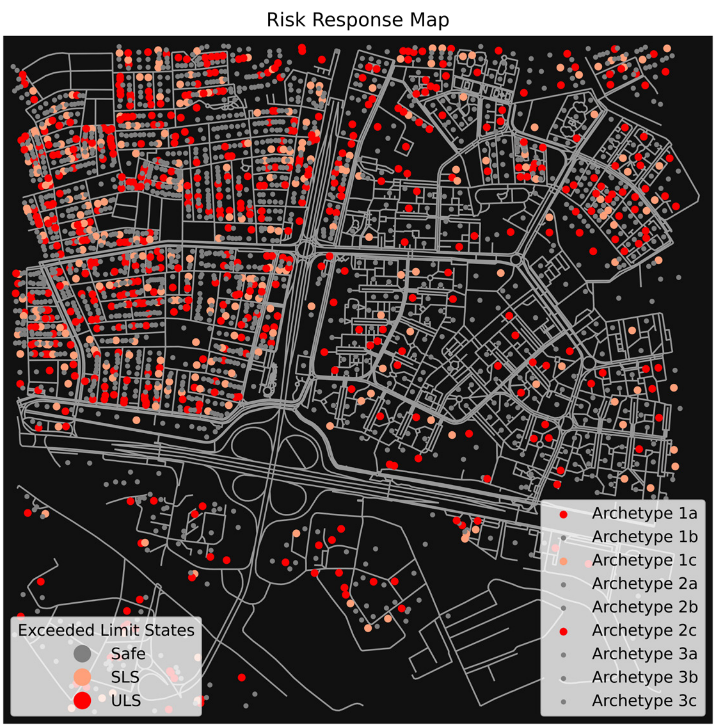


Figure 1. Visual outputs.

Neighbourhood Map



Risk Response Map

Figure 2. Risk mapping.

Conclusions

Project RED demonstrates a feasible and scalable method for rapid post-earthquake risk estimation. It significantly shortens the critical time gap before search and rescue operations can be launched, addressing a long-standing bottleneck in disaster response workflows. However, limitations remain especially regarding the lack of a publicly accessible, nationwide GIS database with structural parameters. Additionally, the reliance on proprietary tools like Rhino-Grasshopper-Karamba3D raises accessibility concerns.

Future research should focus on: (i) developing an open-source GIS database for seismic risk modelling; (ii) incorporating machine learning to improve predictive accuracy; (iii) expanding structural archetype libraries for diverse geographic regions. The study underscores the need for community-involved, data-driven solutions to improve resilience in earthquake-prone areas.

References

1. C. Preisinger, “Linking Structure and Parametric Geometry, ” *Architectural Design*, vol. 83, pp. 110-113, 2013, doi: 10.1002/ad.1564.
2. R. McNeel et al., “Rhinoceros 3D, Version 6.0,” Robert McNeel & Associates, Seattle, WA, 2010.

Custom Emergency Shelter Design in Türkiye Based on Japanese Wood Joinery

Elisa van Klink, Amir Ghadirilangari

Tsugite, responds to an urgent need for customizable and sustainable emergency shelters in earthquake-prone regions. Inspired by traditional Japanese wood joinery, the project aims to create a shelter design that is easily assembled, transportable and capable of withstanding the forces of aftershocks. Additionally, it provides an opportunity for users to actively engage in the construction process. Employing a computational design methodology utilizing Python, Rhino and Grasshopper, the project creates an environment that allows disaster victims or planners to interactively design their own custom shelter. The project translates users' needs into a digital design, which is then converted into CNC-milled components, enabling on-site assembly without requiring specialized skills or equipment. Key innovations include modular grid systems allowing for lateral stability by bracing, and optimized structural elements specific to desired spatial configurations. The results demonstrate the feasibility of this method through prototypes and a fully functional scale model. Several challenges remain to be addressed, including the durability of joints during construction, automation of seismic load simulations, integration between software and hardware, and optimization of material usage. However, Tsugite represents an important first step toward providing a solid foundation for scalable, earthquake-resistant shelter design, strengthening the connection between emergency relief and permanent housing solutions.

Keywords: Emergency shelter, Earthquake-resistant design, Timber construction, Modular design, Computational design

Introduction

Annually, millions of people are displaced by conflicts and natural disasters. According to the 2023 Global Report on Internal Displacement (IDMC)[1], the number of internally displaced persons (IDPs) has risen steadily over the past nine years, from 33.3 million to 71.1 million, with displacement due to natural disasters increasing by 45% compared to the previous year.

Shelter provision is critical in addressing displacement, offering immediate protection and fostering recovery by stabilizing communities. However, designing disaster shelters is complex, as they must balance immediate and long-term stability, adaptability and cultural appropriateness. Additional challenges include logistical constraints, limited resources and ensuring structural resilience for future disasters. This complexity is particularly evident in earthquake-prone regions like Türkiye. The 1999 Marmara earthquake displaced 500,000 people, with months of aftershocks causing further destruction. More recently, in February 2023, two devastating earthquakes in southern Türkiye and northern Syria displaced millions, compounding existing crises. Recovery has been slow, with homelessness, disrupted social cohesion and mental health challenges persisting.

In response, this research aimed to develop earthquake-resistant shelters tailored to Türkiye's challenges. The focus was on designing shelters that are quick to assemble, customizable and efficient to transport. To achieve this, the project developed a user-centered interface combined with computational tools, allowing for the rapid customization and production of CNC-milled timber structures. This approach seeks to simplify shelter delivery and bridge the gap between disaster and recovery, providing innovative, adaptable and resilient shelter solutions for affected populations.

Method

The workflow followed in this project is illustrated in Figure 1. The first phase involved a literature review of existing shelter solutions, vernacular architecture and traditional wood joinery techniques like Tsugite, Hımış and Dougong. These were studied alongside computational design approaches for disaster management to conceptualize a modular design that aligns with the research objectives: easy assembly, disassembly, transportation and customization. A digital platform using Python[2] and Tkinter was then developed to allow users to sketch floorplans and customize their shelters. The user inputs were processed into digital models via Grasshopper, Rhino[3] and CSV files. Structural evaluations were conducted using the Karamba3D plugin in Grasshopper to ensure stability and optimize the designs. Finally, the design was tested by creating a scale model based on digital outputs, assessing construction ease and joint performance to identify and address any overlooked details.

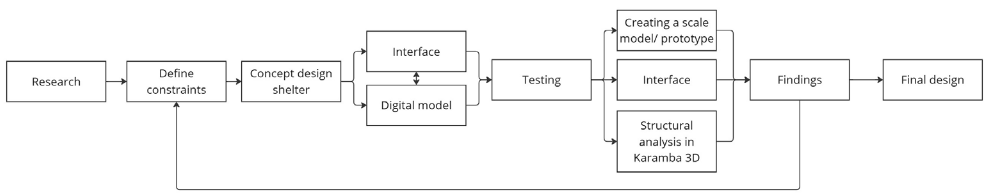


Figure 1. Project workflow.

Results

To create a shelter that is easy to assemble and resilient to aftershocks, the project focused on traditional wood joinery techniques relying solely on friction for structural integrity. These methods, requiring no specialized tools or large machinery, have proven durable, with numerous timber structures using such techniques, surviving for centuries in seismic regions. Key inspirations included:

- *Tsugite (Japanese wood joinery)*: Tsugite, a Japanese wood joinery method, involves intricate puzzle-like connections. Despite their precision and durability, the complexity of these joints makes mass production challenging. Inspired by a tool developed at the University of Tokyo[4] that simplified Tsugite joinery by utilizing CNC-milling and computational tools, the project adopted similar methods to create customizable, user-friendly joints for emergency shelters.

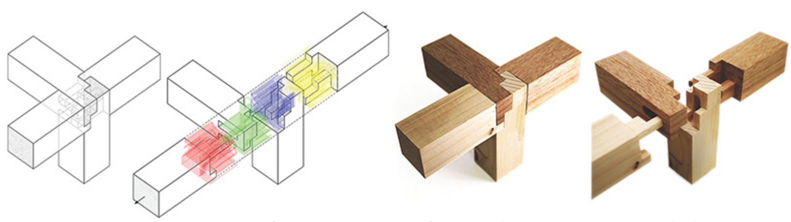


Figure 2. Tsugite, project of the University of Tokyo (Larsson et al. [4]). (copyrighted)

- *WAAS (Wooden Adaptive Architecture System)*: The WAAS project[5] demonstrated modular adaptability with Dougong and Chidori joints. Its grid-based system influenced the shelter's modular design, enabling flexible, user-defined layouts.
- *Hımış construction*: Traditional Hımış techniques, used in Turkey and other regions across the globe, involve timber frames subdivided into smaller sections often filled with either bricks, stone or adobe. Known for their seismic performance, these structures inspired our grid system, emphasizing bracing and smaller subdivisions for stability under seismic loads.

Resulting Modular Design

The final modular design incorporated seven joint types, eight beams, one column type and two bracing elements (Figures 3 and 4). Joints were based on Chidori, bracing and frames on Hımış, and a 1-meter grid size was selected for scalability and simplicity in construction.

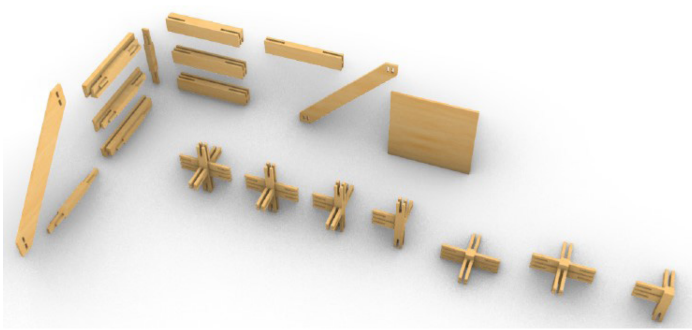


Figure 3. Modular design elements.

Figure 4. Example of a shelter.

Developing the digital model

The modular design was brought to life through a parametric digital model, allowing users to create their shelters. The process began with a Python-Tkinter[2] interface where users sketched layouts. These inputs were exported as CSV files and processed in Grasshopper and Rhino[3] to generate 3D models. Structural components like beams, columns and joints were automatically created using Python[2] scripting and parametric tools. Structural analysis in Karamba3D[6] ensured stability and material efficiency.

However, the process presented its own challenges:

- Drawing-to-grid conversion: Early freehand drawings caused inaccuracies, such as overlapping or misaligned points. Snap-to-grid functionality was introduced to enhance precision, though it reduced flexibility.
- Data transfer issues: Initial attempts to use the HOPS plugin for data transfer led to errors. Switching to CSV-based point storage improved reliability but required manual updates in Grasshopper[3].
- Boundary challenges: Open spaces in layouts were sometimes misinterpreted, leading to unintentional filling. Script refinements addressed but did not fully eliminate this issue.

Final outcome

After iterative refinements, the workflow successfully translated user designs into structurally sound digital models (Figure 5). A scale model validated the system's ease of assembly, confirming the feasibility of integrating traditional techniques with computational tools. The resulting shelter system is modular, adaptable and resilient, bridging user-friendly customization and seismic safety.

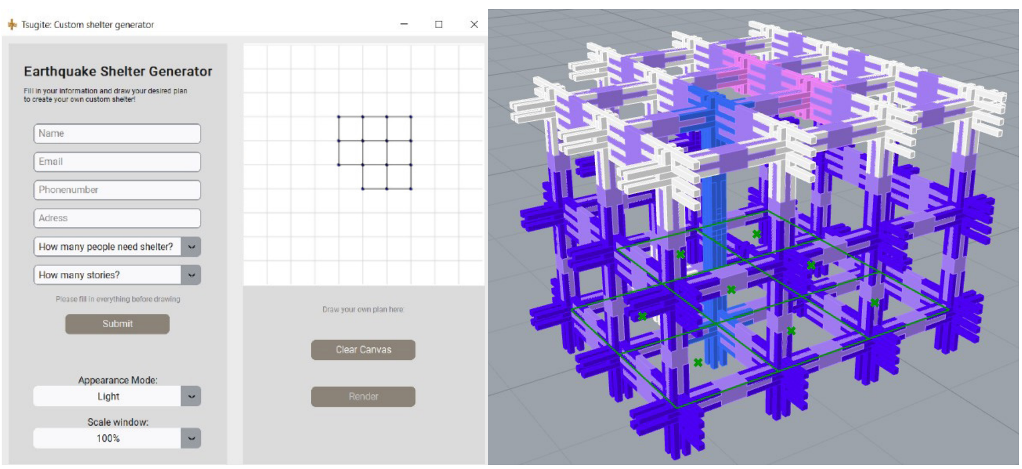


Figure 5. User Interface and Grasshopper model.

Conclusions

This study demonstrates how traditional construction methods, such as Japanese interlocking joinery and Hımış techniques, combined with modern computational tools, can create sustainable, adaptable and resilient shelters. These designs minimize the need for specialized tools and materials, are easy to assemble and disassemble, and empower users to contribute through simple drawings.

While the project shows promise, it remains in its early stages, with several areas for improvement. Future developments include automating processes further, creating an online platform to replace Grasshopper installations, and generating CNC milling files automatically. Integrating seismic force analysis, optimizing joint sizes and reducing material redundancy could enhance structural performance and sustainability. Exploring alternative materials, such as steel, also offers exciting opportunities for adaptability and efficiency.

Additionally, moving beyond the uniform 1x1 grid to incorporate varied geometries and architectural elements, such as stairs and openings, could enhance usability and livability. These advancements would build upon the foundation established by this project, empowering disaster-affected individuals to participate in shelter design and accelerating recovery through quicker, more adaptable solutions.

References

1. Internal Displacement Monitoring Centre, “Global Report on Internal Displacement (Geneva: IDMC, 2023),” Available: https://www.internal-displacement.org/global-report/grid2023/.
2. Python Software Foundation. Available: http://www.python.org.
3. R. McNeel et al., “Rhinoceros 3D, Version 6.0,” Robert McNeel & Associates, Seattle, WA, 2010.
4. M. Larsson, H. Yoshida, N. Umetani, and T. Igarashi, “Tsugite: Interactive Design and Fabrication of Wood Joints,” Proceedings of the 33rd ACM Symposium on User Interface Software and Technology, 2020.
5. A. Potvin, C. Demers, and C. DuMontier, “Wooden Adaptive Architecture System (WAAS),” Proceeding of International Conference on Adaptation and Movement in Architecture (ICAMA2013), 2013.
6. C. Preisinger, “Linking Structure and Parametric Geometry, ” *Architectural Design*, vol. 83, pp. 110-113, 2013, doi: 10.1002/ad.1564.

Satellite Image Segmentation: Identifying Collapsed Buildings and Assessing Vulnerable Types

Veronique van Minkelen, Kuba Wyszomirski, Jair Lemmens

This project focuses on developing a web-based tool for identifying collapsed buildings in earthquake-affected regions, leveraging satellite imagery and machine learning. The tool uses two deep learning models, Mask R-CNN and Visual Transformer, to perform image segmentation and classify damaged buildings. A key component of the project is a database that provides additional building details—such as construction year, height and materials—that can inform rescue efforts and assess building vulnerabilities. The models are compared for accuracy, robustness and biases, with a focus on identifying patterns that increase collapse risk.

The final web interface integrates these components, providing real-time updates and geospatial data, designed to assist emergency responders in making fast, informed decisions during disaster recovery. The project aims to streamline the identification of damaged buildings, prioritize resources and guide future construction practices to mitigate earthquake risks.

Keywords: Disaster recovery, Satellite imagery, Building damage, Image segmentation, Web interface

Introduction

In the aftermath of an earthquake, buildings often suffer damage or complete collapse, leading to the entrapment of people in remote areas. Providing guidance to emergency services becomes crucial in such situations, improving the odds of rescuing those in need.

The project aims to create a user-friendly web interface that can pinpoint buildings damaged during an earthquake based on satellite imagery. For additional context and better resource allocation, this interface connects these buildings to a database that provides additional information, such as building height, the presence of hazardous materials, and the primary structural system of the damaged building.

The first part of the project aims to develop, train and assess a deep learning model to perform image segmentation and object classification on the post-disaster satellite imagery. To find the most suitable algorithm for this problem two deep neural network architectures are developed. These are then compared in terms of solution robustness, biases and effectiveness.

The second part adds a database containing building properties. This has two functions, firstly, it helps assess the extent of the damage and prioritize rescue and relief efforts. Secondly, it aids in understanding the vulnerabilities of construction methods and materials, which can inform future building practices to mitigate earthquake risks.

Finally, the detection algorithm and database are integrated into a user interface, whose development is guided by research in data visualization and user experience (UX) design. The interface prioritizes clarity and usability to support rapid decision-making. Key features include real-time data updates, high accuracy, intuitive navigation tailored to diverse users, integration with mapping and geospatial data, and accessibility for a wide range of responders.

The investigation of the problem leads to the formulation of the following research questions, which will be addressed by the study: (i) How can Machine Learning tools help to identify collapsed buildings from a satellite image? (ii) Which building typologies and on the basis of what parameters have a higher chance to collapse? (iii) How can we communicate the information to users (emergency services) on a unified web interface?

Method

Figure 1 depicts a general flowchart of the workflow, which consists of five main parts:

- *Machine Learning*: The training dataset is downloaded, assessed and selected. Then it is formatted to fit each of the machine learning models. Two machine learning models are created, trained on the formatted data and evaluated. This creates a feedback loop for the training.
- *Model evaluation*: Both models are examined regarding their performance on the training dataset.
- *Building dataset construction*: For the database, five key building properties have been gathered from the available data: construction year, type, area, number of floors and the damage grade after the earthquake. Other characteristics have been manually added to the dataset to expand on it. Then building footprints from Open Street Map[1] are connected to the properties.
- *Statistical analysis*: This stage involves conducting various analyses to identify patterns of collapsed buildings in each city and comparing them with the detections of the neural network. The characteristics of collapsed buildings are analyzed to identify common traits. Additionally, hazardous materials are determined from the building properties.
- *User interface*: The trained machine learning model is deployed into a web application. The created database for the selected towns in Turkey is overlayed with satellite imagery after the disaster for a case study.

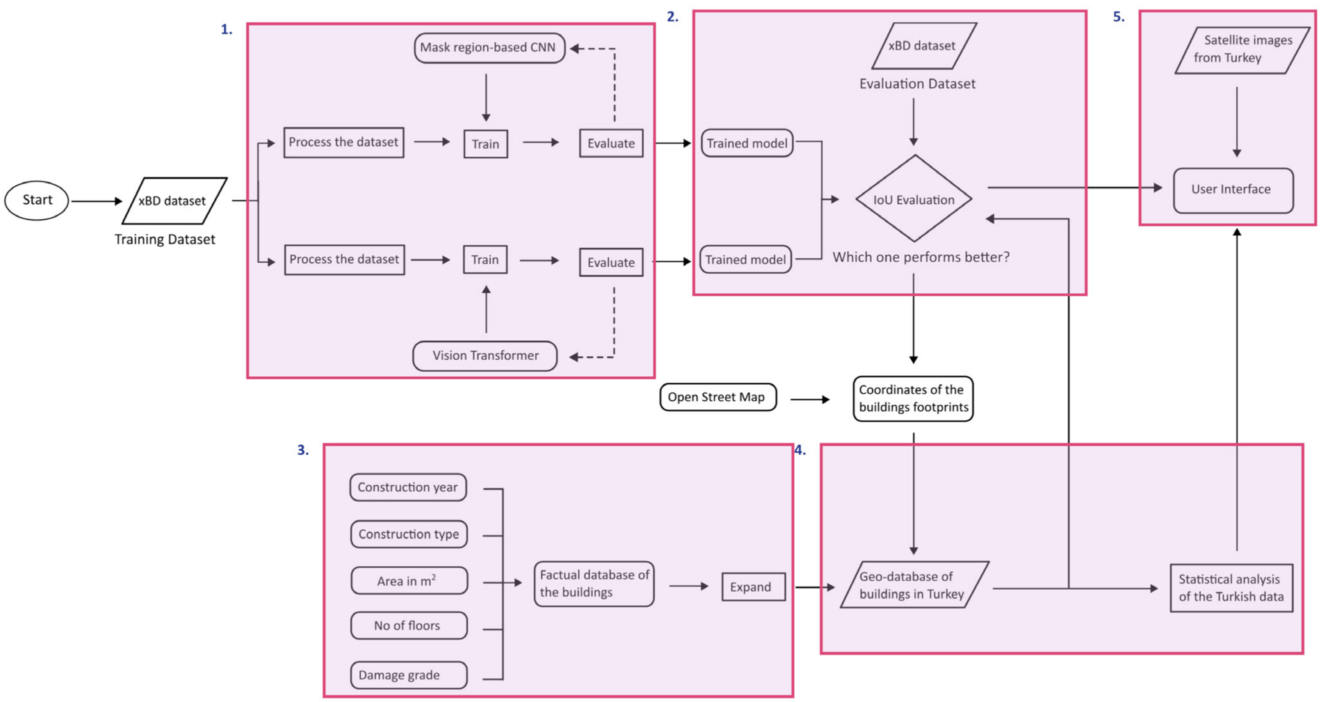


Figure 1. Research workflow.

Results

Mask R-CNN

Mask R-CNN is a deep learning architecture designed for a variety of computer vision tasks, with a particular focus on instance segmentation. It is an extension of the Faster R-CNN framework, which combines object detection and region proposal networks. It extends the capabilities of Faster R-CNN by adding an additional branch to the network that is dedicated to predicting pixel-wise object masks in addition to bounding boxes and class labels. It has been widely used in various applications, such as object instance segmentation, human pose estimation, and interactive image segmentation.

In this specific application, the following steps are involved (Figure 2):

- *Input data*: Mask R-CNN takes as input RGB images with the following associated targets: bounding boxes that specify the location of objects within the images, class labels for each object within a box, and pixel-level masks for objects indicating which pixels belong to each object instance.
- *Convolutional encoder*: The input image goes through a backbone network, typically a deep convolutional neural network like ResNet or VGG. This backbone network extracts feature maps from the image, which are crucial for subsequent stages of the network.
- *Region Proposal Network*: Just like Faster R-CNN, Mask R-CNN includes an RPN. The RPN generates region proposals, which are bounding boxes that potentially enclose objects of interest in the image.
- *Region of Interest*: RoI Align employs bilinear interpolation to sample features from the original feature map, resulting in precise feature alignment and accurate localization of object boundaries corresponding to each region proposal. It overcomes the problem of misalignment of Faster R-CNN's RoI pooling.

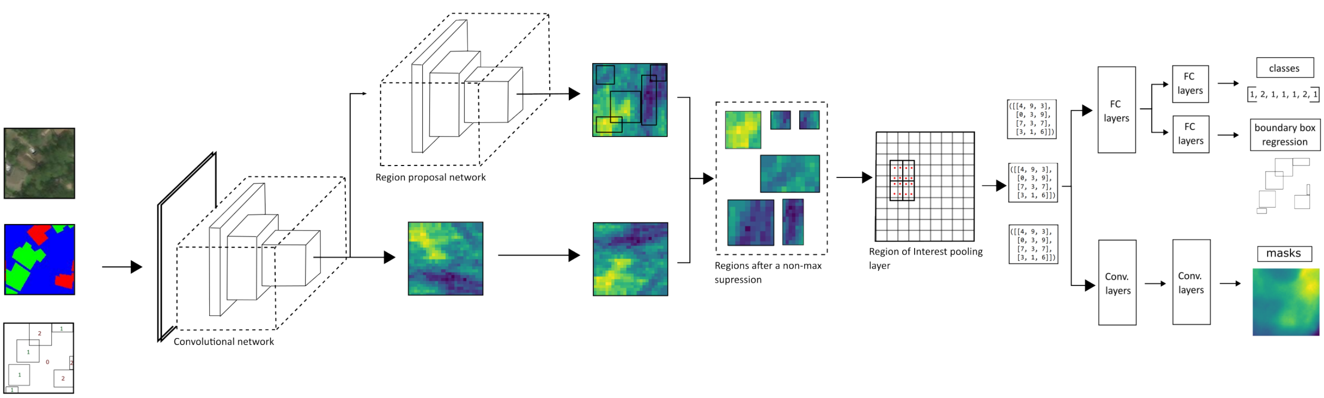


Figure 2. Mask R-CNN approach.

- *Object Detection Head*: Fully connected networks that in addition to predicting class labels and bounding box coordinates, the object detection head of Mask R-CNN also predicts class probabilities and refines the bounding box coordinates for each region proposal.
- *Mask Head*: Another convolutional network branch predicts instance specific masks for objects within each region proposal. It generates binary masks for each object, indicating which pixels in the image belong to that object. These masks are highly detailed and provide pixel-level segmentation.

Visual Transformer

The Visual Transformer (ViT) architecture (Figure 3) relies primarily on the use of the Attention mechanism. Both the encoder and decoder of a state of the art ViT such as SegViT, on which this project is largely based, are built up from repeating blocks containing an attention block (ATTN) followed by a multi-layer perceptron (MLP). Attention is a colloquial term for the scaled dot-product attention mechanism which as the name suggests relies on the dot-product operation. In a ViT, it is used to determine how relevant each part of the image is to all other parts of the image or class tokens.

The architecture of the encoder is a convolutional neural network (CNN) based on ConvNeXt developed by FAIR and UC Berkeley[2]. This architecture integrates multiple design features developed for both CNNs and transformers. A convolutional neural network is as the name suggests based on the mathematical operation of convolution. Typically, the convolutions are used to down- up sample the data in a cascading manner exchanging width and height for depth. In this case the CNN is responsible for translating the 16x16x3 patches into 1x1x48 feature maps. The model is built up from blocks which are repeated in layers that progressively down sample the data into the features maps.

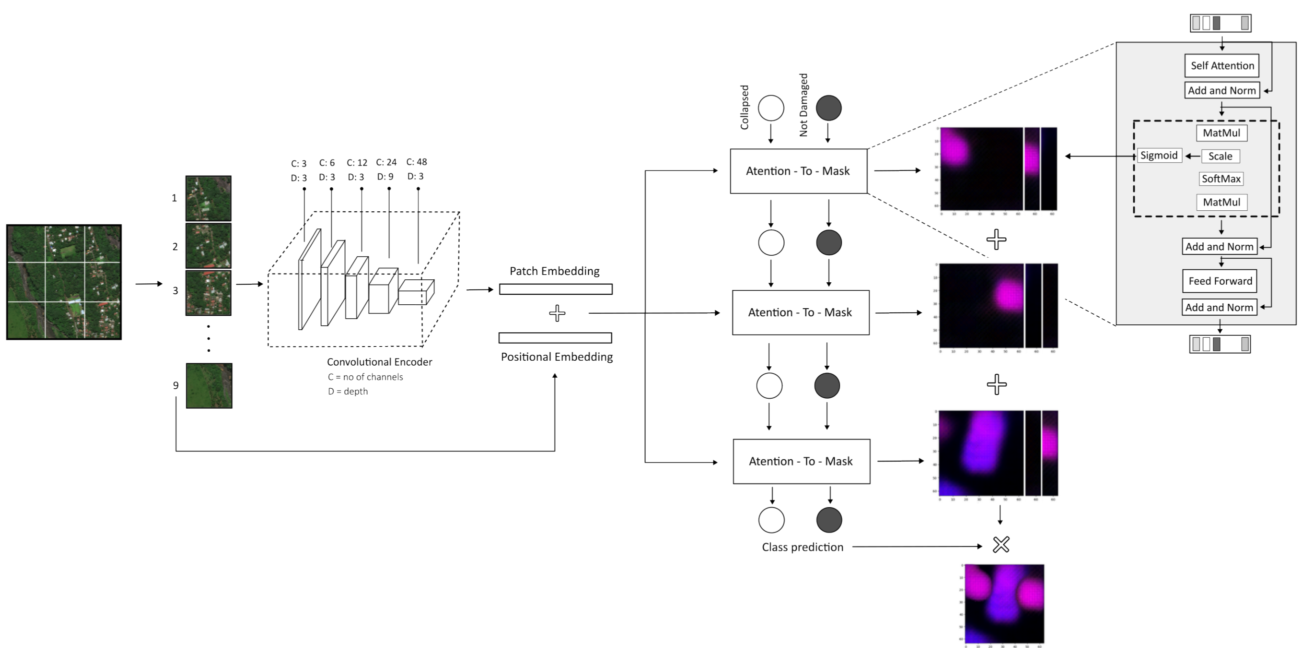


Figure 3. ViT approach.

The decoder uses Cross attention which correlates image patches with the classes that have to be identified. To achieve this the Q contains the learnable class embeddings for the metaphorical cats and dogs and the K and V both contain linear transformations of the image patches. The last piece of the puzzle is the conversion from attention to masks, which is actually quite straightforward since the attention map already shows which parts of the image correlate most with each class. All that is needed is a sigmoid function which maps the activation from 0 for definitely not a cat to 1 or absolutely a cat, this sigmoid function was later removed but more about that later. The only problem is that these attention maps are on a patch basis so as a result the resolution of the output is only 1/16th of the original image (16 since this is the size of a patch), to address this the results are up sampled using a bilinear interpolation.

Database

Figure 4 depicts the database management flowchart, focusing on the collection of information pertaining to damaged and collapsed buildings in a (remote) area. The focus is specifically on four cities located near the epicenter of the February 6, 2023 earthquake in Turkey. The figure illustrates how the programming was ultimately executed. However, not all the required data could be obtained, necessitating the use of randomizers to generate dummy datasets. The flowchart comprises five primary stages, each of which will be elucidated individually.

Open street map and earthquake data

The investigation of the four cities, namely Islahiye, Marash, Nurdagi and Turkoglu, is carried out using Open Street Map (OSM)[1]. OSM provides geographical coordinates for building footprints, presented in longitude and latitude, along with information about the area covered by these footprints.

This step is dedicated to understanding the earthquake's location, its aftermath, and the relationship between the distance of the cities from the epicenter. Factors such as the earthquake's magnitude and strength are taken into consideration to assess the extent of damage.

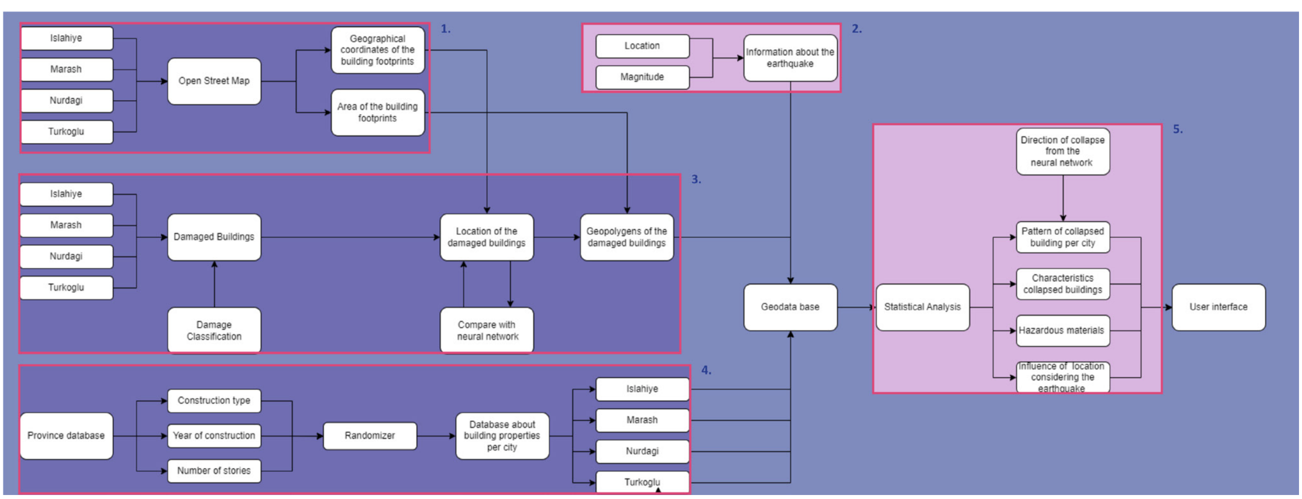


Figure 4. Database management flowchart.

Assessment of damaged buildings

For the four cities, a classification of building damage, ranging from undamaged to collapsed, is performed. Using the coordinates provided, the precise location of each undamaged, damaged, and collapsed building can be determined. This data is subsequently compared with the generated network to evaluate if the network produces a comparable damage map. Multiple damage maps are created based on area, coordinates, and damage level.

A properties database is created for the provinces of Gaziantep and Kahramanmaras, where the four cities are situated. However, specific information about each building's properties is unavailable. To address this, a randomizer is employed to generate attributes such as construction type, year of construction, and the number of stories. As a result, four databases are established for each building footprint, containing these characteristics.

Statistical analysis

This stage involves conducting various analyses to identify patterns of collapsed buildings in each city, comparing them with the neural network (Figure 5). The characteristics of collapsed buildings are analyzed to identify common traits. Additionally, hazardous materials are determined from the building properties. Lastly, an analysis is carried out to understand how the earthquake's epicenter's location influences the damage pattern. In conclusion, all the collected data from Open Street Map, earthquake information, damaged buildings, and building properties are integrated into a single GeoDataFrame.

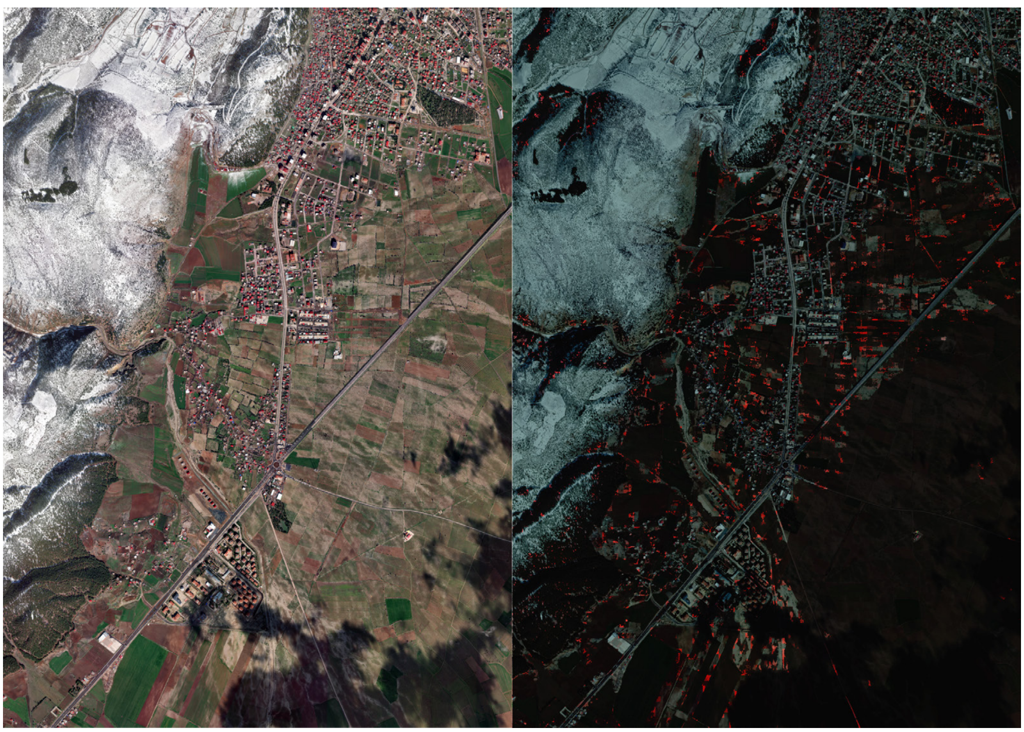


Figure 5. Example of satellite image and interference. (source: Open Street Map [1])

Conclusions

This project has demonstrated that machine learning can effectively detect collapsed buildings in satellite imagery. However, achieving optimal results necessitates a high-quality and more representative database. In terms of choosing between the ViT and Mask R-CNN workflows, this project does not provide a clear-cut answer. Both approaches have their merits, with ViT being a newer option and Mask R-CNN a more mature methodology. The choice would depend on specific project requirements and available resources. Furthermore, the project highlighted the challenges of transitioning between different development environments. This shift can bring unforeseen compatibility issues between machines, underscoring the need for robust deployment strategies to ensure smooth implementation in real-world scenarios.

Currently, due to limited data availability, determining which building typologies are more likely to collapse is not feasible. Nevertheless, the project has developed a methodology that could be applied in the future when real-world data becomes accessible. This methodology focuses on extracting patterns based on building locations, as this information is readily obtainable. Moreover, the communication approach emphasizes visual presentation and is designed not to place any computational burdens on the user's side. The design of the user interface, although simple, enhances the accessibility of the project, making the information easily understandable and readily available.

In conclusion, the project has made significant strides in creating a user-friendly web interface that can aid in earthquake response efforts. By allowing users to access post-earthquake satellite images of rural areas, the process of pinpointing damaged buildings is streamlined, thus saving crucial time for emergency services. The potential of Machine Learning tools to identify collapsed buildings in satellite images has been demonstrated. Despite challenges that highlighted the importance of a high-quality database and logistical considerations, the project remained on track toward a promising solution. Moving forward, it is clear that data availability and further research are key. The project has laid the foundation for a methodology that can identify building typologies with a higher likelihood of collapsing, and this could be applied in real-life as geo-data and satellite images become accessible. Large spatial information system was developed to communicate information within our dataset to potential users in a form that can be rapidly used. This could when developed further save lives during future disasters especially in rural environments.

References

1. OpenStreetMap contributors, "OpenStreetMap," OpenStreetMap Foundation. Available: openstreetmap.org.
2. Z. Liu, C. Y. Wu, C. Feichtenhofer, T. Darrell, S. Xie, Facebook AI Research (FAIR), UC Berkeley, "A ConvNet for the 2020s," doi: 10.48550/arXiv.2201.03545.

SARO: A Decision Support System for Search and Rescue Optimisation in the Aftermath of an Earthquake

Shreya Kejriwal, Pavan Sathyamurthy, Brent Smeekes, Bo Valkenburg

SARO (Search and Rescue Optimization) is a Decision Support System dashboard designed to aid city/country level management in Search and Rescue (SAR) operations in the aftermath of earthquakes. The SARO program functions in two distinct phases. The first involves initial damage assessment and preliminary SAR allocation. In this stage, SARO relies on theoretical models to predict building damage, estimate occupant injuries and generate priority rankings to guide the assignment and deployment of SAR teams. The second phase focuses on advanced resource allocation and scheduling, driven by real-time data. Here, high-resolution information on injuries and hazards enables a more sophisticated response algorithm to optimize the allocation and sequencing of rescue efforts. A case study conducted in Gaziantep, Turkey, serves as the program's primary demonstrator. Synthetic data is used to model the city's building stock, factoring in injury profiles and the life decay of trapped individuals. Some real-world complexities, such as resource scarcity, transportation issues and chaotic environments, are also considered.

Developed in Python, SARO provides meaningful data and recommendations for emergency response planning. However, scalability has proven challenging due to the significant computational demands of its algorithms. Furthermore, the project highlights the critical role of reliable input data - particularly regarding buildings and rescue teams - not only in terms of availability but also in the types and characteristics required to ensure the tool's effectiveness.

Keywords: Disaster response, Earthquake, Search and rescue, Multi-objective optimization, Python programming

Method

The tool's computational process is organized into two main components: (i) building and context assessment and (ii) allocation and scheduling (Figure 1).

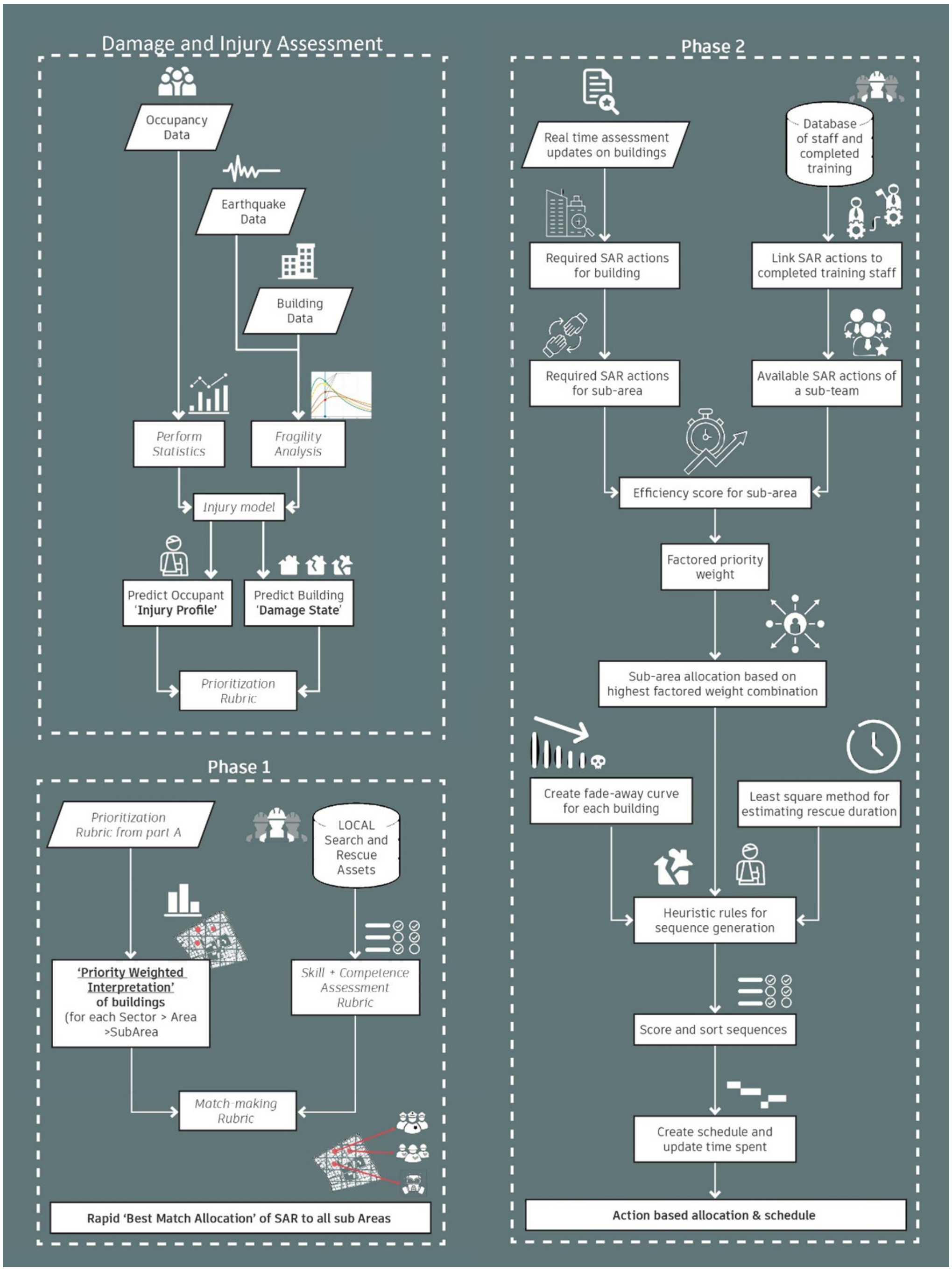


Figure 1. SARO workflow.

Building and context assessment

This phase aims to quickly gather data on building damages and consequent occupant injuries in the aftermath of an earthquake. Real data collection on injuries and structural damage can take hours or days of effort. Therefore, to facilitate a rapid Search and Rescue (SAR) response, the tool first predicts probable building damage and injuries.

Using occupancy data, earthquake characteristics and building profiles, the tool creates fragility curves and occupancy graphs. These estimates probabilistically assess the extent of building damage and the number of victims trapped in affected structures. Based on this assessment, the tool assigns an "Injury Profile" to each building, estimating the number and severity of injuries. A "fade-away" function, represented by a decay curve, is also assigned, estimating how long victims can survive without aid. Both Damage and Injury Profiles (Figure 2) help guide allocation and scheduling decisions in the next phase.

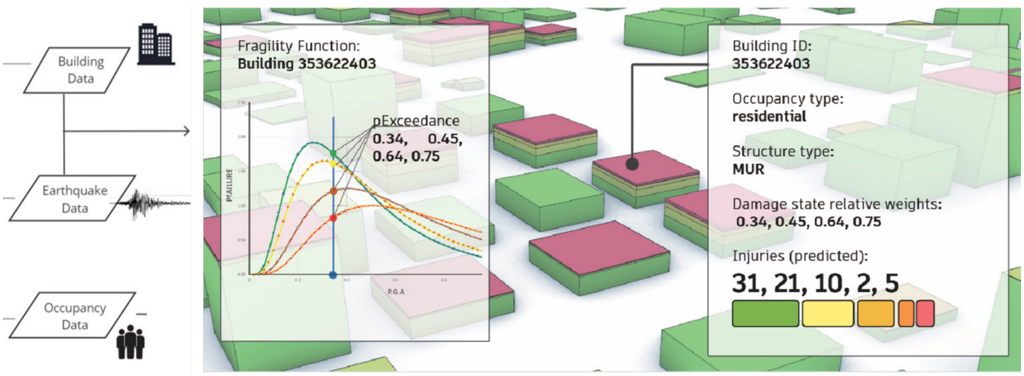


Figure 2. Visualization of predicted injury profiles and damage states based on a Fragility Curve data analysis. This data is presented in the SARO database.

Allocation and scheduling

This phase involves the distribution of rescue resources and their scheduling at rescue sites. Allocation is structured in two phases:

- *Phase 1*: This phase focuses on an initial allocation of rescue resources based on the predicted Damage and Injury Profiles. Buildings are given a priority weight, with higher-priority buildings receiving rescue assets first. This phase enables SAR operations to start before real-time data is available.
- *Phase 2*: After 24 hours, once sufficient real-time data has been gathered, this phase is activated to refine the allocation process. Action-based allocation and scheduling occur on a building level, using "action data" to match rescue teams to specific tasks. This data includes the necessary actions based on the building's damage state and the training level of the rescue workers. Accurate matching ensures that rescue teams are assigned to sites where their skills align with the actions required.

The final step is "scheduling and sequencing" the deployment of rescue teams. The goal is not only to send the right team to the right site but to ensure they arrive at the optimal time, prioritizing the most urgent cases. Time is crucial due to the fade-away function linked to injury severity. The objective is to create a schedule that maximizes the number of lives saved by focusing on the most time-sensitive situations (Figure 3).

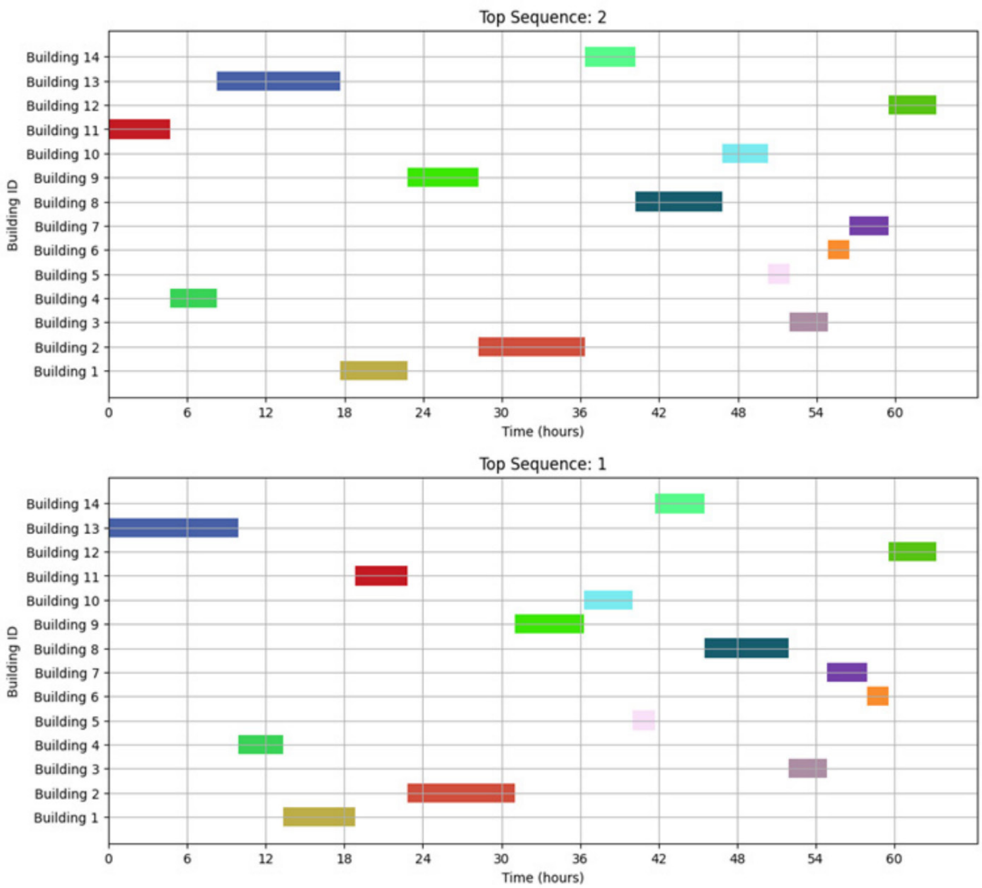


Figure 3. An example of recommended rescue sequences for a given sub-area. The solution is based on a Monte Carlo simulation and comparison method.

Case study

The SARO tool was tested in a case study centered on Gaziantep, a city heavily impacted by the recent 2023 earthquake in Turkey. Gaziantep was selected due to its proximity to the epicenter and the availability of partial data from the local municipality. Three neighborhoods . Pancarlı Mahallesi, Gazi Mahallesi and Sarıgüllük Mahallesi - were modeled using synthetic data to simulate building characteristics, damage states and injury profiles. This was necessary due to the difficulty in obtaining comprehensive GIS and other real-world data. The synthetic data was prepared using European Seismic Risk Model (ESRM2020)[1] databases, developed by the European Facilities for Earthquake Hazard and Risk (EFEHR), to reflect the city's demographics and building stock. Despite relying on synthetic data, SARO's predictive models provided valuable insights into how SAR resources could be allocated in such scenarios (Figure 4).

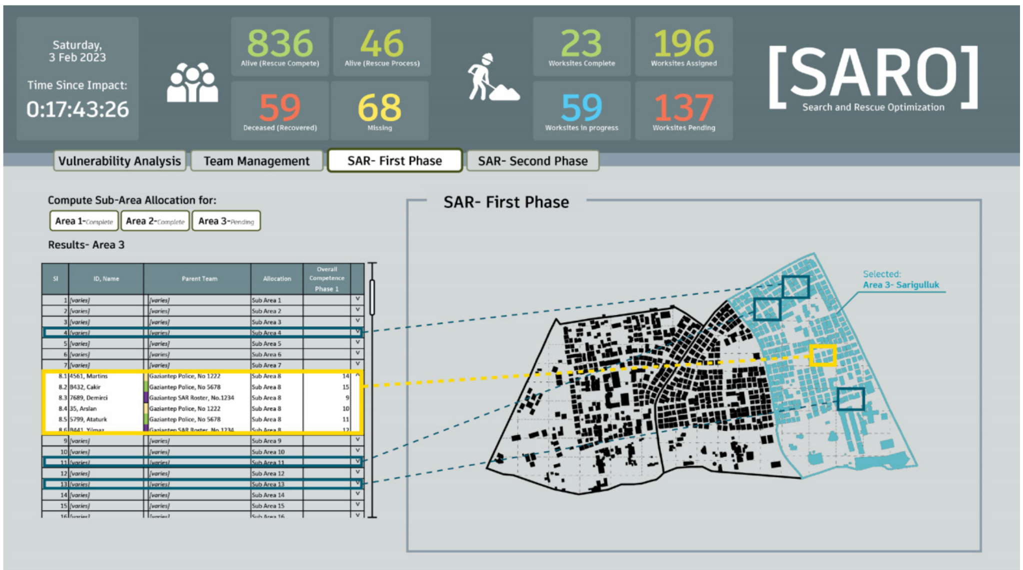


Figure 4. Proposed SARO dashboard. In the SAR First Phase response, the tool provides a recommended allocation of available response teams according to a weight-based allocation to sub-areas. The weights are assigned to sub areas based on occupancy, severity of damage and building types.

Results

The tool successfully computed both allocation and scheduling solutions for the selected neighborhoods across different earthquake magnitudes. However, the Monte Carlo computation implemented in the tool proved computationally intensive and was considered impractical for scaling to larger geographic areas. More efficient computations are required, and if not adequate, it may be required to use machine-learning methods and data-trained models to predict effective solutions. Furthermore, as the project is hypothetical, evaluating the practical effectiveness of the solutions remains challenging.

Nevertheless, the study revealed several key insights and areas for improvement:

- *Data Accessibility and Accuracy*: The First Phase relies heavily on predicted building damage, which is contingent on the accuracy of building attribute data (e.g., construction materials and types). Acquiring this data at a large scale is difficult, but it is necessary for accurate predictions. This data must be compiled and made available for future disaster response efforts.
- *Injury Prediction Accuracy and Secondary Disasters*: The relation between building types, damage states and occupant injuries is complex, as is the probability of secondary disasters (e.g., gas explosions). The current model uses a deterministic approach, which is unlikely to reflect real-world complexities. The true “relation” needs to be established through empirical studies over a history of earthquake statistics in modern times.
- *Rescue Effort Time and Fade-Away Functions*: The optimization algorithms require a time-function for rescue efforts. How long does a team with specific skill levels need to address a building of a given size, type, and damage severity? What is the estimated time required per person? These once again are difficult to deterministically relate, and real-world statistics must be used to “train” the algorithm to understand the time demand. The same is true for the “fade away” of a human life, given an injury profile. This is the most sensitive and ethically delicate issue of the project, projecting causality and probability of survival based on building damage.

Conclusion

The value of this project lies in highlighting the diverse types of data required to operate a computational decision support tool for Search and Rescue (SAR) operations following earthquakes. It also underscores the critical need for proactive preparation in anticipation of future disasters. While the tool’s computational demands may be met with higher processing power in real-world applications, it is clear that this tool has significant potential to enhance real-time decision-making in SAR efforts moving forward. However, as a decision support system, the complexity of the challenges it addresses suggests that its effectiveness is maximized when used in conjunction with the expertise and judgment of experienced professionals within a Task Force Cell.

References

1. H. Crowley et al., “European Seismic Risk Model (ESRM20),” EFEHR Technical Report 002, V1.0.1, 2021.

RE_CONC_STRUCT: A Tool for Designing with Reusable Reinforced Concrete Elements

Nefeli Karadedou, Tahir Zahid Ishrat

This project offers a practical framework to address immediate housing needs while promoting sustainable construction practices, with a focus on future disaster recovery efforts. Natural disasters, such as earthquakes, result not only in loss of life but also in widespread homelessness, creating an urgent demand for large-scale housing solutions. Reconstruction in areas dominated by reinforced concrete structures demands carbon-intensive materials, adding another layer of complexity to recovery efforts.

The project's goal is to tackle these challenges by researching the salvage, retrofitting and reuse of reinforced concrete beams. The methodology includes identifying potential structures for deconstruction, testing the structural integrity of salvaged beams, and developing retrofitting techniques for reuse. Additionally, a Python-based tool is developed to generate structural grid designs for mass housing using available retrofitted beams.

The findings show that salvaged beams can be effectively repurposed for non-structural and mild structural applications, reducing both waste and CO2 emissions in the construction process. These results highlight the potential for innovative design solutions to reduce the environmental impact of disaster recovery while addressing urgent housing needs for affected populations. However, although the technology is not yet economically feasible, its development warrants further exploration due to its transformative potential.

Keywords: Disaster recovery, Reinforced concrete, Reuse, Deconstruction, Smart structural grids

Introduction

As the demand for sustainable construction grows, there is increasing pressure to rethink conventional building methods, particularly in terms of reusing materials. While materials like wood and steel are commonly reused in the construction industry, the reuse of concrete, especially reinforced concrete (RC), is still uncommon. With rapid urbanization and dwindling natural resources, there is a pressing need to design buildings that not only meet safety and performance standards but also reduce environmental impacts. This challenge becomes even more critical in the aftermath of natural disasters, where rebuilding often relies on resource-intensive methods like the widespread use of new reinforced concrete, which significantly increases CO2 emissions.

Natural disasters such as earthquakes destroy large amounts of infrastructure, particularly in regions where reinforced concrete is the primary building material. Rebuilding homes quickly and sustainably is crucial, but the production of new RC structures is both time-consuming and environmentally unsustainable due to the high carbon footprint. Moreover, the demolition and disposal of debris from damaged buildings create additional environmental concerns, filling landfills and requiring substantial labor.

This research seeks to address these challenges by exploring how RC elements from structurally intact but uninhabitable buildings can be salvaged, tested, retrofitted and reused in new constructions. The project includes the development of a Python-based tool to design optimized structures based on the salvaged beams' size and location, ensuring that the new designs are safe and efficient. The overall goal is to introduce a framework that demonstrates how RC elements can be reused, reducing waste, minimizing CO2 emissions and accelerating post-disaster recovery (Figure 1).

Method

The overall research approach is a two-tiered approach that deals with the theoretical analysis and development of a computational tool. The theoretical analysis begins with a literature review and proceeds to practical considerations for harvesting reinforced concrete (RC) beams, aiming to create an inventory of reusable elements. In parallel, the computational tool focuses on developing an algorithm that optimizes structural grid configurations, providing support to architects, engineers or builders engaged in mass housing projects. Grid optimization is performed based on the available stock of reusable beams, aiming to minimize overall structural mass, reduce transportation distance from the warehouse to the construction site, and select grid layouts that align with the available beam lengths.

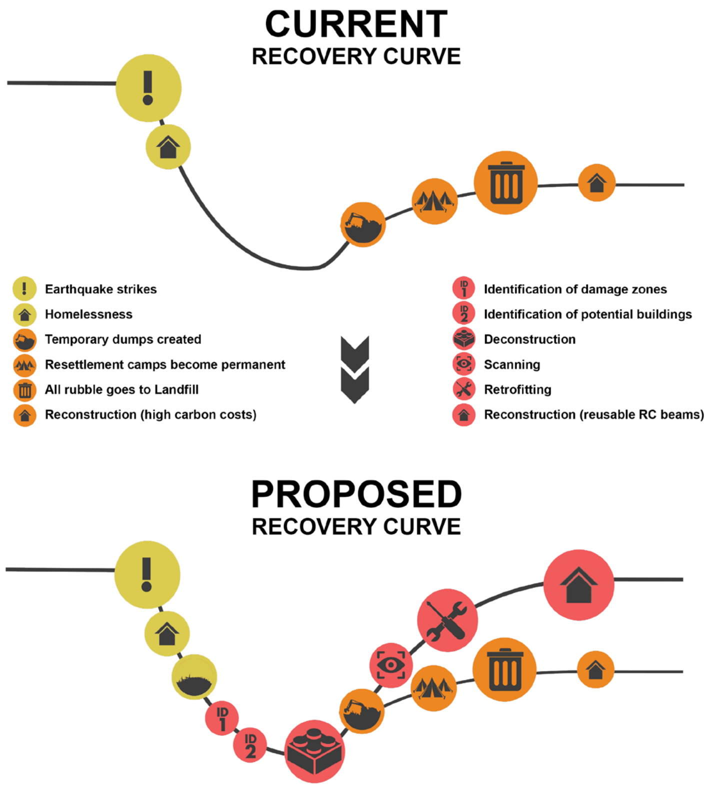


Figure 1. Project aim: improving the recovery of a Disaster Recovery Curve.

The Theoretical Analysis includes:

- *Identification of Potential Buildings*: how potential salvaging sites in damaged zones can be identified and documented.
- *Deconstruction*: how verified buildings can be deconstructed instead of demolished.
- *Testing Beams for Structural Integrity*: how potential beams can be scanned for structural integrity.
- *Retrofitting*: how structurally sound salvaged beams can be strengthened using Fiber reinforced Polymer (FRP), as they may experience reduced shear resistance due to end cuts during deconstruction (Figure 2).

The Computational Tool development (in Python[1]) includes:

- *Data Generation*: database generation based on existing data on RC beams from the Marmara region in Turkey.
- *Data Manipulation*: Script development for automated creation of structural grids using available beam elements. Various grid combinations are

generated based on user inputs and optimized for structural integrity, material availability, self-weight and proximity to warehouses. The goal is to create adaptable grids matching available construction elements' lengths. Grids are filtered and refined to save computational time, with primary objectives being structural soundness and sufficient beam quantities. Secondary goals include minimizing transportation distance to reduce embodied carbon costs and selecting the lightest structurally compatible beams to reduce material usage. The code development is incremental and iterative, with objectives expanding as the code evolves.

- *Data visualization*: To use the tool, users must input the site area, location and number of structures to be built. The output is presented through excel spreadsheets containing detailed information, and visualized in Rhino[2] through the use of a Hops component connected to Grasshopper. Furthermore, an app version of the tool is envisioned and visualized for wider application on mobile phones (Figure 3).

Through these phases, the research seeks to establish a robust framework for the practical application of reused structural elements in modern construction practices.

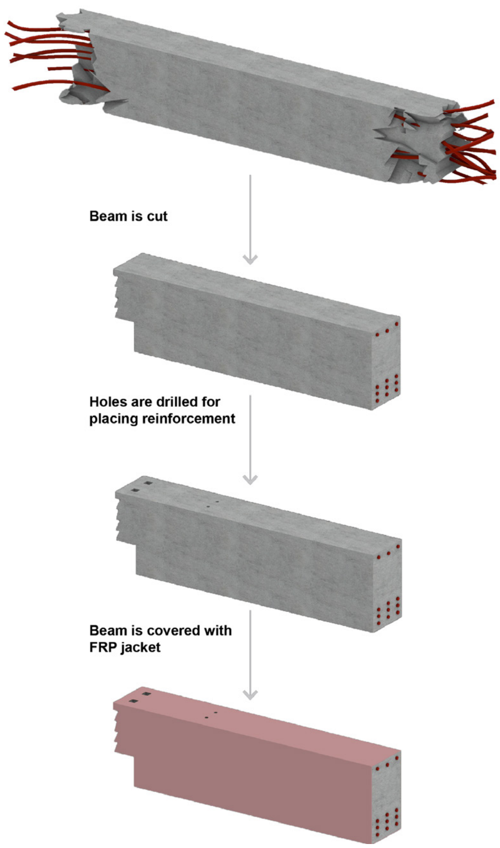


Figure 2. Process of cutting concrete beams to retrofitting with FRP.

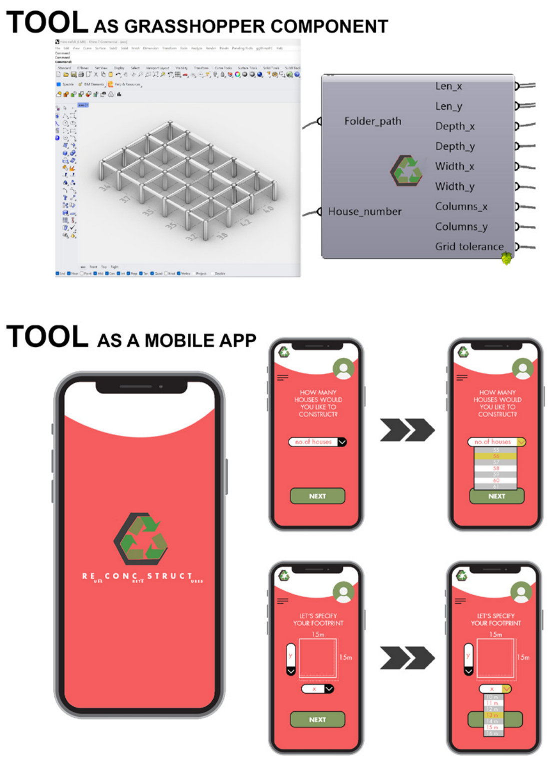


Figure 3. The computational tool as a Hops component for Grasshopper and visualization for a mobile app.

Results

The key findings of this research offer important insights into the reuse of structural beams and their integration into modern construction practices. First, the study shows that salvaged beams can be successfully retrofitted to meet structural integrity and safety standards, provided they undergo rigorous testing and load calculations. This highlights the potential to reuse materials that would otherwise contribute to waste, supporting sustainability in the construction industry. Second, the creation of a comprehensive database of regional beam stock proved crucial for identifying and selecting suitable materials for reuse. This database not only simplifies the salvaging process but also provides valuable insights into the requirements such a tool must meet to facilitate informed decision-making in design. Additionally, the research found that automating the design process significantly reduces the complexity of integrating reused elements. The design tool developed allows engineers, constructors and contractors to generate optimized structural grids based on available stock, eliminating the need for manual beam searches, new design calculations and optimizations. This software streamlines structural design and promotes sustainable building practices.

Overall, these findings offer a practical framework for reusing structural materials, addressing both environmental and economic concerns. This research sets the stage for future construction methodologies that minimize resource consumption and waste, encouraging a more sustainable and resilient construction industry.

Conclusions

The study highlights the untapped potential of reusing reinforced concrete (RC) elements, especially in seismic regions, where rebuilding quickly and sustainably is critical. By leveraging algorithms and data, the reconstruction process can be accelerated, offering faster, cheaper and more environmentally sustainable solutions by utilizing existing materials in the region. The development of automated design tools has shown promise in streamlining the reuse of salvaged beams, enabling faster, optimized structural designs for disaster recovery efforts.

However, there are several challenges and limitations to consider. Testing and rehabilitating RC elements is a rigorous and potentially costly process, which may limit the feasibility of widespread adoption. Alternative methods or the use of more sustainable materials should be further researched as complementary or alternative solutions. Future construction should prioritize "building for deconstruction" by incorporating demountable connections, enabling easier reuse of materials.

Moreover, the lack of comprehensive data on RC element reuse remains a significant barrier. Expanding data collection and integrating it into design tools could lead to faster, more optimized and sustainable construction practices. Future research on the software tool could explore complex grid layouts, multi-story buildings, cost analyses, edge-to-edge beam connections and the quantitative impact on bending moment and shear resistance capacity.

References

1. Python Software Foundation. Available: http://www.python.org.
2. R. McNeel et al., "Rhinoceros 3D, Version 6.0," Robert McNeel & Associates, Seattle, WA, 2010.

Interdisciplinary education matters because the most significant questions are too complex to be answered with the knowledge of a single field. This book presents a perspective on the pedagogical foundations necessary for interdisciplinary learning, specifically in the built environment education. It is one of the outcomes of the CORE Studio, a course taught in the Building Technology MSc program at the Faculty of Architecture and the Built Environment of TU Delft between 2022 and 2024.

In response to the devastating 2023 earthquake in Türkiye, the CORE studio focused on earthquake resilience. It explored how computational thinking and digital technologies can help address this challenging issue, drawing on an interdisciplinary body of knowledge within built environment education. The approach and results of this endeavour are presented in this book, which is enriched by contributions from many international scholars who have tackled the same theme in their own contexts. We hope this book can influence researchers and educators by inspiring innovative approaches to resilience in the built environment through interdisciplinary collaboration.