Safe Housing in Seismic Zones: The Modular Path

[redacted]

Abstract

Seismic vulnerability in informal settlements remains a structural and governance challenge across Latin America, where rapid urban expansion frequently occurs on geotechnically unstable terrains and under conditions of regulatory exclusion. There are plenty of historical precedents that suggest the necessity of a change in the way we built out houses, examples like earthquakes that happened in Lima (1746), Valparaíso (1906), and Pisco (2007) illustrate a recurring pattern: technological innovation in earthquake-resistant construction often appear in the aftermath of disaster but rarely permeates the informal sector, leaving self-built housing disproportionately exposed. This paper investigates whether modular construction, defined by prefabricated components and incremental adaptability, can be useful to provide a reliable pathway for this issue. The analysis combines historical case studies and recent advances in modular engineering to evaluate the extent to which modularity aligns with incremental self-building practices and community-led design. Furthermore, the paper argues that modular strategies achieve their highest potential when integrated with participatory frameworks, in order to ensure that structural predictability does not undermine local agency. In that line, the findings highlight that resilience is a matter of institutional embedding and iterative adaptation. Therefore, a hybrid approach that combines engineering precision with community-driven incrementalism is proposed as an ideal model for seismic safety and social sustainability in the urban peripheries of Latin America.

Keywords

Engineering Mechanics; Civil Engineering; Seismic resilience; Informal settlements; Modular construction; Latin America

Introduction

Informal settlements located in areas prone to seismic activity, including slums and squats, are frequently established under urgent circumstances and lack the essential structural support necessary to endure earthquakes. Even though it might be considered as a coincidental event at some point, it is merely the result of systemic issues that ecos the intersection of uncontrolled urban expansion and the emphasis on immediate needs over structural soundness. In these environments, residences are typically built through self-initiated efforts, generally without professional supervision, often utilizing recycled or low-quality materials. As these homes develop gradually, the routes for load distribution become irregular and the connections among structural components are seldom designed to withstand seismic pressures.

To add more pressure, the geological hazards further exacerbate this vulnerability. For example, in Lima, informal settlements often occupy steep inclines or sandy soils, where the landscape and soil conditions amplify seismic activity. A similar trend can be observed in Valparaíso, where hillside communities exhibit the outcomes of makeshift construction practices influenced by exclusionary urban policies.

Historically, society's responses to the main issue have typically been reactive. The 1906 earthquake in Valparaíso led to the establishment of seismic regulations and improvements in construction techniques for the near future. But these developments did not happen uniformly; while formal building sectors adopted new materials and practices, informal housing continued to be shaped by decisions made at the household level. In consequence, the damage in informal areas during recent earthquakes has been disproportionately complicated, and letting the people know that the ongoing shortcomings of state responses highlight the need for safer solutions.

In that line, modular construction represents a quality avenue for enhancing resilience. Prefabricated elements and simplified connections explain how structural reliability can be maintained while accommodating the irregular and gradual nature of self-constructed housing. Notwithstanding, for this method to thrive in informal settings, it must be reconfigured. This paper argues that modularity, when combined with participatory design and incremental methods, has the potential to create safer and more adaptable housing solutions where technical accuracy meets local empowerment.

Background and Historical Precedents

Understanding how societies have historically responded to seismic events is a key aspect for evaluating the viability of modular construction in today's informal settlements in Latin America. Throughout history, earthquakes have exposed structural vulnerabilities, as well as prompted critical issues in building cultures and technical practices (Oliver-Smith, 1999). In other words, those shifts emerge from a real necessity, particularly in contexts where widespread damage compels institutional reflection.

As Walker (2003) notes, the collapse of elite housing provides a striking counterpoint to Oliver-Smith's (1999) broader interpretation of vulnerability in Peru's seismic history. Understanding this contrast requires recognizing how earthquakes physically operate. According to an article from *Discovering Geology*, "Earthquakes are the result of sudden movement along faults within the Earth. The movement releases stored-up 'elastic strain' energy in the form of seismic waves, which propagate through the Earth and cause the ground surface to shake. Such movement on the faults is generally a response to long-term deformation and the buildup of stress". As a consequence, a large number of buildings in difficult conditions are the most prone to collapse after those natural disasters, in particular, the ones not designed for lateral resistance.

By way of illustration, the 1746 Lima earthquake provides a noticeable example of these processes. Approximately 90% of Lima's structures failed, and the accompanying tsunami devastated the port of Callao, killing nearly all of its 10,000 inhabitants out of pre-disaster populations of 55,000 in Lima and 10,000 in Callao (Walker, 2003). A historical seismic coupling map of the event (Figure 1) highlights zones of concentrated ground motion in red, which correspond closely with the areas that suffered the greatest destruction.

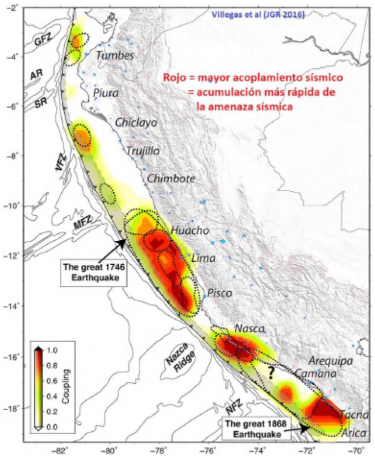


Figure 1. Seismic Coupling Map Showing Zones of Low to High Ground Motion During the 1746 Lima Earthquake.

To complement this scientific visualization, a historical map documents the spatial configuration of Callao before and after the event (Figure 2).

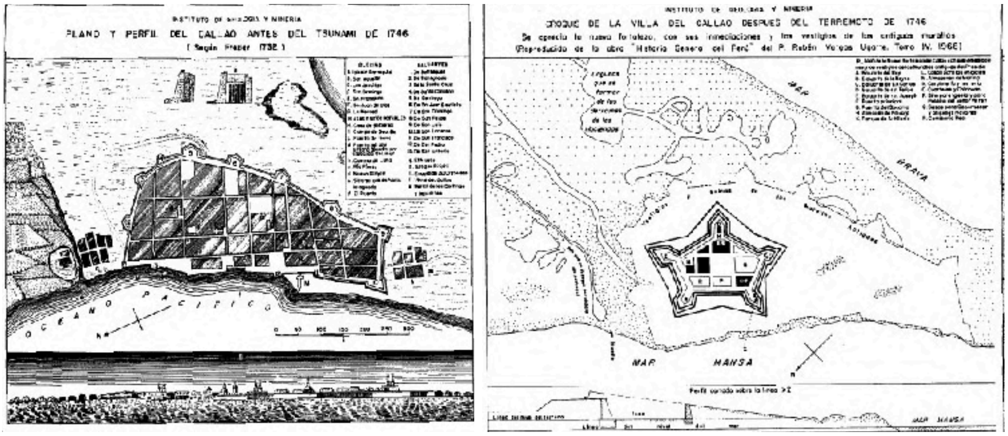


Figure 2. Historical Map of Callao District Before and After the 1746 Earthquake

Indeed, the change between the two diagrams is profound, signaling a radical territorial reconfiguration in that year. By contrast with the pre-disaster cartography, the post-earthquake and tsunami landscape shows how natural disasters can destroy established spatial orders and generate entirely new ones. That is to say that the transformation of Callao was entirely geographical, as a whole piece of the port city was erased due to the proximity to the sea and how the society at the time managed to build without a guide or sense of danger.

In the aftermath, Peru's authorities implemented a notorious change in construction logic. That is why they started to work with quincha, a traditional system that uses a timber framework filled with cane and covered in mud plaster, to improve energy dissipation during the earthquake (Vergara, 2014). It is worth noting that quincha exemplifies what is now referred to as ductile construction, which allows a building to deform without sudden failure. Although this system predated formal concepts such as dynamic load resistance or structural redundancy, it marked a turning point in local practice in the entire continent. But, we need to be clear that this transition relied on top-down planning and technical enforcement, which later proved inconsistent across Peru's rapidly expanding peripheries (Fernández-Maldonado and Bredenoord, 2010).

Even if we, as a continent, learned from that event, in Valparaíso, Chile, a similar dynamic unfolded years later. The 1906 earthquake caused massive destruction, particularly in hillside neighborhoods that had been built informally. Consequently, the disaster was catalogued as an important moment in Chilean engineering history due to the fact that it pushed institutions and practitioners to reconsider the materials and systems employed in construction, starting a repetitive pattern that helped Chile to be considered a seismic country later on in its buildings. That being said, the key factor that started this new construction Chilean era was reinforced concrete since it could resist both compression and tension by combining steel bars with cast concrete. At the same time, earthquake engineering codes became more formal and construction schools added courses on structural dynamics to their curricula, marking the professionalization of earthquake engineering in Chile (Maino & Tobriner, 2024). At odds with these innovations, which mostly reached formal urban projects, many residents of unstable hillside settlements remained beyond the scope of engineering regulations and institutional supervision even in our current time.

Furthermore, the seismic oscillation intensity map of Valparaíso is particularly relevant, providing detailed insights into the spatial variability of ground shaking across the city (Figure 5). Particularly in the hills, informal neighborhoods were disproportionately affected as unstable slopes and weakly compacted soils increased structural vulnerability. This additional resource is needed to underscore that vulnerability was shaped by broader spatial and urban planning factors.

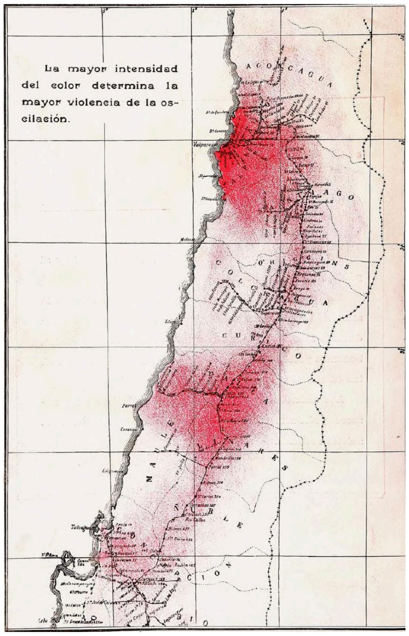


Figure 5. Seismic Oscillation Intensity Map of Valparaíso During the 1906 Earthquake

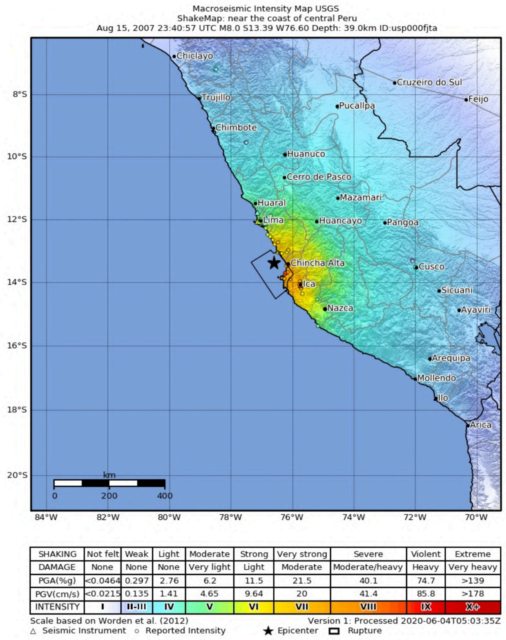
In conjunction with a contemporaneous photograph documents the collapse of a typical informal structure, adding a human dimension to the technical evidence (Figure 6). Unlike official engineering reports, which highlight the material performance and regulatory frameworks, the image tells us a direct and visceral record of the precarious conditions in which many inhabitants lived. The fragility of self-built dwellings and how residents are trying to reconstruct each building was captured in this picture, which also reveals how the absence of technical oversight left entire communities exposed to a catastrophic failure, as shown.

Figure 6. Photographic Evidence of Collapsed Informal Housing in Valparaíso, 1906 Earthquake

More recently, the 2007 earthquake in Pisco (Peru) revealed enduring tensions between official design codes and the realities of informal construction. According to the NZSEE reconnaissance report (Hopkins et al., 2008), the disaster engendered the destruction of more than 38,000 homes, displaced over 100,000 people and precipitated nearly 600 fatalities among more than 70,000 affected families. For instance, Figure 7 depicts the post-earthquake housing conditions in Pisco, where the generational trauma for a whole country increased in an irregular way, with the widespread collapse of unreinforced masonry walls and poorly anchored structures.

Figure 7. Post-Earthquake Building Conditions in Pisco, 2007.

Additionally, the macroseismic intensity map (Figure 8) shows how seismic impact was unevenly distributed across the region. In other terms, peripheral and low-income neighborhoods were disproportionately afflicted, which corroborates the notion that seismic disasters are also social events, since vulnerability is conditioned by income levels and unequal access to technical assistance.



SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	None	None	None	Very light	Light	Moderate	Moderate/heavy	Heavy	Very heavy
PGA(%g)	<0.0464	0.297	2.76	6.2	11.5	21.5	40.1	74.7	>139
PGV(cm/s)	<0.0215	0.135	1.41	4.65	9.64	20	41.4	85.8	>178
INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based on Worden et al. (2012) Version 1: Processed 2020-06-04T05:03:35Z
△ Seismic Instrument ○ Reported Intensity ★ Epicenter ▭ Rupture

Figure 8. Macroseismic Intensity Map of the 2007 Pisco Earthquake.

Although there were seismic standards, their implementation was still dispersed. And, knowing that the most damaged areas were informal neighborhoods, there were lots of things to change related to unreinforced masonry walls and out-of-plane collapse, which are usually used in these locations. That is why crucial knowledge remained unconnected to self-built habitats despite decades of seismic research. With brittle materials and flimsy foundations devoid of lateral resistance, builders kept improvising.

Pisco's earthquake also suggests the notorious gap between short-term aid and long-term recovery. In that line, the reconstruction efforts often introduced predesigned housing without consulting local families, sidelining the potential of participatory design. For that reason, numerous units were either abandoned or unable to respond to cultural preferences. Even so, 95.5% of damaged buildings were reoccupied by 2012, with significant new urban expansion, including 2,116 new buildings—17.6% of total lots—constructed after 2007 (Ismail et al., 2017).

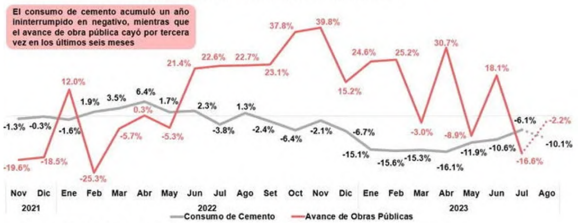


Figure 9. Trends in Cement Usage and Public Infrastructure Development in Peru, 2023. INEI

As shown in Figure 12, recent data from the INEI in 2023 reveal a contraction in construction activity in Peru, with a 7.9% decrease in August 2023 and an 8.8% decrease in January 2023. This downward trend manifests itself in three interconnected dimensions (INEI, 2023). First, the reduction in cement consumption reflects a slowdown in private housing construction, which weakens the demand base necessary to sustain the diffusion of modular systems. Second, the decrease in public infrastructure projects signals limited state investment capacity, reducing the possibility of integrating modular technologies into large-scale programs such as schools or social housing. Third, the overall decline in construction activity erodes confidence among investors and contractors, who may perceive modular construction as a risky or unnecessary innovation in a shrinking market. Overcoming these three factors requires the stabilization of the construction sector and the reinvention of fiscal incentives and policy frameworks that can ensure continuity and scale in the adoption of modular technologies.

As previously discussed, a recurring pattern becomes evident throughout this historical account of structural misfortunes, where innovation alone cannot mitigate seismic risk at all. That is why seismic resilience must be understood as the physical capacity to absorb shocks and the ability of construction practices to adapt and endure in evolving urban settings.

Current Risks and Spatial Patterns

The spatial growth of informal settlements in seismic regions uncovers systemic neglect in urban planning and takes the opportunity to still show a recurring pattern of structural vulnerability (Sandoval and Sarmiento, 2020). At this part of the globe, urban expansion into hazardous terrains has become a common phenomenon that prevails the inability of formal planning frameworks to respond to rapid population growth (Sakay et al., 2011). Therefore, a large number of cities across Peru, including Lima, have developed huge peripheral zones (see Figure 10) where basic infrastructure is nonexistent and environmental conditions increase disaster risk continuously.

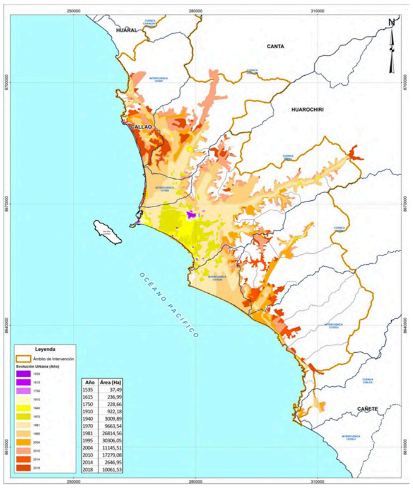


Figure 10. Urban growth map of Metropolitan Lima (1535–2018). (Equipo Técnico Plan Met 2040, 2020) *The map uses color-coded layers (purple for 1535, yellow for 1940, etc.) to illustrate the city's expansion from its colonial core to peripheral areas.*

Namely, the metropolitan area of Lima confirms this disorganized growth by far. Geotechnical surveys reveal that coarse alluvial soils in some valleys can support up to 4 kg/cm²; simultaneously, fine sands and silts common in peripheral settlements might support less than 1 kg/cm², making them highly susceptible to collapse under seismic stress (Gutiérrez et al., 2020). In this way, these conditions, combined with the absence of formal construction standards in self-built housing, amplify the risk of structural failure during earthquakes of the magnitude historically recorded in Peru.

The analysis of the available space in this area further reinforces that poor neighborhoods in Lima frequently cluster in zones where seismic motion is amplified by local geomorphology. In this regard, areas with deep alluvial deposits and unconsolidated sediments intensify by a great scale the seismic waves, which produce localized peaks in shaking intensity. That is how GIS overlays of settlement maps with hazard zonation layers indicate that a great proportion of communities are located within such amplification zones, as shown in Figure 11 (INEI, 2007). The outcomes of it are intensified by social vulnerability, and related to that, surveys show that more than 60% of residents in high-risk districts have never received earthquake preparedness training, while over 40% do not know evacuation routes, even if they are living in seismically active areas (Quesada-Román, 2022).

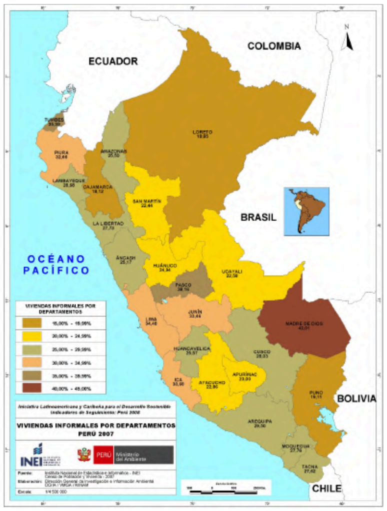


Figure 11. Distribution of Informal Settlements in Lima (INEI, 2007).
GIS map showing informal clusters overlapping seismic hazard zones.

In Lima's informal settlements, the effectiveness of emergency response is severely constrained by narrow. In fact, housing density frequently exceeds 1,000 inhabitants per hectare, with combustible materials such as timber and cardboard prevalent in more than 70% of dwellings. In some districts, the incidence of household fires is two to three times higher than in formally planned areas and delays in emergency response can reach 40 minutes or more due to access constraints of the location (Ismail et al., 2017). Although this is not exclusive to Latin American countries since there are comparable dynamics that appear in other global contexts: in Warsaw, Poland, for example, inadequate remediation of nearly 300 contaminated industrial sites disproportionately affects lower-income districts, that situation actually exposes residents to health risks related to high pollution levels (Maciejewska and Ulanicka-Raczyńska, 2023). And that is how, in the city of Lima, with a large population and centralized tendencies, construction in hazard-prone areas stresses governance errors that tend to push low-income households into dangerous places.

Modular Construction and Seismic Resilience

Modular construction is a building method that uses prefabricated parts and efficient on-site assembly, and it has evolved to be an optimal approach for improving structural safety in vulnerable locations. It should be noted that this method enhances the design and partial or complete assembly of structural modules within controlled environments. Historically speaking, modern modular construction is not an isolated innovation but rather an evolution of prefabrication practices that date back to monumental works of antiquity and were later implemented during the British colonization, the California Gold Rush and both World Wars (Smith, 2010). Over the past years, they were transformed through robotic and additive manufacturing, and specialized transportation systems, which allow high levels of precision and quality control that are rarely attainable with traditional methods of construction (AlDairi, 2021).

From this general background, it is fundamental to mention the structural implications. Unlike informal construction, which often develops through unplanned and incremental additions (Green, 2008), modular systems are based on standardized dimensions and connection methods. Thereupon, they eliminate common weak points and make sure that each piece performs predictably under stress (Lawson & Richards, 2010). To understand that, we should analyze Figure 13, where different gusset plate configurations, of which the most notable are double-hole for external joints, single-hole for corner joints, and four-hole for internal joints, illustrate how modular housing ensures continuous and predictable load transfer paths. Likewise, Figure 12 shows the detailing of a typical modular structural joint and emphasizes the engineered nature of these connections in a dynamic diagram. Moreover, the modular approach is linked to incremental building patterns observed in low-resource contexts because individual modules can be fabricated and installed in stages without compromising overall stability (Fernández-Maldonado & Bredenoord, 2010). In fact, there are historical precedents related to that, such as the reconstruction of Valparaíso after the 1906 earthquake, which represent how seismic disasters have catalyzed a shift from empiricism toward engineering-led solutions (Maino & Tobriner, 2024).

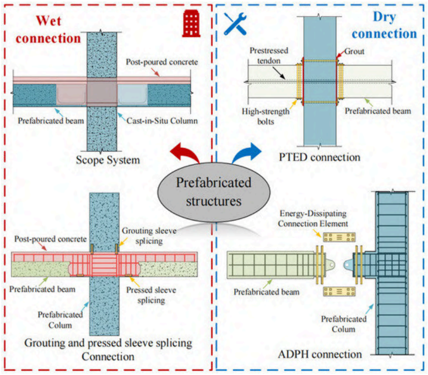


Figure 12. Structural Joint Diagram in Modular Construction Systems.

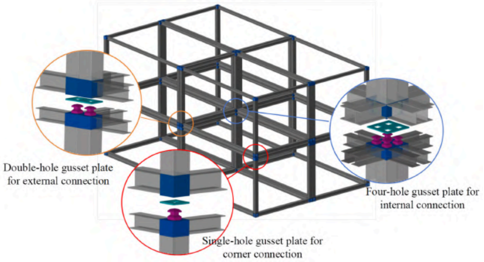


Figure 13. Connection Types in Modular Housing Assemblies

Taking into account that information, one of the most critical determinants of seismic resilience in modular buildings is based on the performance of their connection systems. Both inter-module and intra-module joints are deliberately engineered to optimize robustness and stability under extreme loading. That is why the most common configurations include tie rod systems with shear keys, bolted plates, VectorBloc connectors and welded cover plates. It is important to highlight that these detailing choices directly influence lateral-force resistance and inter-story drift (Ginigaddara et al., 2023). To illustrate that, Figure 14 points out a bolted plate connection, showing how load transfer and ductility are enhanced when joints are carefully designed.

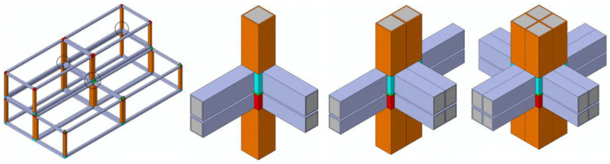


Figure 14. Detail of Bolted Plate Modular Connection.

It is also important to consider the performance under real earthquakes. Recent research has shown that modular buildings are vulnerable to pulse-type ground motions (PLGMs) from nearby earthquakes. Elias et al. (2024) suggest that these pulses induce worse structural shaking and increase the chance of total collapse. As Figure 15 shows with seismic fragility curves, the probability of failure is significantly higher under PLGMs.

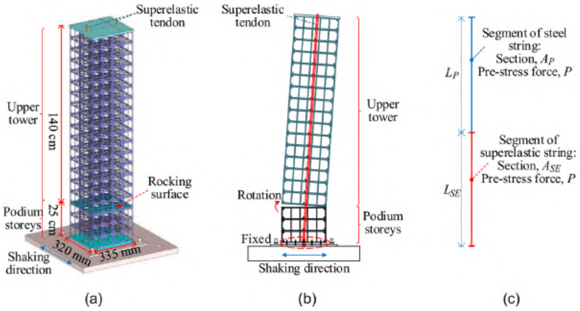


Figure 15. Seismic Fragility Curve Analysis for Modular Buildings.

A real-world example shows how modular construction works in practice. Its main advantage is using factory-made parts that are assembled on-site. This is seen in Peru, where the most advanced modular system from ALQUIMODUL SAC (Figure 16) builds earthquake-resistant structures that can also be expanded later. Nonetheless, the immediate success depends not just on training and respecting local culture.

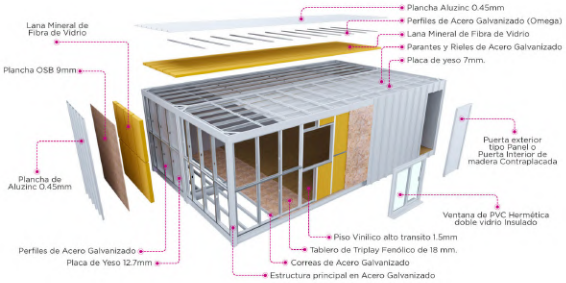


Figure 16. Advanced Modular Concrete Construction System in Peru, 2012.

Beyond seismic performance, recent literature underscores the necessity of multi-hazard resilience that addresses cyclones, floods, pandemics and fire. As it turns out, cyclones dictate extreme wind pressures and debris impacts, which call for reinforced interconnections to prevent fatigue failures (Di Sarno & Forgione, 2024). And, to prove that we can overcome that kind of obstacle, Figure 17 depicts a highly competitive design option for hurricane-proof modular houses. Likewise, floods have motivated amphibious pavilion systems and floating foundations, such as those represented in Figure 18, which illustrate the adaptability of modular approaches to changing environmental conditions (Abdur Rehman, 2024). Coupled with this, the adaptability of modular construction was evident during the COVID-19 emergency, which is also exemplified by rapid medical facilities such as the Leishenshan Hospital (Ismail et al., 2017). Despite these advances, relevant gaps remain in full-scale testing for multi-hazard and fire performance (Bhandari et al., 2023). Figure 19 shows a rendered model of a modular housing unit as a symbol of the integration of aesthetics with resilience-oriented design.

Figure 17. Hurricane-Proof Houses: Designs, Costs, and Construction Methods.

Figure 18. Multi-Hazard Resilient Modular Building Design Example at Leishenshan Hospital.

Figure 19. Rendered Model of a Modular Housing Unit

With respect to these considerations and examples, modular construction may be the most competitive and reachable option as a combination of control, quality assurance and performance consistency that is rarely achievable in informal contexts (Sandoval & Sarmiento, 2020). In other words, prefabrication allows continuous testing of materials and load-bearing assemblies before deployment, thereby reducing the likelihood of design or assembly flaws. Moreover, the modular nature of post-disaster recovery permits damaged units to be replaced individually without dismantling unaffected sections (Eren, 2012). But it is important to notice that true resilience depends on integrating modular construction into comprehensive disaster management frameworks. When adapted to local cultural practices, environmental conditions, and resource constraints, modular construction delivers a synthesis of safety and rapid deployment (Hussainzad & Gou, 2024).

Participatory Design and Incremental Housing

Societal structures rest upon the presence and agency of people. That is why engagement from community members and incremental building strategies can enhance both the social cohesion and structural integrity of informal settlements, as they are related to safety objectives with the progressive construction methods employed by residents while maintaining their independence (Fernández-Maldonado & Bredenoord, 2010). Research derived from participatory approaches portrays the advantages of collaboration in achieving better results: Project-Based Learning at University College Dublin indicated that 90% of surveyed students expressed an improved comprehension through collaborative problem-solving, with the quality of group work (23%) and individual skill (21%) being of utmost importance; yet issues such as imbalanced contributions and significant time commitments were also noted (Gavin, 2011). At the same time, the application of Quality Function Deployment in the construction industry has shown some advantages that include reductions in engineering modifications and design durations by approximately 50%, decreased startup costs by 20-60% and a 20-50% decline in warranty claims (Abdul-Rahman et al., 1999).

The result of the previous information was that the social and demographic changes highlight the need to build connected living spaces. A thorough examination of 46 studies revealed that retirement communities accounted for 15%, assisted living frameworks for 39%, and cohousing models for 24%. In fact, a large proportion of participants were women (76%), half of whom said they had health problems. And, success factors were the access to basic services and flexible rules; social isolation, a condition affecting 24% of North American elderly adults, underlined the need for participatory frameworks for enhancing well-being; this importance also applied to younger and low-income groups (Nguyen & Levasseur, 2023).

Additionally, variations in how cities use space since COVID-19 started give them even more chances to develop. That is how remote work in the European Union reached a maximum of 37% and caused a office occupancy rates to decline to just 10%, and vacancy rates in Sydney's central business district to increase to 10-11%, which is in stark contrast to the 60-70% occupancy rates recorded before the outbreak. Also, in locations that were suffering from land shortage, the conversion of these underused areas could boost incremental housing efforts. Concurrently, climate-related catastrophes were part of the problem: the 2019-2020 Australian bushfires destroyed 3,000 homes and impacted 30 million hectares, while the 1960 Chilean tsunami affected four nations within a 12-20 hour span. And, innovative projects, such as the Nature Urbaine rooftop garden in Paris, which yields 200 kg of produce daily over 14,000 m², or the relocation of Kiruna in Sweden, involving 6,000 residents and 39 historic buildings, show how participatory and flexible design may greatly improve sustainability and community cohesiveness (Anguelovski et al., 2016).

Synthesis and Future Implications

It is theoretically true that the integration of modular construction, participatory design and incremental housing can be the best solution for improving seismic safety and multi-hazard resilience in vulnerable environments. Also, this combined approach draws simultaneously from vernacular knowledge and participatory governance (Rashidfarokhi, 2024), ensuring that innovation is grounded in local realities. In simple terms, by linking technical rigor with community agency, it delivers housing and infrastructure that are affordable of evolve alongside the needs of residents (Nguyen & Levasseur, 2023).

The convergence of evidence from diverse cases strongly validates this synthesis. In rural Colima, Mexico, the transformation of the conventional wattle-and-daub technique into a geodesic dome has demonstrated the required effectiveness in resisting seismic activity and adapting to climate, alongside low building expenses and the potential for community-led construction (Ismail et al., 2017). Moreover, in Pakistan, the use of modular flat-pack homes made from cold-formed steel and fiber cement boards facilitates swift assembly after disasters (Abdur Rehman, 2024). Related experiences in British Columbia's critical infrastructure projects and Cape Town's flood management strategies demonstrate that resilience is most effective when technical solutions are verified through participatory methods that are specific to the local context and involve collaboration among institutions (Genik & Chouinard, 2015).

Needless to say, these examples show up a broader concept: resilience should be customized to meet local hazards and governance frameworks. Whether it is through the thermal mass of Colima’s earth constructions, the flood-resilient modular designs in Pakistan, or urban initiatives like the Inner City Suburbia framework (Kotila, 2010), successful strategies merge structural advancements with social and environmental adjustments (Green, 2008). Furthermore, ongoing experimentation, as illustrated by the Stickbot prototyping approach or interdependency mapping in Canada, highlights that designs start working and evolving through persistent testing and modifications in real-world scenarios (Carroll et al., 2023).

For Latin America, the conclusions are explicit. Housing that withstands hazards should merge traditional low-carbon building methods with contemporary seismic engineering (Ye et al., 2025), incorporate co-design practices from the initial phases and view modularity and incremental development as proactive strategies rather than merely reactive measures (Lawson & Richards, 2010). Indeed, it is primordial to prioritize pilot initiatives as living laboratories because they will be useful for technical verification and alignment of policies (Varela et al., 2022). Even if it is a repetitive concept now, resilience ought to be perceived as a dynamic ability fostered through the integration of knowledge and society.

Conclusion

The evidence analyzed in this study shows that conflating modular construction, participatory design and incremental housing can constitute a viable pathway in terms of seismic resilience in informal settlements.

This combined approach capitalizes on the structural reliability of prefabricated systems while remaining consistent with the incremental and adaptive construction practices characteristic of resource-constrained communities. Actually, resilience must therefore be conceived as a dynamic capacity, reinforced through the continuous interaction between governance and community engagement equally.

For Latin America, the adoption of hybrid modular-incremental models needs more than the replication of technical prototypes. In reality, and even if it takes a long time, it necessitates the institutionalization of participatory frameworks within official planning processes and the development of financing mechanisms that simultaneously address structural safety and social stability.

Truly, future research is obliged to evaluate hybrid housing communities longitudinally in post-disaster contexts and compare their structural and social performance with conventional approaches. It is also worth mentioning the exploration of accessible training programs for informal labor networks, the incorporation of digital tools such as participatory mapping and GIS-based hazard modeling, and the alignment of seismic design with climate adaptation strategies in dual-hazard regions. That is how we, as a society that actually has learned something from the past catastrophes, must advance seismic safety in informal urban areas demands recognition of resilience as both an engineering challenge and a socio-political endeavor; one that needs deliberate coordination between technical excellence, community capacity and institutional support to maintain the cities in a stable condition.

Acknowledgements

The author extends a huge gratitude to [redacted] whose mentorship and feedback shaped the analytical depth of this work, and to [redacted] whose constructive critique and constant follow-up of the paper brought motivation at every stage. In addition, I wanted to thank my family since they always support this journey related to improving the construction world in a positive way.

Above all, the deepest respect is reserved for the communities living each day under seismic risk around the globe. Their resilience in transforming limited resources into enduring solutions embodies the conviction that guides this study: true safety surfaces when technical knowledge is interwoven with collective agency and rooted in local wisdom.

Bibliography

1. Abdul-Rahman, H., Kwan, C. L., & Woods, P. C. (1999). Quality function deployment in construction design: Application in low-cost housing design. International Journal of Quality & Reliability Management, 16(6), 591–605. https://doi.org/10.1108/02656719910268198
2. Abdur Rehman, Z. (2024). Modular emergency relief: A proposal for integrating modular buildings into post-flood reconstruction and recovery. https://www.theseus.fi/handle/10024/868097
3. AlDairi, S. (2021). Modular construction in the civil engineering industry [Master's thesis, Stevens Institute of Technology]. ProQuest. https://search.proquest.com/openview/21cf00c2a57b6ad03ed474d4fdbff151/1?pq-origsite=gscholar&cbl=18750&diss=y
4. Anguelovski, I., Shi, L., Chu, E., Gallagher, D., Goh, K., Lamb, Z., Reeve, K., & Teicher, H. (2016). Equity impacts of urban land use planning for climate adaptation: Critical perspectives from the Global North and South. Journal of Planning Education and Research, 36(3), 333–348. https://doi.org/10.1177/0739456X16645166
5. Bhandari, S., Riggio, M., Jahedi, S., Fischer, E. C., Muszynski, L., & Luo, Z. (2023). A review of modular cross-laminated timber construction: Implications for temporary housing in seismic areas. Journal of Building Engineering, 63, 105485. https://doi.org/10.1016/j.jobe.2022.105485
6. Calderon, C. (2008). Learning from slum upgrading and participation: A case study of participatory slum upgrading in the emergence of new governance in the city of Medellín, Colombia. https://www.diva-portal.org/smash/record.jsf?pid=diva2:126733
7. Carroll, D., Ang, V., & Yim, M. (2023). StickBot: A methodology for building robots and other functional elements from tree branches and string. https://doi.org/10.1115/DETC2023-109541

8. Di Sarno, L., & Forgione, R. (2024). Innovative steel modular housing system for multiple natural hazard mitigation. International Journal of Disaster Risk Reduction, 111, 104734. https://doi.org/10.1016/j.ijdrr.2024.104734
9. Eren, O. (2012). A proposal for sustainable temporary housing applications in earthquake zones in Turkey: Modular box system applications. Gazi University Journal of Science, 25(1), 269–288.
10. Fernández-Maldonado, A. M., & Bredenoord, J. (2010). Progressive housing approaches in the current Peruvian policies. Habitat International, 34(3), 342–350. https://doi.org/10.1016/j.habitatint.2009.11.018
11. Gavin, K. (2011). Case study of a project-based learning course in civil engineering design. European Journal of Engineering Education, 36(6), 547–558. https://doi.org/10.1080/03043797.2011.624173
12. Genik, L., & Chouinard, P. (2015). An overview of pilot projects in support of critical infrastructure resilience. https://apps.dtic.mil/sti/html/tr/AD1004218/
13. Ginigaddara, T., Ekanayake, C., Gunawardena, T., & Mendis, P. (2023). Resilience and performance of prefabricated modular buildings against natural disasters. Electronic Journal of Structural Engineering, 23(4), 85–92.
14. Green, R. (2008). Informal settlements and natural hazard vulnerability in rapid growth cities. En J. J. Pinkham & R. Green (Eds.), Hazards and the built environment (pp. 218–237). Routledge. https://www.taylorfrancis.com/chapters/edit/10.4324/9780203938720-14
15. Gutiérrez, R. M., Esenarro, D., Pingo, P. A., & Rodriguez, C. R. (2020). Vulnerability of the soils of Metropolitan Lima and their relationship with urban sustainability. 3C Tecnología: Glosas de Innovación Aplicadas a La Pyme, 9(1), 161–177.
16. Hussainzad, E. A., & Gou, Z. (2024). Climate risk and vulnerability assessment in informal settlements of the Global South: A critical review. Land, 13(9), 1357.
17. Ismail, F. Z., Halog, A., & Smith, C. (2017). How sustainable is disaster resilience? An overview of sustainable construction approach in post-disaster housing reconstruction. International Journal of Disaster Resilience in the Built Environment, 8(5), 555–572. https://doi.org/10.1108/IJDRBE-07-2016-0028
18. Kechebour, B. E. (2015). Relation between stability of slope and the urban density: Case study. Procedia Engineering, 114, 824–831.
19. Khan, R. M. A. H., Mubin, S., & Masood, R. (2025). Land-sharing hybrid models for low-cost housing. International Journal of Housing Markets and Analysis. https://doi.org/10.1108/IJHMA-02-2025-0045
20. Kotila, R. (2010). Inner city suburbia: A hybrid solution to sustainable urban middle-income housing [Master's thesis, University of Cincinnati]. https://rave.ohiolink.edu/etdc/view?acc_num=ucin1274195125
21. Lawson, R. M., & Richards, J. (2010). Modular design for high-rise buildings. Proceedings of the Institution of Civil Engineers – Structures and Buildings, 163(3), 151–164. https://doi.org/10.1680/stbu.2010.163.3.151
22. Maciejewska, A., & Ulanicka-Raczyńska, M. (2023). Lack of spatial planning as a cause of environmental injustice in the context of the provision of health safety to urban residents based on the example of Warsaw. Sustainability, 15(3), 2521. https://doi.org/10.3390/su15032521
23. Maino, S., & Tobriner, S. (2024). The search for earthquake-resistant construction systems in Chile after the 1906 Valparaíso earthquake. Construction History – International Journal of the Construction History Society, 39(2). https://www.researchgate.net/publication/389893944
24. Mehrotra, S., Bardhan, R., & Ramamritham, K. (2018). Urban informal housing and surface urban heat island intensity: Exploring spatial association in the city of Mumbai. Environment and Urbanization ASIA, 9(2), 158–177. https://doi.org/10.1177/0975425318783548
25. Moya, L., Vilela, M., Jaimes, J., Espinoza, B., Pajuelo, J., Tarque, N., Santa-Cruz, S., Vega-Centeno, P., & Yamazaki, F. (2024). Vulnerabilities and exposure of recent informal urban areas in Lima, Peru. Progress in Disaster Science, 23, 100345. https://doi.org/10.1016/j.pdisas.2024.100345
26. Murao, O., Hoshi, T., Estrada, M., Sugiyasu, K., Matsuoka, M., & Yamazaki, F. (2013). Urban recovery process in Pisco after the 2007 Peru earthquake. Journal of Disaster Research, 8(2), 356–364.

27. Nguyen, T. H. T., & Levasseur, M. (2023). How does community-based housing foster social participation in older adults: Importance of well-designed common space, proximity to resources, flexible rules and policies, and benevolent communities. Journal of Gerontological Social Work, 66(1), 103–133. https://doi.org/10.1080/01634372.2022.2133199
28. Oliver-Smith, A. (1999). Peru's five-hundred-year earthquake: Vulnerability in historical context. En A. Oliver-Smith & S. Hoffman (Eds.), The angry earth (pp. 88–102). Routledge. https://doi.org/10.4324/9780203821190-13
29. Quesada-Román, A. (2022). Disaster risk assessment of informal settlements in the Global South. Sustainability, 14(16), 10261.
30. Qin, J., Tan, P., Cai, G., Zhou, C., Mi, P., Tang, M., & Zhou, F. (2025). Seismic performance investigation on simplified modular loading-bearing and energy-dissipating joints for modular steel buildings. Structures, 79, 109409. https://doi.org/10.1016/j.istruc.2025.109409
31. Rashidfarokhi, A. (2024). Resilience by whom and for whom? Empowering local communities for community-led resilience-building. En Real estate and sustainable crisis management in urban environments (p. 39). https://library.oapen.org/bitstream/handle/20.500.12657/90572
32. Sakay, C., Sanoni, P., & Deng, T. H. (2011). Rural to urban squatter settlements: The micro model of generational self-help housing in Lima-Peru. Procedia Engineering, 21, 473–480. https://doi.org/10.1016/j.proeng.2011.11.2040
33. Sandoval, V., & Sarmiento, J. P. (2020). A neglected issue: Informal settlements, urban development, and disaster risk reduction in Latin America and the Caribbean. Disaster Prevention and Management: An International Journal, 29(5), 731–745.
34. Smith, R. E. (2010). Prefab architecture: A guide to modular design and construction. John Wiley & Sons.
35. Unger, E.-M., Zevenbergen, J., Bennett, R., & Lemmen, C. (2019). Application of LADM for disaster prone areas and communities. Land Use Policy, 80, 118–126. https://doi.org/10.1016/j.landusepol.2018.10.012
36. Varela, S. L., Moncagatta, A. R., & Huamán, C. O. T. (2022). Blue and green infrastructure as public spaces: Five proposals for resilient urban development and social integration in Peru. In Handbook of waterfront cities and urbanism. Routledge. https://cris.pucp.edu.pe/en/publications
37. Walker, C. F. (2003). The upper classes and their upper stories: Architecture and the aftermath of the Lima earthquake of 1746. Hispanic American Historical Review, 83(1), 53–82.
38. Ye, Z., Bu, H., Liu, Z., Lu, D., Min, D., & Shan, H. (2025). Seismic resilience design of prefabricated modular pressurized buildings. Resilient Cities and Structures, 4(1), 53–70.
39. Zeballos-Velarde, C. (2021). Urban linkages: A methodological framework for improving resilience in peripheral areas: The case of Arequipa, Peru. En J. Martinez, C. A. Mikkelsen, & R. Phillips (Eds.), Handbook of quality of life and sustainability (pp. 533–550). Springer. https://doi.org/10.1007/978-3-030-50540-0_27
40. Zohourian, M., Pamidimukkala, A., Kermanshachi, S., & Almaskati, D. (2025). Modular construction: A comprehensive review. Buildings, 15(12), 2020.
41. Hopkins, D., Bell, D., Benites, R., Burr, J., Hamilton, C., & Kotze, R. (2008). The Pisco (Peru) earthquake of 15 August 2007: NZSEE reconnaissance report, June 2008. Bulletin of the New Zealand Society for Earthquake Engineering, 41(3), 109–192. https://doi.org/10.5459/bnzsee.41.3.109-192

This paper looks into improving seismic safety in the informal settlements of Latin America by using modular construction and participatory design. The paper's main strength lies in its central claim: that a hybrid approach combining the technical rigor of modular systems with the local agency of community-led, incremental building practices is essential for true resilience. The paper also nicely incorporates historical case studies from Lima, Valparaíso, and Pisco effectively. Those cases help establish the recurring patterns of vulnerability and the limitations of top-down technical solutions. That said, the manuscript in its current form requires major revisions before it can be considered for publication. The central idea and chosen topic are strong, but the paper suffers from significant structural disorganization in the later sections, poor integration and presentation of its many figures, and overall issues with flow. These issues collectively obscure writing and make the paper difficult to follow. The author should address the following comments:

(1) **Organization.** The section "Participatory Design and Incremental Housing" is highly disorganized. It presents a collection of disparate statistics on topics ranging from student learning in Dublin and remote work after COVID-19 to retirement communities and Australian bushfires. While these points touch on collaboration or housing, their direct relevance to modular construction in Latin American informal settlements is not established. Please rewrite this section and focus on the central topic. Instead of citing general studies on collaboration, the author should seek out and synthesize literature that deals specifically with participatory planning and incremental building within informal housing contexts, preferably in Latin America or other relevant areas of the Global South..

(2) Figures. The paper has many figures, which is great but they have several issues with numbering. For example, Figure 4 is missing. The text on page 6 refers to "Figure 12" when discussing cement usage, but the corresponding figure is labeled Figure 9. Moreover, several figures contain untranslated Spanish text like figure 1 and figure 5. For an English-language publication, all text within figures must be translated or explained. The captions often simply state what the image is, without explaining its relevance to the argument. Please revise the issues with the figures.

(3) Literature. Right now, the literature reads like disconnected facts. It would make the paper much stronger if the sources could be merged and flow better together to build a clean argument.

Given the above comments and the paper's inherent strengths, it has the potential to be published. I recommend that the author undergo **major revisions** of the paper so it can be worthy of publication.

Review: *Safe Housing in Seismic Zones: The Modular Path*

I would like to preface by saying that the paper takes on a very timely and pressing question that applies to many regions beyond Latin America: how informal settlements often built under precarious conditions might be made more resilient to earthquakes through modular construction. This is already an ambitious undertaking, and what I appreciate most is the way the author tries to hold together several different kinds of evidence and perspectives. Weaving together historical case studies with engineering concepts like modular jointing systems and seismic fragility curves, and then social frameworks (which are often harder to pin down in technical writing!), the paper shows real intellectual courage. It could feel as though the argument is moving on three tracks at once, but the interdisciplinarity of the project is refreshing.

The historical examples are particularly strong. They ground the argument in moments when disasters forced societies to rethink how they built, and they remind us that innovation has often been reactive. The section on quincha in eighteenth-century Peru was particularly vivid in showing how vernacular techniques anticipated modern engineering principles. I can also commend the use of a wide range of visual material, which is impressive for a student paper and gives a strong sense of how lived environments have been reshaped by disaster.

Where the paper could most improve is in clarifying the through-line of the argument. At the moment, there is so much fascinating material that the central claim about modularity sometimes gets a little buried. One way forward might be to structure the essay more explicitly in three parts: historical precedents, then the engineering aspects of modular construction, and finally the social and participatory frameworks. Each section should end with a short synthesis paragraph that builds momentum toward the next. That would allow the reader to see more clearly how the pieces fit together.

The bibliography is wide-ranging, which is excellent, but the engagement with it sometimes feels a bit quick. I would encourage the author to slow down at key points and draw out what individual thinkers are contributing. For example, Fernández-Maldonado and Bredenoord’s work on progressive housing (or Oliver-Smith on vulnerability), could be tied more directly to the hybrid model the author is proposing. This would strengthen the scholarly voice and show how the author is participating in existing debates, not just reporting them.

The figures, too, could do more argumentative work (they are not mere illustrations, but visual evidence!) Rather than only describing them, the author might explain what they reveal about urban form, resilience, or vulnerability. For example, the map of Callao after the 1746 earthquake could be used to underscore how disasters completely reconfigure the spatial order of cities, which in turn supports the case for adaptable systems like modular housing.

Overall, this is a very promising and ambitious paper. It shows strong initiative and maturity in drawing connections across disciplines. With restructuring, deeper engagement with sources, and tighter analysis of the figures, it has real potential. **My recommendation is to <u>accept it with major revisions</u>**.

Safe Housing in Seismic Zones: The Modular Path

Abstract

In many Latin American cities, informal settlements still grow on unstable ground because urban planning and enforcement often fail, where rapid urban expansion frequently occurs on geotechnically unstable terrains and under conditions of regulatory exclusion. Numerous historical precedents suggest the necessity of a change in the way we build houses. Examples like earthquakes that occurred in Lima (1746), Valparaíso (1906), and Pisco (2007) illustrate a persistent situation: technological innovation in earthquake-resistant construction often appears in the aftermath of disasters but rarely permeates the informal sector. The study examines whether modular construction, characterized by prefabricated elements and flexible design, can serve as a practical way to address this problem. By drawing on past experiences and recent innovations in modular construction, the paper shows how modular design can fit into the way communities build and plan their own spaces. Additionally, the paper argues that the combination of modular strategies with participatory frameworks is fundamental and successful in ensuring that structural predictability does not undermine local agency. In this line, the conclusions emphasize that resilience is a matter of institutional embedding and iterative adaptation. In short terms, a blended strategy that merges engineering precision with community-driven incrementalism is proposed as an ideal model for seismic safety and social sustainability in the urban peripheries of Latin America.

Keywords

Disaster Risk Reduction; Civil Engineering; Seismic resilience; Informal settlements; Modular construction; Latin America

Introduction

Informal settlements in seismically active regions, including slums and squatter areas, often emerge under conditions of urgency and exclusion. In that way, these environments are typically shaped by necessity rather than regulation, resulting in homes that lack the structural capacity to withstand earthquakes. Even though it might be considered a coincidental event at some point, it is merely the result of systemic issues that echo the intersection of uncontrolled urban expansion and the emphasis on immediate needs over structural soundness. In these environments, residences are typically built through self-initiated efforts, generally without professional supervision, often utilizing recycled or low-quality materials. As these homes develop gradually, the routes for load distribution become irregular, and the connections among structural components are seldom designed to withstand seismic pressures. Such dynamics are consistent with Ginigaddara's (2023) observations that informal construction, shaped by socioeconomic constraints rather than technical guidance, inherently amplifies seismic vulnerability.

Geological conditions further intensify these risks. In Lima, for instance, informal settlements are frequently located on sandy soils or steep hillsides where ground motion is amplified during earthquakes. A similar trend can be observed in Valparaíso, where hillside communities exhibit the outcomes of makeshift construction practices influenced by exclusionary urban policies. In both cities, the physical instability of the terrain intersects with social and institutional fragility, creating environments where even moderate seismic events can lead to catastrophic damage. In fact, this pattern aligns with broader regional evidence showing that spatial injustice and cumulative environmental degradation have systematically concentrated vulnerable populations in geotechnically unstable areas (Maciejewska & Ulanicka-Raczyńska, 2023).

Even though human beings tend to learn from challenging situations, in our entire history, the responses to this issue have been reactive. The 1906 earthquake in Valparaíso led to the establishment of seismic regulations and improvements in construction techniques for the near future. However, these developments did not happen in a uniform while formal building sectors adopted new materials and practices, informal housing continued to be shaped by decisions made at the household level. Consequently, the damage in informal areas during recent earthquakes has been disproportionately complicated, which highlights the need for safer solutions. These recurring inequalities demonstrate that technical progress alone cannot guarantee safety. Instead, new approaches must weave the threads between engineering innovation and the lived realities of informal builders (Rashidfarokhi, 2024).

Recent reviews show that modular systems using cross-laminated timber (CLT) can significantly reduce construction time while maintaining robust seismic performance, positioning them as viable options for rapidly deployable housing in earthquake-prone contexts (Bhandari et al., 2023). Similarly, experimental work with full-scale modular steel prototypes has demonstrated that standardized connections can sustain seismic demands within multi-hazard design conditions, providing structural evidence that modularity can support safe and repeatable construction in contexts with elevated earthquake risk (Di Sarno & Forgione, 2024). Accordingly, modular construction represents a quality avenue for enhancing resilience. By employing prefabricated components and standardized connections, it can deliver structural consistency while accommodating the gradual and adaptive nature of self-built housing. Nevertheless, its successful application in informal contexts requires more than the transfer of technology. It demands the integration of participatory design and incremental development, ensuring that modular systems reinforce community agency rather than replace it. This paper, therefore, examines how modular construction, when reinterpreted through collaborative and context-sensitive approaches, can provide a viable pathway toward seismic resilience and social sustainability in Latin America's informal settlements.

Historical Precedents

Understanding how societies have historically responded to seismic events is a key aspect for evaluating the viability of modular construction in today's informal settlements in Latin America. Throughout history, earthquakes have exposed structural vulnerabilities, as well as prompted critical issues in building cultures and technical practices (Oliver-Smith, 1999). In other words, those shifts emerge from a real necessity, particularly in contexts where widespread damage compels institutional reflection.

As Walker (2003) observes, the collapse of elite housing provides a striking contrast to Oliver-Smith's (1999) broader interpretation of vulnerability in Peru's seismic history. Understanding this dynamic requires acknowledging how earthquakes operate not only as physical but also as social phenomena. According to Discovering Geology, earthquakes result from "sudden movement along faults within the Earth, releasing stored-up elastic strain energy as seismic waves." The severity of their consequences, however, depends largely on the resilience of the built environment. Structures that lack lateral resistance or rely on brittle materials are especially prone to collapse, particularly within informal settlements.

By way of illustration, the 1746 Lima earthquake provides a noticeable example of these processes. Nearly all of Lima's 3,000 buildings collapsed, with only about 25 left standing, and the accompanying tsunami destroyed the port of Callao, killing around 6,000 of its inhabitants and leaving only 200 survivors. In total, approximately 1,141 people perished in Lima out of an estimated 60,000 residents, while the combined earthquake–tsunami death toll exceeded 5,900 (NCEI, 2023). Walker (2003) states that a historical seismic coupling map of the event (Figure 1) highlights zones of concentrated ground motion in red, which correspond closely with the areas that suffered the greatest destruction. By visualizing how seismic energy is distributed unevenly across the territory, the figure strengthens the argument that earthquakes do more than damage individual structures. They also reshape urban form by creating spatial corridors of extreme impact, a pattern that reveals the need for construction systems such as modular housing that can preserve structural predictability even under highly irregular seismic demands.

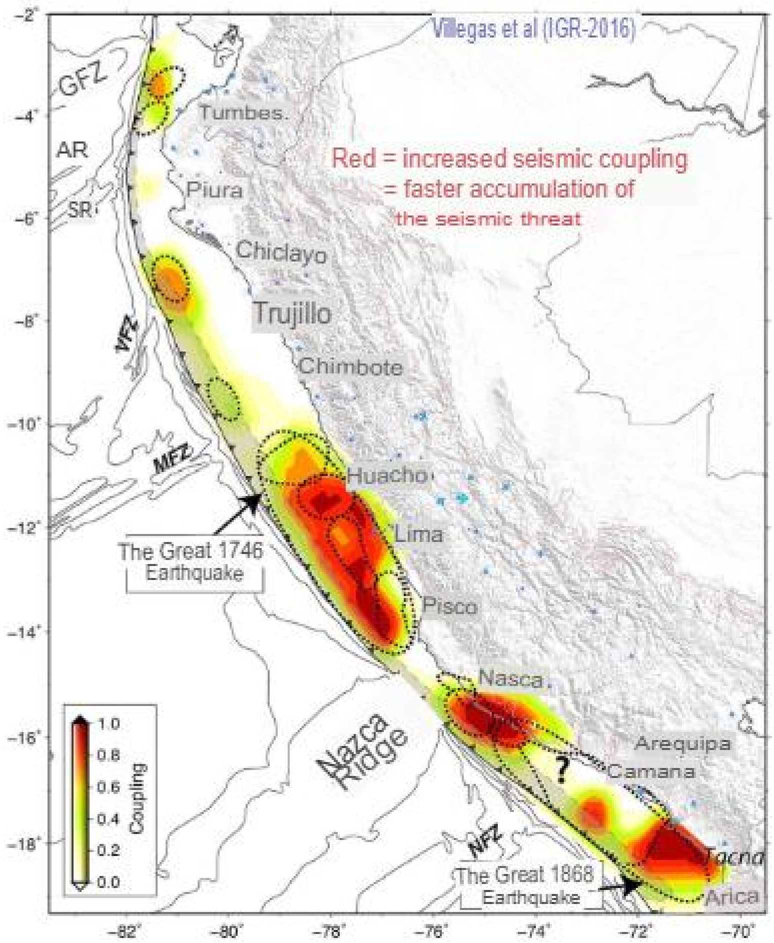


Figure 1: *Seismic coupling map showing zones of low to high ground motion during the 1746 Lima earthquake.*

Note. The map visualizes the spatial distribution of seismic energy accumulation and release, illustrating how zones of high coupling (in red) correspond to the sectors where built structures suffered the most intense damage. By highlighting the unevenness of ground motion, the figure reveals that vulnerability is not uniform across the urban fabric, but instead strongly conditioned by geotechnical and morphological factors already present before the event.

To complement this scientific visualization, Walker (2003) also shares a historical map documents the spatial configuration of Callao before and after the event (Figure 2).

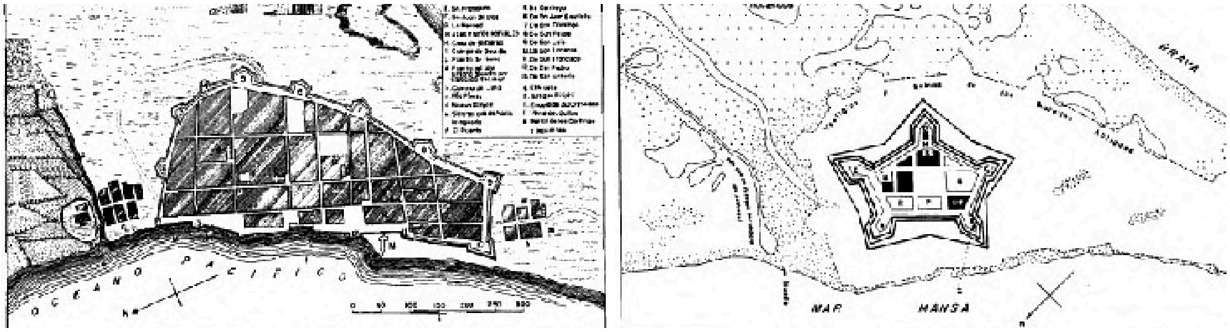


Figure 2: *Historical Map of Callao District Before and After the 1746 Earthquake*

Note. The juxtaposition reveals the scale of territorial transformation caused by the disaster: entire neighborhoods disappeared, the coastline receded, and previously inhabited areas became permanently uninhabitable. The figure illustrates how catastrophic events can obliterate existing spatial organization, forcing cities to confront sudden and irreversible reconfigurations of land and settlement patterns.

It is worth highlighting that this visual evidence also shows that resilience requires adaptability at both the structural and territorial scales. Modular housing aligns with this need as its disassemblable and relocatable components allow rapid reoccupation and spatial reorganization after disasters that significantly alter the built environment, as occurred in Callao. The transformation of Callao's territory was profound, as disasters significantly altered its urban landscape. In the earlier map, the city of Callao is shown as a consolidated port settlement; in the later one, the coastline is fragmented, and large tracts have vanished. The tsunami erased entire neighborhoods, permanently reshaping the region’s geography. This transformation demonstrates how disasters can simultaneously dismantle physical infrastructure and reorder urban space. Callao’s port vanished not only due to its location but also because of the city’s lack of proper planning, which highlights how inadequate urban planning can exacerbate the effects of natural events.

In the aftermath, Peru’s authorities implemented a significant change in construction logic. They started to work with quincha, a traditional system that uses a timber framework filled with cane and covered in mud plaster, to improve energy dissipation during earthquakes (Vergara, 2014). Quincha became an early example of ductile construction, enabling buildings to flex rather than collapse. Although the technique preceded formal theories of dynamic load resistance, it marked a decisive shift in Latin American seismic adaptation. Nonetheless, the centralized enforcement of building codes and limited technical support hindered authorities from implementing quincha, resulting in uneven adoption across expanding urban peripheries. (Fernández-Maldonado & Bredenoord, 2010). Many low-income families continued building with fragile materials, illustrating how access to safer methods remained conditioned by social and spatial inequality.

Years later, a similar situation unfolded in Valparaíso, Chile, where the 1906 earthquake devastated the hillside neighborhoods, particularly those that had grown without much engineering guidance, echoing the challenges faced in Callao. Accordingly, this panorama became an imperative moment in Chilean engineering history since it prompted institutions and professionals to rethink the materials and structural systems used in construction. In addition, the scenario itself signified the onset of a long-term transformation that eventually positioned Chile as a leading seismic nation. All things considered, a key part of this shift was the arrival of reinforced concrete, a mix of steel and concrete strong enough to handle both compression and tension. Likewise, during the same period, seismic codes were formalized, and engineering schools began offering courses in structural dynamics, which marked the professionalization of earthquake engineering in the country (Maino & Tobriner, 2024). Despite these improvements, most progress remained within the formal parts of the city. In fact, many hillside neighborhoods kept expanding on their own, lacking official assistance and direction.

The seismic oscillation intensity map of Valparaíso provides useful insights into the spatial variability of ground shaking throughout the city, highlighting areas of increased vulnerability, as shown in Figure 3. Drawing on the mapping approach presented by Maino and Tobriner (2024), the figure makes clear that seismic impacts are not evenly distributed and instead follow patterns shaped by topography, soil conditions, and the spatial logic of urban expansion. In that matter, there is an existing pattern that keeps showing up at this stage, where informal growth on unstable slopes can magnify the effects of ground motion, and it will turn certain sectors into concentrated zones of structural failure. The hills, in particular, illustrate the compounded effects of informal urban growth and geological fragility, as unstable slopes and weak soils heightened structural damage.

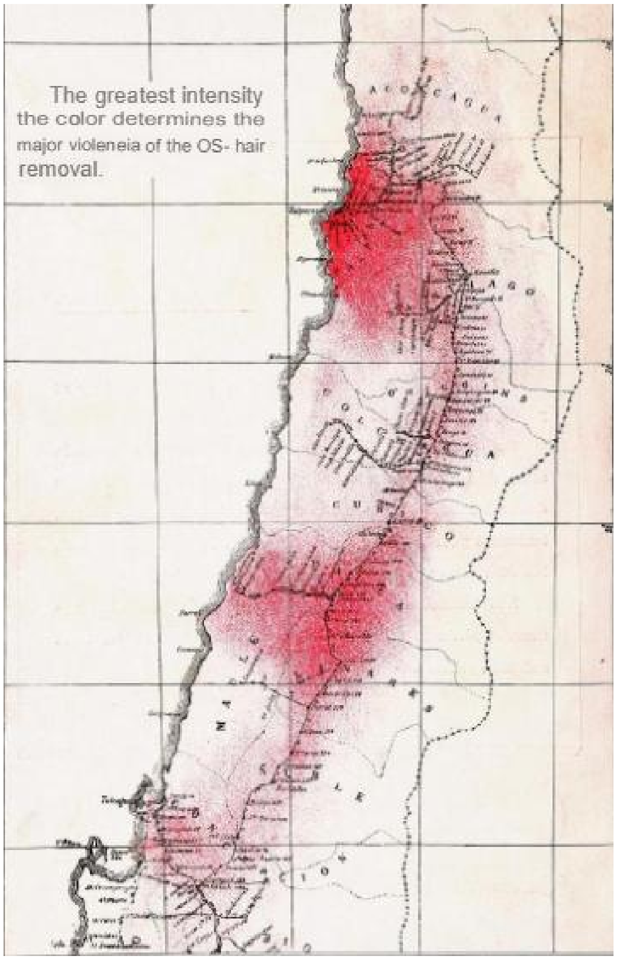


Figure 3: *Seismic Oscillation Intensity Map of Valparaíso During the 1906 Earthquake.*

Note. Darker zones indicate severe shaking, particularly in hillside neighborhoods where informal settlements coincided with geologically unstable slopes. The figure highlights how local soil conditions, topography, and unregulated expansion converged to intensify structural failures during the event. Mapping differential shaking provides a spatial explanation for why certain communities experienced more catastrophic outcomes than others.

In line with the representation developed by Maino and Tobriner (2024), a contemporaneous photograph complements this technical record, which documents the collapse of a typical informal dwelling and adds a human dimension to the empirical data (Figure 4). Unlike official engineering reports that emphasize materials or regulatory frameworks, this picture illustrates a direct portrayal of the lived experience of disaster. It captures the fragility of self-built housing and the efforts of residents to reconstruct amid destruction, which reveals how the absence of technical oversight exposed entire communities to structural collapse. In doing so, this figure highlights that vulnerability is produced through both physical limitations and everyday construction practices that are shown in the picture that are shown in the picture such as irregular load paths and brittle joints, and it clarifies why damage became so concentrated in neighborhoods where precarious building methods were widespread.

Figure 4: *Photographic Evidence of Collapsed Informal Housing in Valparaíso, 1906 Earthquake*

Note. The photograph captures the complete structural failure of a typical self-built home, highlighting brittle connections, irregular load paths, and the absence of lateral resistance. It documents the intimate scale of disaster, showing how families faced immediate displacement and were forced to reconstruct with the same precarious methods that had failed in the first place.

Several decades later, the 2007 earthquake in Pisco, Peru, once again exposed the tension between formal engineering codes and the realities of informal construction. According to the NZSEE reconnaissance report (Hopkins et al., 2008), the disaster destroyed more than 38,000 homes, displaced over 100,000 people, and caused nearly 600 fatalities among 70,000 affected families. For instance, the same report from Hopkins et al. (2008) documented the Figure 5, which depicts post-earthquake conditions in Pisco and shows widespread failure of unreinforced masonry and poorly anchored structures, as well as the social trauma that followed across generations. Beyond documenting the physical destruction, the image also reveals how long-standing construction habits shaped the pattern of damage, since layers of incremental additions and limited technical guidance produced structural inconsistencies that intensified collapse across entire neighborhoods.

Figure 5: *Post-Earthquake Building Conditions in Pisco*, 2007.

Note. The figure shows widespread failure of unreinforced masonry, shallow foundations, and poorly anchored structural systems typical of incremental informal construction. It also reveals the social dimension of disaster by depicting households navigating the loss of homes, stability, and inherited building knowledge.

In addition, the macroseismic intensity map (Figure 6) provides visual evidence that seismic impact is not randomly dispersed but spatially patterned, revealing that the darkest intensity zones coincide with low-income and self-built districts (Hopkins et al., 2008). Rather than acting as a simple illustration, the figure shows that extreme shaking clusters directly over areas with pre-existing socioeconomic fragility, which confirms that urban form and inequality shape the geography of disaster itself. This overlap is useful for the argument that earthquakes become social events due to the severity of damage is conditioned by limited access to technical assistance and the concentration of vulnerable housing types in peripheral neighborhoods.

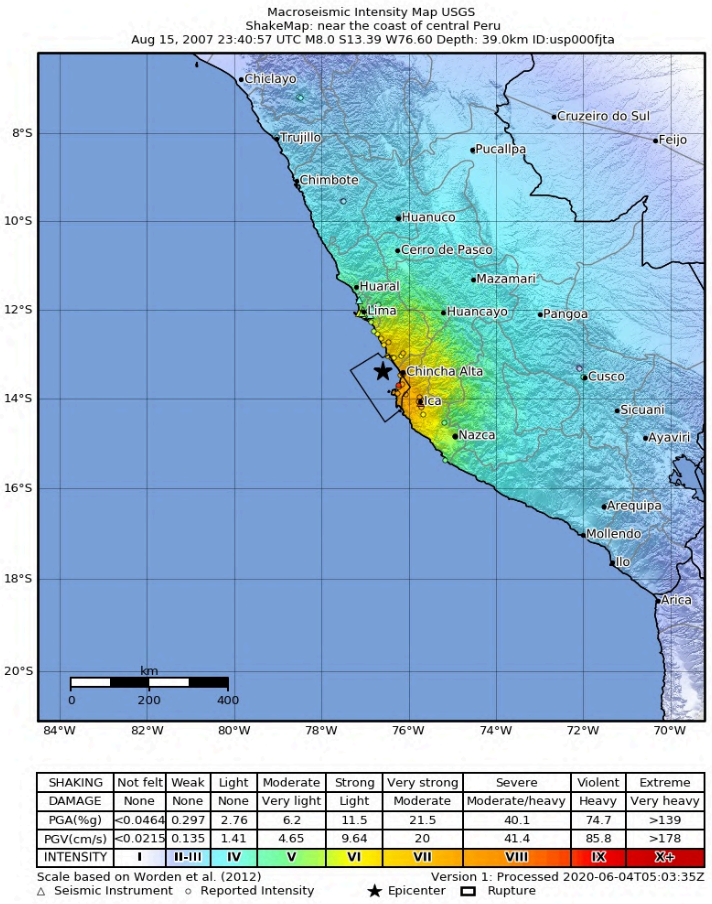


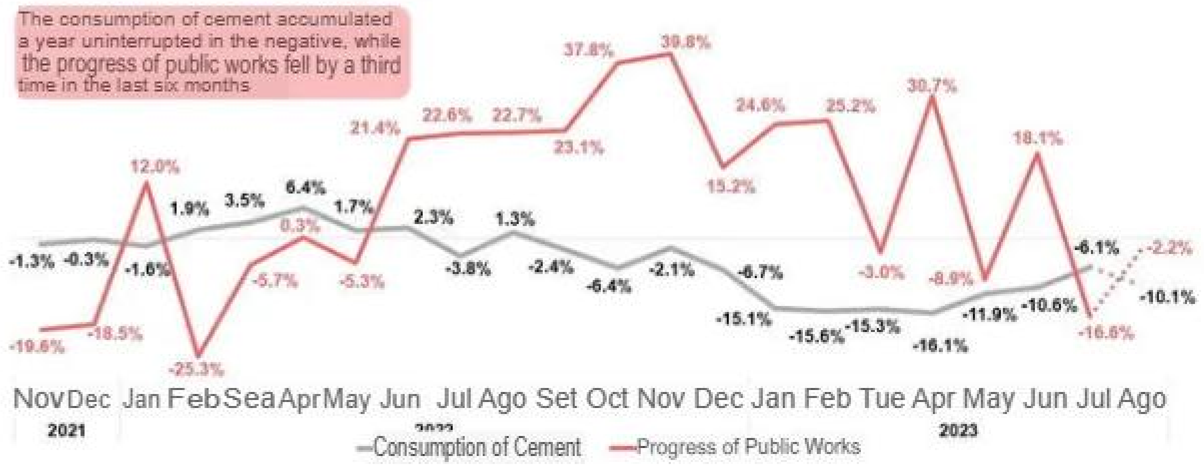
Figure 6: *Macroseismic Intensity Map of the 2007 Pisco Earthquake.*

Note. The darkest zones correspond to areas that experienced extreme shaking, many of which were low-income districts with dense informal housing. The figure conveys how seismic impacts are spatially uneven and correlate strongly with socio-economic marginalization, revealing a pattern in which disadvantaged communities absorb the highest levels of physical and social disruption.

Despite the existence of seismic regulations, enforcement remained inconsistent. Informal areas, where unreinforced masonry and deficient connections were widespread, continued to suffer the most severe losses. The prominent gap between research knowledge and real-world application underscores the persistent disconnect between engineering innovation and self-built housing practices. The prevalence of brittle materials and shallow foundations without lateral resistance forced builders to improvise under precarious conditions.

The Pisco earthquake also revealed the divide between immediate humanitarian response and sustained reconstruction. In many cases, predesigned housing units were imposed without considering local needs or cultural habits, reducing the long-term viability of the recovery process. As a result, numerous houses were abandoned or repurposed. Nevertheless, by 2012, 95.5% of damaged homes were reoccupied, accompanied by significant new construction—over 2,100 new buildings representing 17.6% of total lots—reflecting the persistence of unplanned expansion (Ismail et al., 2017).

Recent data from the INEI (2023), shown in the Figure 7, shed light on the broader structural challenges facing Peru's construction sector today. Both cement usage and public infrastructure investment have declined, with a 7.9% decrease in August and an 8.8% decrease in January of the same year. In that manner, this downward trend reflects three interrelated dimensions. First, the reduction in cement consumption indicates a slowdown in private housing construction, undermining the economic base required to sustain the diffusion of modular technologies. Second, the contraction of public infrastructure projects reveals the state's limited investment capacity, which constrains opportunities to incorporate modular systems into social programs such as educational or affordable housing initiatives. Most importantly, the overall decline in construction activity has weakened investor confidence, as many perceive modular housing as an uncertain or unnecessary innovation amid a shrinking market. Overcoming these challenges demands the stabilization of the construction sector and the development of fiscal and regulatory mechanisms capable of ensuring continuity and scalability in the adoption of modular approaches.



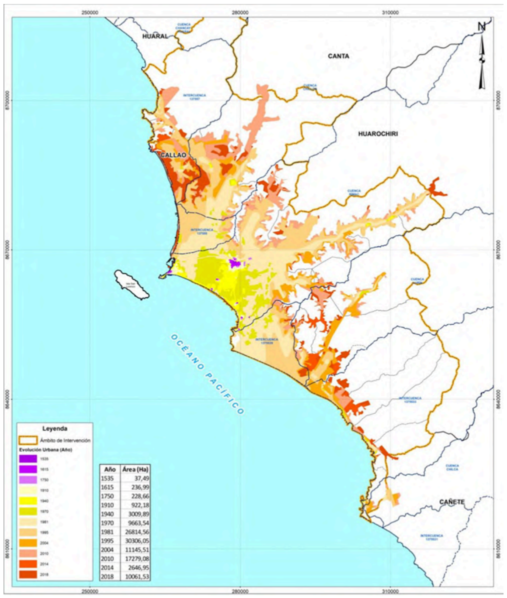
The consumption of cement accumulated a year uninterrupted in the negative, while the progress of public works fell by a third time in the last six months

Figure 7: *Trends in cement usage and public infrastructure development in Peru*, 2023.

Note. Both indicators show significant declines, revealing a downturn in the construction sector that constrains the diffusion of innovative technologies such as modular construction. Reduced investment affects the availability of public programs and large-scale procurement processes required to scale affordable modular housing across high-risk regions.

This contemporary decline mirrors the long-term historical pattern in which periods of innovation have often failed to consolidate into lasting resilience frameworks. Across centuries, Latin America's experience has shown that technological progress alone does not guarantee safety in any circumstance. In consequence, seismic resilience must instead be understood as both a physical capacity to absorb shocks and a social capacity to institutionalize and sustain improved building practices over time.

Understanding these continuities becomes even more critical when examining the spatial dynamics of current risk. The expansion of informal settlements into hazardous terrains reveals how historical neglect in planning continues to shape vulnerability today (Sandoval and Sarmiento, 2020). In many Latin American cities, and especially in Peru, rapid urban growth has consistently outpaced formal regulatory frameworks it resulting in extensive peripheral zones where basic infrastructure is either deficient or absent (Sakay et al., 2011). Figure 8 shows that Lima's urban expansion has historically pushed development into peripheral terrains with low geotechnical stability, revealing a long-term pattern in which the city grows faster than planning institutions can regulate. (Equipo Técnico Plan Met 2040, 2020). This map is therefore a visual evidence that vulnerability is produced by the spatial logic of expansion itself, as households settle in environmentally fragile areas that magnify seismic and hydrological risks.



Año	Área (Ha)
1535	37,49
1615	236,99
1750	228,66
1910	922,18
1940	3009,89
1970	9663,54
1981	26814,56
1995	30306,05
2004	11145,51
2010	17279,08
2014	2646,95
2018	10061,53

Figure 8: Urban growth map of Metropolitan Lima (1535–2018).

Note. The map shows how the city expanded progressively into peripheral areas with low geotechnical stability, limited infrastructure, and high exposure to natural hazards. As urban growth outpaced planning, these zones became concentrated pockets of informal settlement and cumulative environmental risk.

It is important to note that geotechnical assessments reinforce this spatial inequality. While coarse alluvial soils in central valleys can support up to 4 kg/cm², fine sands and silts, common in peripheral settlements, sustain less than 1 kg/cm², and this makes them highly susceptible to liquefaction and collapse during seismic events (Gutiérrez et al., 2020). Also, when combined with the absence of professional guidance in self-built housing, these conditions amplify structural fragility at a high level.

Moreover, GIS analyses demonstrate that many of Lima's informal districts overlap with seismic amplification zones. Figure 9 makes this convergence particularly visible by mapping dense clusters of self-built housing directly onto areas characterized by unconsolidated soils and deep alluvial deposits (INEI, 2007). Instead of merely locating informal settlements, the figure exposes how urban growth interacts with geological conditions to intensify risk, revealing that the most disadvantaged groups inhabit precisely the environments where ground motion is most likely to be amplified. Indeed, areas characterized by unconsolidated sediments and deep alluvial deposits intensify ground motion during earthquakes, generating localized peaks in shaking intensity. It is important to add the fact that current surveys show that more than 60% of residents in high-risk areas have never received earthquake preparedness training, and over 40% are unaware of evacuation routes, even while living in seismically active zones (Quesada-Román, 2022).

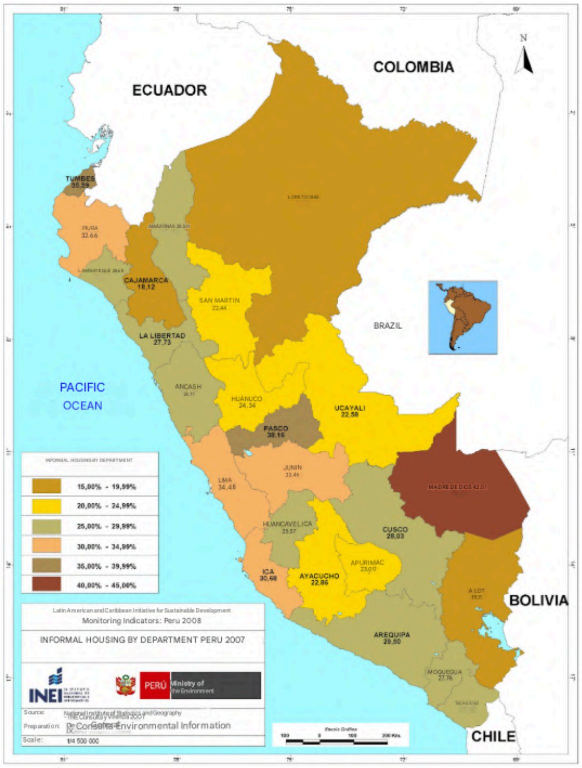


Figure 9: *Distribution of informal settlements in Lima.*

Note. The brown clusters indicate areas with high concentrations of informal housing, many of which overlap with zones of amplified ground motion and poor soil conditions. The figure reveals a persistent pattern whereby the most vulnerable groups occupy the most hazardous environments.

Madre de Dios, Pasco, Tumbes, and Lima are the districts with the highest concentrations of informal settlements, which means that these areas have an emergency response capacity that is further constrained by narrow streets and overcrowded conditions. Adding to this, population density exceeds 1,000 inhabitants per hectare, and combustible materials such as timber and cardboard are used in over 70% of dwellings. As a result, household fires occur two to three times more frequently than in planned neighborhoods, with emergency response delays reaching 40 minutes or more (Ismail et al., 2017). That is to say that these factors heighten seismic risk and compound exposure to secondary hazards.

Although this configuration is characteristic of many Latin American cities, similar processes are evident elsewhere. To illustrate this point, in Warsaw, Poland, inadequate remediation of nearly 300 contaminated industrial sites disproportionately endangers low-income populations, which reveals how socio-spatial inequality perpetuates environmental vulnerability (Maciejewska and Ulanicka-Raczyńska, 2023). In addition, in Lima, the concentration of risk in marginal zones reflects the persistent failures of centralized governance and continues to push low-income households into unstable terrains.

To integrate these findings, these contemporary dynamics extend the historical trajectory traced throughout this section. From colonial-era collapses to modern construction downturns, seismic vulnerability in Latin America has remained closely tied to structural inequality and the uneven diffusion of technical knowledge. In the same way, these takeaways from past and present events emphasize the urgent need for new housing paradigms that combine structural innovation with social participation, objectives that modular construction, when properly adapted, has the potential to fulfill.

Examining these dimensions, we can see that the evolution of seismic adaptation across Latin America embodies the fact that resilience is associated with a socio-structural process shaped by history, inequality, and institutional capacity. Hence, each precedent reveals how progress in engineering has repeatedly faltered when disconnected from local realities and social participation.

Engineering Aspects of Modular Construction

Modular construction is a building method that employs prefabricated components and efficient on-site assembly, which has progressively evolved into an optimal strategy for improving structural safety in vulnerable settings. More precisely, this approach involves the design and partial or complete fabrication of structural modules in controlled environments. Over time, modular construction must be viewed as the continuation of prefabrication practices that date back to monumental works of antiquity and later reappeared during the British colonization, the California Gold Rush, and both World Wars (Smith, 2010). Moreover, technological advances such as robotic manufacturing and specialized transportation systems have refined these methods to achieve high standards of quality control and efficiency rarely matched by conventional construction (AlDairi, 2021).

This historical continuum elucidates essential implications for structural systems. In contrast with informal housing that grows through unregulated additions (Green, 2008), modular systems depend on standardized dimensions and precisely engineered joints that ensure predictable behavior under load (Lawson & Richards, 2010). As shown in Figure 10, the detailing of a typical modular structural joint substantiates how these components maintain continuity of forces throughout the system. Along similar lines, Figure 11 shows the optimal depiction of the different gusset plate configurations—double-hole for external joints, single-hole for corner joints, and four-hole for internal joints—that promote consistent load transfer and minimize weak points. Distinctly, this engineered coherence is sharply different from the irregular load paths found in self-built dwellings. Complementarily, modular systems are compatible with the incremental building logic often observed in low-income contexts, as individual modules can be manufactured and added over time without compromising global stability (Fernández-Maldonado & Bredenoord, 2010). This compatibility drives the whole scenario to a distant level of technical, it is now urbanistic, since it provides a controlled alternative to the incremental growth patterns that shape much of Latin America's peripheral urban form. In this regard, the reconstruction of Valparaíso after the 1906 earthquake evidenced this progression by showing how seismic disasters have repeatedly triggered transitions from empirical to engineering-based construction approaches (Maino & Tobriner, 2024). The visual evidence provided by Figures 10 and 11, therefore, helps address a major issue that is that modular design operationalizes lessons historically learned after major disasters by embedding seismic logic directly into the joints and incremental assembly processes that define how cities in high-risk regions continue to expand.

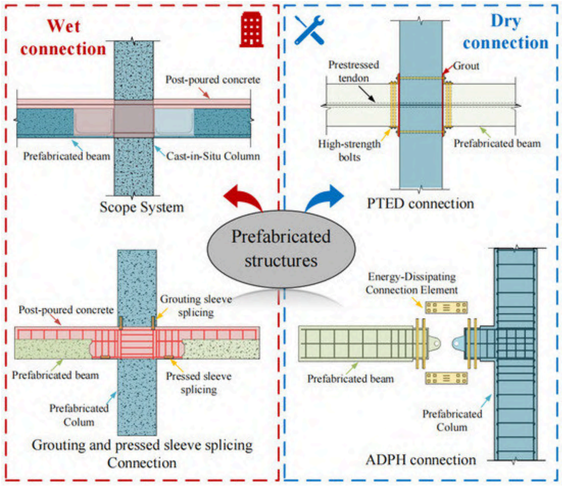


Figure 10: Structural joint diagram in modular construction systems.

Note. Illustrates engineered load paths that maintain force continuity across modules, ensuring predictable behavior under seismic loads.

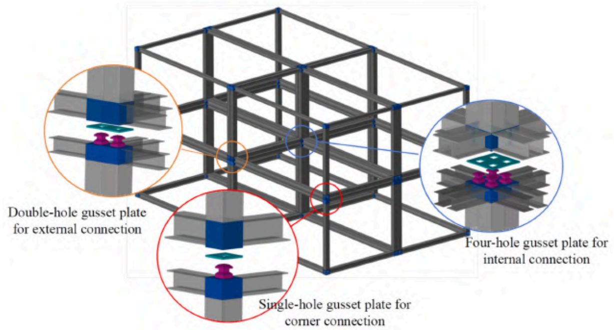


Figure 11: Connection types in modular housing assemblies.

Note. Shows connection types that minimize stress concentration and enable consistent energy dissipation.

Considering that structural logic, the connection systems stand out as the critical determinants of seismic resilience. Notably, both inter-module and intra-module joints are designed to optimize robustness and energy dissipation under extreme loading. The most common arrangements include tie rods with shear keys, bolted plates, VectorBloc connectors, and welded cover plates. Furthermore, each configuration directly affects lateral-force resistance and inter-story drift, defining the building's overall ductility (Ginigaddara et al., 2023).

Against this backdrop, Figure 12 offers a representative example of these mechanics by depicting a bolted plate connection that enhances deformation capacity while ensuring efficient load transfer across prefabricated assemblies. As the diagram shows, such systems can accommodate considerable displacement demands without compromising structural integrity, thereby lowering the likelihood of abrupt failure. Consequently, this type of connection underscores that modular construction is not merely a substitute for conventional methods; rather, it constitutes a structurally rigorous strategy capable of meeting the specific performance requirements of high-risk seismic environments.

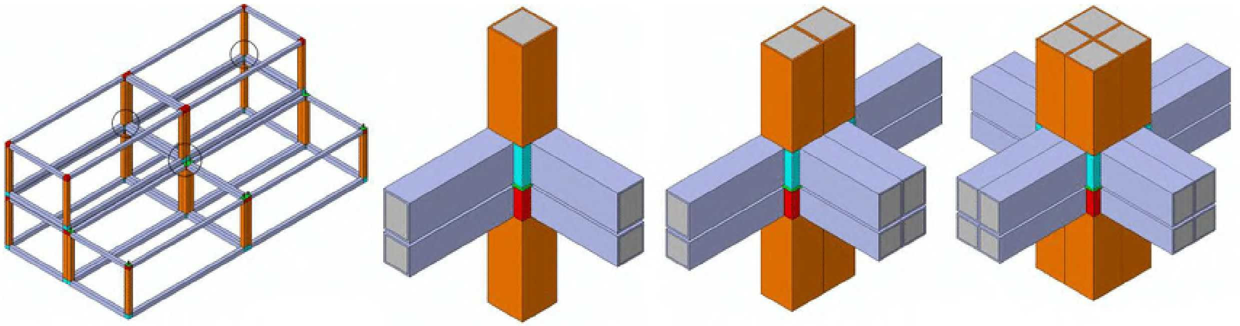


Figure 12: Detail of bolted plate modular connection.

Note. Demonstrates how prefabricated joint systems achieve ductility and reduce failure risks.

Transitioning from theoretical modeling to experimental validation, Figure 13 is a crucial link between conceptual seismic mechanisms and their behavior under dynamic conditions. The scaled modular tower tested by Sheng Li et al. (2022) incorporates a superelastic tendon system that enables controlled rocking while preserving the building's ability to re-center after strong ground motions. Concurrently, this detailed diagram highlights the placement of rotation sensors, strain gauges, and acceleration monitors, which together reveal how the tendon redistributes seismic demands away from brittle connections and toward components capable of sustaining large, recoverable deformations. Through shaker table tests, the authors compared fixed-base, and tendon-restrained configurations subjected to identical near-fault impulses. By extention, the tendon-restrained model reduced internal forces by 36 percent and rocking rotations by 61 percent relative to the other two systems. By visualizing how the tendon anchors the upper module and restricts excessive rotation, the figure clarifies why this mechanism is effective in preventing catastrophic joint failures, one of the most persistent weaknesses in modular construction. In consequence, the experimental evidence demonstrates that integrating superelastic NiTi tendons can significantly strengthen modular high-rise structures while preserving the fabrication efficiency that defines industrialized building methods.

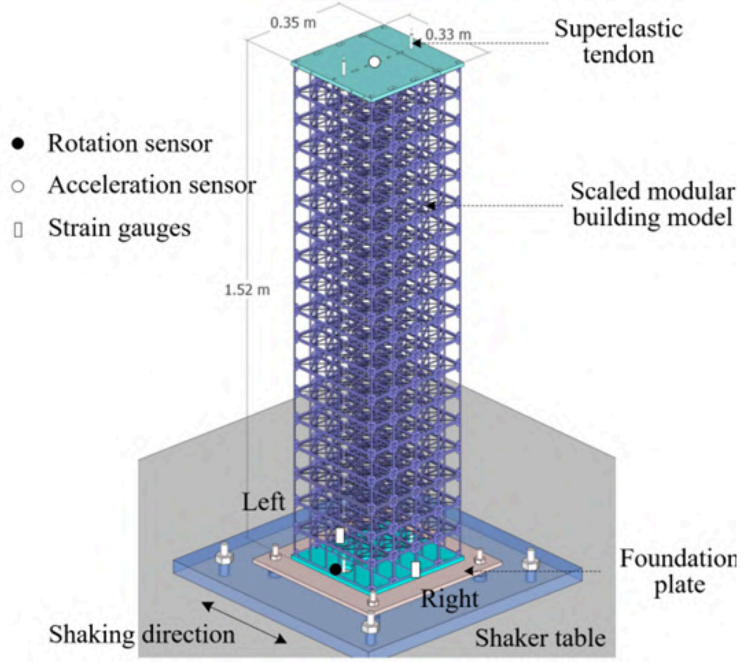


Figure 13: Scaled modular building model with superelastic tendon system and test set-up.

Note. The tendon mechanism restricts rocking motion and reduces internal forces during near-fault excitations, demonstrating how advanced seismic technologies can be integrated into modular typologies without compromising prefabrication efficiency.

A practical reference for the implementation of modular systems in Latin America can be observed in Peru. In substantive terms, Figure 14 presents the ALQUIMODUL SAC construction model, which assembles prefabricated concrete and steel components produced in controlled factory environments. Rather than simply illustrating the pieces involved, the image delineates how insulation layers, gypsum boards, galvanized profiles, and phenolic plywood panels are arranged to create a thermally efficient and structurally stable envelope. This configuration shows that locally manufactured components can achieve the precision and material continuity required for seismic reliability, contradicting the assumption that advanced prefabrication is unattainable in low- and middle-income economies. The figure also attests to that modular construction reduces on-site variability, since dimensional accuracy and quality control occur upstream during fabrication. Nevertheless, the long-term success of these systems depends on the development of specialized training programs and alignment with local construction practices so that factory-based production can scale beyond prototype deployments and become a sustainable alternative to informal urban expansion.

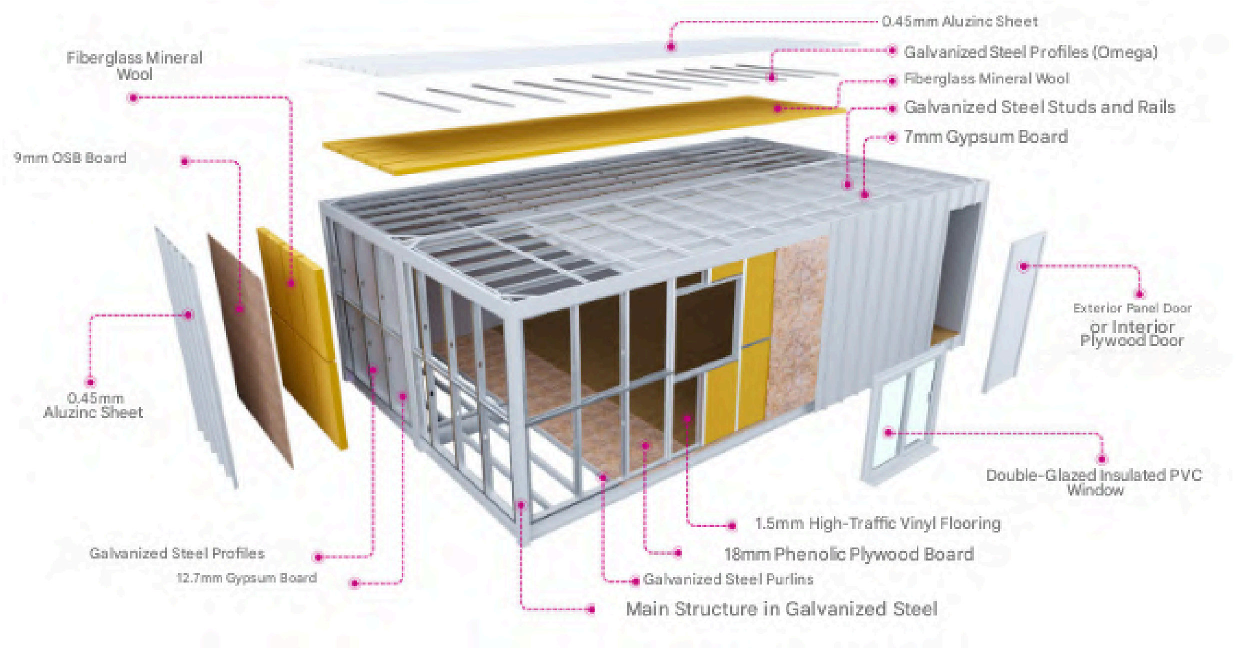


Figure 14: Advanced Modular Concrete Construction System in Peru, 2012.

Note. The diagram presents prefabricated wall panels, insulation layers, and structural frames manufactured under controlled conditions. It exemplifies how national industries can produce modular components that bring seismic reliability within reach for low-income populations.

Beyond seismic performance, modular construction has proven adaptable to multiple hazards such as cyclones, floods, pandemics, and fires. In areas exposed to strong winds, for example, reinforced interconnections and fatigue-resistant joints are necessary to counteract high lateral pressures and debris impacts (Di Sarno & Forgione, 2024). Figure 15 presents a hurricane-resistant modular housing design that integrates aerodynamic geometry and improved panel anchoring. Similarly, Figure 16 showcases amphibious pavilion systems and floating foundations, which exemplify how modular structures can adapt to recurrent flooding and changing hydrological conditions (Abdur Rehman, 2024). During the COVID-19 emergency, this flexibility was demonstrated by rapidly constructed modular medical facilities such as the Leishenshan Hospital (Ismail et al., 2017). Nevertheless, significant research gaps remain concerning large-scale tests for combined hazards and fire performance (Bhandari et al., 2023). Figure 17, a rendered model of a modular housing unit, represents the integration of structural resilience with aesthetic and spatial considerations, demonstrating that functionality and design innovation can coexist within resilient architecture.

Figure 15: *Hurricane-Proof Houses: Designs, Costs, and Construction Methods.*

Note. Shows aerodynamic profiles and reinforced anchoring systems developed for cyclonic regions.

Figure 16: *Multi-Hazard Resilient Modular Building Design Example at Leishenshan Hospital.*

Note. Depicts floating or amphibious modules designed for recurrent flooding scenarios.

Figure 17: *Rendered Model of a Modular Housing Unit.*

Note. Illustrates how structural resilience and architectural quality can coexist in modular design.

Considering these perspectives, modular construction can be recognized as one of the most viable strategies for enhancing safety, efficiency, and quality in high-risk environments. Prefabrication enables continuous testing of materials and load-bearing assemblies before installation, minimizing the likelihood of design flaws or assembly errors (Sandoval & Sarmiento, 2020). Furthermore, its modular logic facilitates post-disaster recovery, allowing damaged units to be replaced individually without dismantling the rest of the structure (Eren, 2012). However, achieving adaptive capacity requires more than technical precision. It demands the incorporation of modular construction within broader disaster management frameworks and its adaptation to the cultural, environmental, and economic realities of each territory (Hussainzad & Gou, 2024). When these conditions are met, modular construction ceases to be a mere technological alternative and becomes a holistic tool for safety and inclusive urban development.

When viewed collectively, the engineering perspective on modular construction highlights that adaptive capacity is not achieved solely through stronger materials or advanced joints but through replicability. As a whole, the previous examples and analyses demonstrate how modular systems can balance technical rigor with flexibility, allowing buildings to be assembled and repaired efficiently in hazard-prone settings. By standardizing structural components while accommodating incremental growth, modularity offers a structural language that can be transferred into informal contexts.

Social and Participatory Frameworks

Social structures depend fundamentally on the participation and agency of communities. Engagement from residents, when combined with incremental building strategies, can strengthen both social cohesion and structural resilience in informal settlements. Along those lines, self-managed and incremental construction has been viewed over time as a community-shaped practice, one that intertwines building decisions with everyday forms of cooperation and adaptation. As Fernández-Maldonado and Bredenoord (2010) argue, progressive housing works precisely due to the fact that it mirrors the temporal rhythms of low-income households. Their perspective is pivotal for the hybrid model proposed here, in which community agency functions as a structural driver of safety, in order to enable housing to evolve without compromising local decision-making.

Research derived from participatory approaches portrays the advantages of collaboration in achieving better results. Gavin's (2011) Project-Based Learning study at University College Dublin, though situated in education, is a valuable parallel: 90% of surveyed students reported improved comprehension through collective problem-solving, with group quality (23%) and individual skill (21%) shaping performance. In this regard, the challenges he identifies, such as imbalanced contributions and heavy time demands, share the realities of community-led construction. That is how they highlight that participation requires facilitation and shared responsibility, conditions essential for incremental housing processes.

At the same time, the application of Quality Function Deployment in the construction industry has revealed how integrating user needs early can reduce costly design modifications and accelerate project completion. Abdul-Rahman et al. (1999) show that QFD can cut engineering revisions and design durations by about 50%, decrease startup costs by 20-60%, and reduce warranty claims by 20-50%. Although derived from formal construction sectors, the underlying principle is strongly linked with informal housing as it underscores that residents (who are both users and builders) can shape decisions from the outset and transform interventions in an efficient way.

These insights connect with broader demographic and social shifts. Nguyen and Levasseur's (2023) review of 46 studies demonstrates a growing need for flexible and supportive living arrangements. Consistent with this, retirement communities represented 15% of cases, assisted living frameworks 39%, and cohousing models 24%, with 76% of participants being women and half reporting health challenges. Those findings emphasize that access to services and social support improves well-being. While the context differs, the underlying logic applies to younger and low-income populations in informal settlements: participatory spaces enable residents to reshape their environments as life circumstances change, reinforcing the long-term adaptability central to incremental construction.

Additionally, variations in how cities use space since COVID-19 began have provided more opportunities for development and adaptation. In other words, urban transformations following COVID-19 further illustrate how spatial conditions influence housing possibilities. Remote work in the European Union peaked at 37%, contributing to office occupancy rates falling to around 10%, while vacancy rates in Sydney's central business district increased to 10-11%. In that sense, these trends contrast sharply with pre-pandemic occupancies of 60-70%. For cities facing land scarcity, the reactivation of underused space offers new possibilities for incremental solutions, especially when repurposing occurs through participatory decision-making that attends to local needs and constraints. At the same time, climate-related events add urgency to this discussion. The 2019-2020 Australian bushfires destroyed 3,000 homes across 30 million hectares, while the 1960 Chilean tsunami affected four nations within 12–20 hours. These past events underscore the vulnerability of built environments. Yet, innovative responses-like the Nature Urbaine rooftop garden in Paris, which produces 200 kilograms of food daily across 14,000 square meters, or the relocation of Kiruna in Sweden, involving 6,000 residents and 39 historic buildings—show how participatory and flexible approaches can strengthen sustainability and social cohesion (Anguelovski et al., 2016). Although geographically distant, these cases reinforce principles that directly support that adaptation works best when communities remain central actors.

It is theoretically true that the integration of modular construction, participatory design, and incremental housing may represent one of the most effective strategies for strengthening seismic safety and multi-hazard adaptability in vulnerable environments. This approach draws on vernacular knowledge and participatory governance structures (Tähtinen, 2024), ensuring that innovation remains grounded in local realities rather than imposed through rigid top-down models. As Nguyen and Levasseur (2023) also suggest, adaptability improves when housing is able to evolve with residents' changing needs in a way that we can preserve affordability and reduce long-term vulnerability.

The convergence of evidence from diverse cases strongly supports this synthesis. In rural Colima, Mexico, the adaptation of traditional wattle-and-daub into geodesic domes demonstrated exceptional seismic performance, climatic suitability, affordability, and compatibility with community-led construction (Ismail et al., 2017). In Pakistan, modular flat-pack homes constructed from cold-formed steel and fiber-cement boards enabled rapid and low-cost reconstruction after disasters (Abdur Rehman, 2024). Additional cases from British Columbia's critical infrastructure projects and Cape Town's flood management strategies show that technical solutions are more effective when validated through participatory methods and multi-institutional coordination (Genik & Chouinard, 2015). It is noticeable that, across all examples, innovation succeeds when local governance and environmental demands are met.

It is worth highlighting that these examples reveal a broader concept: resilience must always be adapted to local hazards and governance systems. Whether considering the thermal performance of Colima's earth constructions, Pakistan's flood-resistant modular units, or urban models like the Inner City Suburbia framework (Kotila, 2010), effective strategies merge technological advancement with social and environmental adaptation (Green, 2008). Experimental methodologies such as Stickbot prototyping and interdependency mapping in Canada further illustrate that design improves through iterative, real-world testing rather than abstract planning (Carroll et al., 2023). Resilience is therefore dynamic, continually shaped by both technical progress and community practice.

For Latin America, the conclusions are explicit. Hazard-resistant housing should combine traditional low-carbon materials with contemporary seismic engineering (Ye et al., 2025), incorporate co-design from the earliest stages, and understand modularity and incremental development as proactive rather than reactive strategies (Lawson & Richards, 2010). Pilot projects must operate as living laboratories for technical validation and policy alignment (Varela et al., 2022). The continuity between local innovation and scientific validation can ensure that resilience becomes embedded in both construction practices and institutional frameworks. Even if it appears repetitive, resilience should always be perceived as a dynamic capability fostered through the integration of technical knowledge, social participation, and long-term cultural learning.

Viewed in aggregate, the evidence drawn from participatory frameworks indicates that adaptive capacity depends as much on collective engagement as on construction technology. When a local agency aligns with technical precision, modular and incremental methods evolve into dynamic systems of adaptation rather than static housing products. Within such frameworks, residents shift from passive recipients to active co-designers of safety and continuity. In this configuration, the interaction among participatory governance, modular engineering, and historical awareness thus defines a new paradigm in which resilience is sustained through cooperation and long-term cultural learning.

Conclusion

The evidence analyzed in this study shows that conflating modular construction, participatory design, and incremental housing can constitute a viable pathway in terms of seismic resilience in informal settlements. This combined approach capitalizes on the structural reliability of prefabricated systems while remaining consistent with the incremental and adaptive construction practices characteristic of resource-constrained communities. Actually, resilience must therefore be conceived as a dynamic capacity, reinforced through the continuous interaction between governance and community engagement equally.

For Latin America, the adoption of hybrid modular-incremental models needs more than the replication of technical prototypes. In reality, and even if it takes a long time, it necessitates the institutionalization of participatory frameworks within official planning processes and the development of financing mechanisms that simultaneously address structural safety and social stability.

Truly, future research is obliged to evaluate hybrid housing communities longitudinally in post-disaster contexts and compare their structural and social performance with conventional approaches. It is also worth mentioning the exploration of accessible training programs for informal labor networks, the incorporation of digital tools such as participatory mapping and GIS-based hazard modeling, and the alignment of seismic design with climate adaptation strategies in dual-hazard regions. That is how we, as a society that has actually learned something from the past catastrophes, must advance seismic safety in informal urban areas demands recognition of resilience as both an engineering challenge and a socio-political endeavor; one that needs deliberate coordination between technical excellence, community capacity, and institutional support to maintain the cities in a stable condition.

Acknowledgements

The author extends a huge gratitude to Dr. Devin Carroll, whose mentorship and feedback shaped the analytical depth of this work, and to Kieran Tait, whose constructive critique and constant follow-up of the paper brought motivation at every stage. In addition, I wanted to thank my family since they have always supported this journey related to positively improving the construction world.

Above all, the deepest respect is reserved for the communities living each day under seismic risk around the globe. Their resilience in transforming limited resources into enduring solutions embodies the conviction that guides this study: true safety surfaces when technical knowledge is interwoven with collective agency and rooted in local wisdom.

Bibliography

45. Abdul-Rahman, H., Kwan, C. L., & Woods, P. C. (1999). Quality function deployment in construction design: Application in low-cost housing design. International Journal of Quality & Reliability Management, 16(6), 591–605. https://doi.org/10.1108/02656719910268198
46. Abdur Rehman, Z. (2024). Modular emergency relief: A proposal for integrating modular buildings into post-flood reconstruction and recovery. https://www.theseus.fi/handle/10024/868097
47. AlDairi, S. (2021). Modular construction in the civil engineering industry [Master's thesis, Stevens Institute of Technology]. ProQuest. https://search.proquest.com/openview/21cf00c2a57b6ad03ed474d4fdbff151/1?pq-origsite=gscholar&cbl=18750&diss=y
48. Anguelovski, I., Shi, L., Chu, E., Gallagher, D., Goh, K., Lamb, Z., Reeve, K., & Teicher, H. (2016). Equity impacts of urban land use planning for climate adaptation: Critical perspectives from the Global North and South. Journal of Planning Education and Research, 36(3), 333–348. https://doi.org/10.1177/0739456X16645166
49. Bhandari, S., Riggio, M., Jahedi, S., Fischer, E. C., Muszynski, L., & Luo, Z. (2023). A review of modular cross-laminated timber construction: Implications for temporary housing in seismic areas. Journal of Building Engineering, 63, 105485. https://doi.org/10.1016/j.jobe.2022.105485

50. Calderon, C. (2008). Learning from slum upgrading and participation: A case study of participatory slum upgrading in the emergence of new governance in the city of Medellín, Colombia. https://www.diva-portal.org/smash/record.jsf?pid=diva2:126733
51. Carroll, D., Ang, V., & Yim, M. (2023). StickBot: A methodology for building robots and other functional elements from tree branches and string. https://doi.org/10.1115/DETC2023-109541
52. Di Sarno, L., & Forgione, R. (2024). Innovative steel modular housing system for multiple natural hazard mitigation. International Journal of Disaster Risk Reduction, 111, 104734. https://doi.org/10.1016/j.ijdrr.2024.104734
53. Eren, O. (2012). A proposal for sustainable temporary housing applications in earthquake zones in Turkey: Modular box system applications. Gazi University Journal of Science, 25(1), 269–288.
54. Fernández-Maldonado, A. M., & Bredenoord, J. (2010). Progressive housing approaches in the current Peruvian policies. Habitat International, 34(3), 342–350. https://doi.org/10.1016/j.habitatint.2009.11.018
55. Gavin, K. (2011). Case study of a project-based learning course in civil engineering design. European Journal of Engineering Education, 36(6), 547–558. https://doi.org/10.1080/03043797.2011.624173
56. Genik, L., & Chouinard, P. (2015). An overview of pilot projects in support of critical infrastructure resilience. https://apps.dtic.mil/sti/html/tr/AD1004218/
57. Ginigaddara, T., Ekanayake, C., Gunawardena, T., & Mendis, P. (2023). Resilience and performance of prefabricated modular buildings against natural disasters. Electronic Journal of Structural Engineering, 23(4), 85–92.
58. Green, R. (2008). Informal settlements and natural hazard vulnerability in rapid growth cities. En J. J. Pinkham & R. Green (Eds.), Hazards and the built environment (pp. 218–237). Routledge. https://www.taylorfrancis.com/chapters/edit/10.4324/9780203938720-14
59. Gutiérrez, R. M., Esenarro, D., Pingo, P. A., & Rodriguez, C. R. (2020). Vulnerability of the soils of Metropolitan Lima and their relationship with urban sustainability. 3C Tecnología: Glosas de Innovación Aplicadas a La Pyme, 9(1), 161–177.
60. Hussainzad, E. A., & Gou, Z. (2024). Climate risk and vulnerability assessment in informal settlements of the Global South: A critical review. Land, 13(9), 1357.
61. Ismail, F. Z., Halog, A., & Smith, C. (2017). How sustainable is disaster resilience? An overview of sustainable construction approach in post-disaster housing reconstruction. International

Journal of Disaster Resilience in the Built Environment, 8(5), 555–572. https://doi.org/10.1108/IJDRBE-07-2016-0028

62. Kechebour, B. E. (2015). Relation between stability of slope and the urban density: Case study. Procedia Engineering, 114, 824–831.
63. Khan, R. M. A. H., Mubin, S., & Masood, R. (2025). Land-sharing hybrid models for low-cost housing. International Journal of Housing Markets and Analysis. https://doi.org/10.1108/IJHMA-02-2025-0045
64. Kotila, R. (2010). Inner city suburbia: A hybrid solution to sustainable urban middle-income housing [Master's thesis, University of Cincinnati]. https://rave.ohiolink.edu/etdc/view?acc_num=ucin1274195125
65. Lawson, R. M., & Richards, J. (2010). Modular design for high-rise buildings. Proceedings of the Institution of Civil Engineers – Structures and Buildings, 163(3), 151–164. https://doi.org/10.1680/stbu.2010.163.3.151
66. Maciejewska, A., & Ulanicka-Raczyńska, M. (2023). Lack of spatial planning as a cause of environmental injustice in the context of the provision of health safety to urban residents based on the example of Warsaw. Sustainability, 15(3), 2521. https://doi.org/10.3390/su15032521
67. Maino, S., & Tobriner, S. (2024). The search for earthquake-resistant construction systems in Chile after the 1906 Valparaíso earthquake. Construction History – International Journal of the Construction History Society, 39(2). https://www.researchgate.net/publication/389893944
68. Mehrotra, S., Bardhan, R., & Ramamritham, K. (2018). Urban informal housing and surface urban heat island intensity: Exploring spatial association in the city of Mumbai. Environment and Urbanization ASIA, 9(2), 158–177. https://doi.org/10.1177/0975425318783548
69. Moya, L., Vilela, M., Jaimes, J., Espinoza, B., Pajuelo, J., Tarque, N., Santa-Cruz, S., Vega-Centeno, P., & Yamazaki, F. (2024). Vulnerabilities and exposure of recent informal urban areas in Lima, Peru. Progress in Disaster Science, 23, 100345. https://doi.org/10.1016/j.pdisas.2024.100345
70. Murao, O., Hoshi, T., Estrada, M., Sugiyasu, K., Matsuoka, M., & Yamazaki, F. (2013). Urban recovery process in Pisco after the 2007 Peru earthquake. Journal of Disaster Research, 8(2), 356–364.
71. Nguyen, T. H. T., & Levasseur, M. (2023). How does community-based housing foster social participation in older adults: Importance of well-designed common space, proximity to

resources, flexible rules and policies, and benevolent communities. Journal of Gerontological Social Work, 66(1), 103–133. https://doi.org/10.1080/01634372.2022.2133199

72. Oliver-Smith, A. (1999). Peru's five-hundred-year earthquake: Vulnerability in historical context. En A. Oliver-Smith & S. Hoffman (Eds.), The angry earth (pp. 88–102). Routledge. https://doi.org/10.4324/9780203821190-13
73. Quesada-Román, A. (2022). Disaster risk assessment of informal settlements in the Global South. Sustainability, 14(16), 10261.
74. Qin, J., Tan, P., Cai, G., Zhou, C., Mi, P., Tang, M., & Zhou, F. (2025). Seismic performance investigation on simplified modular loading-bearing and energy-dissipating joints for modular steel buildings. Structures, 79, 109409. https://doi.org/10.1016/j.istruc.2025.109409
75. Rashidfarokhi, A. (2024). Resilience by whom and for whom? Empowering local communities for community-led resilience-building. En Real Estate and Sustainable Crisis Management in Urban Environments: Challenges and Solutions for Resilient Cities (pp. 39-56). Routledge. https://doi.org/10.1201/9781003474586-3
76. Sakay, C., Sanoni, P., & Deng, T. H. (2011). Rural to urban squatter settlements: The micro model of generational self-help housing in Lima-Peru. Procedia Engineering, 21, 473–480. https://doi.org/10.1016/j.proeng.2011.11.2040
77. Sandoval, V., & Sarmiento, J. P. (2020). A neglected issue: Informal settlements, urban development, and disaster risk reduction in Latin America and the Caribbean. Disaster Prevention and Management: An International Journal, 29(5), 731–745.
78. Smith, R. E. (2010). Prefab architecture: A guide to modular design and construction. John Wiley & Sons.
79. Unger, E.-M., Zevenbergen, J., Bennett, R., & Lemmen, C. (2019). Application of LADM for disaster prone areas and communities. Land Use Policy, 80, 118–126. https://doi.org/10.1016/j.landusepol.2018.10.012
80. Varela, S. L., Moncagatta, A. R., & Huamán, C. O. T. (2022). Blue and green infrastructure as public spaces: Five proposals for resilient urban development and social integration in Peru. In Handbook of waterfront cities and urbanism. Routledge. https://cris.pucp.edu.pe/en/publications
81. Walker, C. F. (2003). The upper classes and their upper stories: Architecture and the aftermath of the Lima earthquake of 1746. Hispanic American Historical Review, 83(1), 53–82.
82. Ye, Z., Bu, H., Liu, Z., Lu, D., Min, D., & Shan, H. (2025). Seismic resilience design of prefabricated modular pressurized buildings. Resilient Cities and Structures, 4(1), 53–70.

83. Zeballos-Velarde, C. (2021). Urban linkages: A methodological framework for improving resilience in peripheral areas: The case of Arequipa, Peru. En J. Martinez, C. A. Mikkelsen, & R. Phillips (Eds.), Handbook of quality of life and sustainability (pp. 533–550). Springer. https://doi.org/10.1007/978-3-030-50540-0_27
84. Zohourian, M., Pamidimukkala, A., Kermanshachi, S., & Almaskati, D. (2025). Modular construction: A comprehensive review. Buildings, 15(12), 2020.
85. Hopkins, D., Bell, D., Benites, R., Burr, J., Hamilton, C., & Kotze, R. (2008). The Pisco (Peru) earthquake of 15 August 2007: NZSEE reconnaissance report, June 2008. Bulletin of the New Zealand Society for Earthquake Engineering, 41(3), 109–192. https://doi.org/10.5459/bnzsee.41.3.109-192
86. National Centers for Environmental Information (NCEI). (2023, January 1). NCEI Hazard Earthquake Information. https://www.ngdc.noaa.gov/hazel/view/hazards/earthquake/event-more-info/1295
87. Colajanni, Piero & D'Anna, Jennifer. (2023). Seismic risk assessment of residential buildings by the Heuristic vulnerability model: influence of fragility curve models and inventory scale. Bulletin of Earthquake Engineering. 22. 1-34. 10.1007/s10518-023-01801-z.
88. Li, S., Lam, N., & Tsang, H.-H. (2022). Engineering modular building towers for improving earthquake safety. In Proceedings of the Australian Earthquake Engineering Society 2022 National Conference (pp. 1–6). Mount Macedon, Victoria, Australia.

Safe Housing in Seismic Zones: The Modular Path

Abstract

In many Latin American cities, informal settlements still grow on unstable ground because urban planning and enforcement often fail, where rapid urban expansion frequently occurs on geotechnically unstable terrains and under conditions of regulatory exclusion. Numerous historical precedents suggest the necessity of a change in the way we build houses. Examples like earthquakes that occurred in Lima (1746), Valparaíso (1906), and Pisco (2007) illustrate a persistent situation: technological innovation in earthquake-resistant construction often appears in the aftermath of disasters but rarely permeates the informal sector. The study examines whether modular construction, characterized by prefabricated elements and flexible design, can serve as a practical way to address this problem. By drawing on past experiences and recent innovations in modular construction, the paper shows how modular design can fit into the way communities build and plan their own spaces. Additionally, the paper argues that the combination of modular strategies with participatory frameworks is fundamental and successful in ensuring that structural predictability does not undermine local agency. In this line, the findings emphasize that resilience is a matter of institutional embedding and iterative adaptation. In short terms, a blended strategy that merges engineering precision with community-driven incrementalism is proposed as an ideal model for seismic safety and social sustainability in the urban peripheries of Latin America.

Keywords

Disaster Risk Reduction; Civil Engineering; Seismic resilience; Informal settlements; Modular construction; Latin America

Introduction

Informal settlements in seismically active regions, including slums and squatter areas, often emerge under conditions of urgency and exclusion. In that way, these environments are typically shaped by necessity rather than regulation, resulting in homes that lack the structural capacity to withstand earthquakes. Even though it might be considered a coincidental event at some point, it is merely the result of systemic issues that echo the intersection of uncontrolled urban expansion and the emphasis on immediate needs over structural soundness. In these environments, residences are typically built through self-initiated efforts, generally without professional supervision, often utilizing recycled or low-quality materials. As these homes develop gradually, the routes for load distribution become irregular, and the connections among structural components are seldom designed to withstand seismic pressures. Such dynamics are consistent with Ginigaddara's (2023) observations that informal construction, shaped by socioeconomic constraints rather than technical guidance, inherently amplifies seismic vulnerability.

Geological conditions further intensify these risks. In Lima, for instance, informal settlements are frequently located on sandy soils or steep hillsides where ground motion is amplified during earthquakes. A similar trend can be observed in Valparaíso, where hillside communities exhibit the outcomes of makeshift construction practices influenced by exclusionary urban policies. In both cities, the physical instability of the terrain intersects with social and institutional fragility, creating environments where even moderate seismic events can lead to catastrophic damage. In fact, this pattern aligns with broader regional evidence showing that spatial injustice and cumulative environmental degradation have systematically concentrated vulnerable populations in geotechnically unstable areas (Maciejewska & Ulanicka-Raczyńska, 2023).

Even though human beings tend to learn from challenging situations, in our entire history, the responses to this issue have been reactive. The 1906 earthquake in Valparaíso led to the establishment of seismic regulations and improvements in construction techniques for the near future. However, these developments did not happen in a uniform while formal building sectors adopted new materials and practices, informal housing continued to be shaped by decisions made at the household level. Consequently, the damage in informal areas during recent earthquakes has been disproportionately complicated, which highlights the need for safer solutions. These recurring inequalities demonstrate that technical progress alone cannot guarantee safety. Instead, new approaches must weave the threads between engineering innovation and the lived realities of informal builders (Rashidfarokhi, 2024).

Recent reviews show that modular systems using cross-laminated timber (CLT) can significantly reduce construction time while maintaining robust seismic performance, positioning them as viable options for rapidly deployable housing in earthquake-prone contexts (Bhandari et al., 2023). Similarly, experimental work with full-scale modular steel prototypes has demonstrated that standardized connections can sustain seismic demands within multi-hazard design conditions, providing structural evidence that modularity can support safe and repeatable construction in contexts with elevated earthquake risk (Di Sarno & Forgione, 2024). Accordingly, modular construction represents a quality avenue for enhancing resilience. By employing prefabricated components and standardized connections, it can deliver structural consistency while accommodating the gradual and adaptive nature of self-built housing. Nevertheless, its successful application in informal contexts requires more than the transfer of technology. It demands the integration of participatory design and incremental development, ensuring that modular systems reinforce community agency rather than replace it. This paper, therefore, examines how modular construction, when reinterpreted through collaborative and context-sensitive approaches, can provide a viable pathway toward seismic resilience and social sustainability in Latin America's informal settlements.

Historical Precedents

Understanding how societies have historically responded to seismic events is a key aspect for evaluating the viability of modular construction in today's informal settlements in Latin America. Throughout history, earthquakes have exposed structural vulnerabilities, as well as prompted critical issues in building cultures and technical practices (Oliver-Smith, 1999). In other words, those shifts emerge from a real necessity, particularly in contexts where widespread damage compels institutional reflection.

As Walker (2003) observes, the collapse of elite housing provides a striking contrast to Oliver-Smith's (1999) broader interpretation of vulnerability in Peru's seismic history. Understanding this dynamic requires acknowledging how earthquakes operate not only as physical but also as social phenomena. According to Discovering Geology, earthquakes result from "sudden movement along faults within the Earth, releasing stored-up elastic strain energy as seismic waves." The severity of their consequences, however, depends largely on the resilience of the built environment. Structures that lack lateral resistance or rely on brittle materials are especially prone to collapse, particularly within informal settlements.

By way of illustration, the 1746 Lima earthquake provides a noticeable example of these processes. Nearly all of Lima's 3,000 buildings collapsed, with only about 25 left standing, and the accompanying tsunami destroyed the port of Callao, killing around 6,000 of its inhabitants and leaving only 200 survivors. In total, approximately 1,141 people perished in Lima out of an estimated 60,000 residents, while the combined earthquake–tsunami death toll exceeded 5,900 (NCEI, 2023). Walker (2003) states that a historical seismic coupling map of the event (Figure 1) highlights zones of concentrated ground motion in red, which correspond closely with the areas that suffered the greatest destruction. By visualizing how seismic energy is distributed unevenly across the territory, the figure strengthens the argument that earthquakes do more than damage individual structures. They also reshape urban form by creating spatial corridors of extreme impact, a pattern that reveals the need for construction systems such as modular housing that can preserve structural predictability even under highly irregular seismic demands.

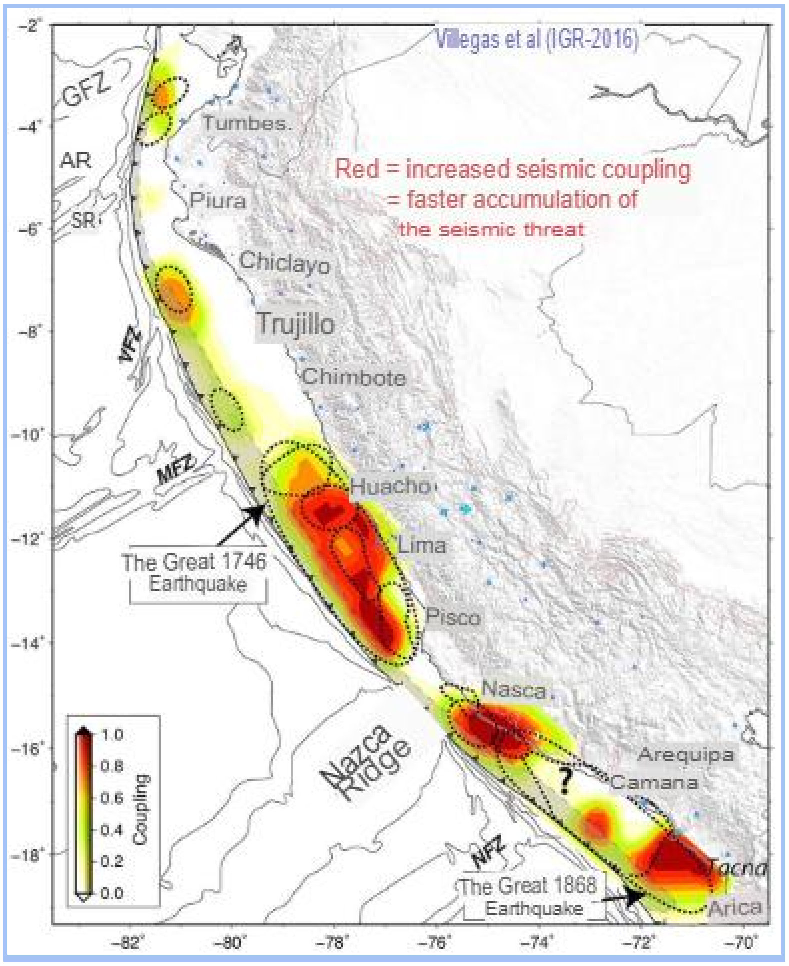


Figure 1: *Seismic coupling map showing zones of low to high ground motion during the 1746 Lima earthquake.*

Note. The map visualizes the spatial distribution of seismic energy accumulation and release, illustrating how zones of high coupling (in red) correspond to the sectors where built structures suffered the most intense damage. By highlighting the unevenness of ground motion, the figure reveals that vulnerability is not uniform across the urban fabric, but instead strongly conditioned by geotechnical and morphological factors already present before the event.

To complement this scientific visualization, Walker (2003) also shares a historical map documents the spatial configuration of Callao before and after the event (Figure 2).

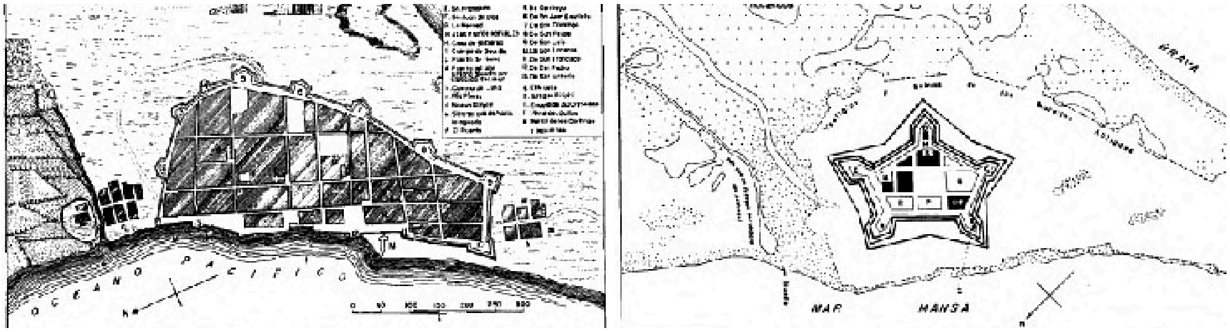


Figure 2: *Historical Map of Callao District Before and After the 1746 Earthquake*

Note. The juxtaposition reveals the scale of territorial transformation caused by the disaster: entire neighborhoods disappeared, the coastline receded, and previously inhabited areas became permanently uninhabitable. Both figures portrays how catastrophic events can obliterate existing spatial organization, forcing cities to confront sudden and irreversible reconfigurations of land and settlement patterns.

It is worth highlighting that this visual evidence also shows that resilience requires adaptability at both the structural and territorial scales. Modular housing aligns with this need as its disassemblable and relocatable components allow rapid reoccupation and spatial reorganization after disasters that significantly alter the built environment, as occurred in Callao. The transformation of Callao's territory was profound, as disasters significantly altered its urban landscape. In the earlier map, the city of Callao is shown as a consolidated port settlement; in the later one, the coastline is fragmented, and large tracts have vanished. The tsunami erased entire neighborhoods, permanently reshaping the region's geography. This transformation demonstrates how disasters can simultaneously dismantle physical infrastructure and reorder urban space. Callao's port vanished not only due to its location but also because of the city's lack of proper planning, which highlights how inadequate urban planning can exacerbate the effects of natural events.

In the aftermath, Peru's authorities implemented a significant change in construction logic. They started to work with quincha, a traditional system that uses a timber framework filled with cane and covered in mud plaster, to improve energy dissipation during earthquakes (Vergara, 2014). Quincha became an early example of ductile construction, enabling buildings to flex rather than collapse. Although the technique preceded formal theories of dynamic load resistance, it marked a decisive shift in Latin American seismic adaptation. Nonetheless, the centralized enforcement of building codes and limited technical support hindered authorities from implementing quincha, resulting in uneven adoption across expanding urban peripheries (Fernández-Maldonado & Bredenoord, 2010). Many low-income families continued building with fragile materials, illustrating how access to safer methods remained conditioned by social and spatial inequality.

Years later, a similar situation unfolded in Valparaíso, Chile, where the 1906 earthquake devastated the hillside neighborhoods, particularly those that had grown without much engineering guidance, echoing the challenges faced in Callao. Accordingly, this panorama became an imperative moment in Chilean engineering history since it prompted institutions and professionals to rethink the materials and structural systems used in construction. In addition, the scenario itself signified the onset of a long-term transformation that eventually positioned Chile as a leading seismic nation. All things considered, a key part of this shift was the arrival of reinforced concrete, a mix of steel and concrete strong enough to handle both compression and tension. Likewise, during the same period, seismic codes were formalized, and engineering schools began offering courses in structural dynamics, which marked the professionalization of earthquake engineering in the country (Maino & Tobriner, 2024). Despite these improvements, most progress remained within the formal parts of the city. In fact, many hillside neighborhoods kept expanding on their own, lacking official assistance and direction.

The seismic oscillation intensity map of Valparaíso provides useful insights into the spatial variability of ground shaking throughout the city, highlighting areas of increased vulnerability, as shown in Figure 3. Drawing on the mapping approach presented by Maino and Tobriner (2024), the figure makes clear that seismic impacts are not evenly distributed and instead follow patterns shaped by topography, soil conditions, and the spatial logic of urban expansion. In that matter, there is an existing pattern that keeps showing up at this stage, where informal growth on unstable slopes can magnify the effects of ground motion, and it will turn certain sectors into concentrated zones of structural failure. The hills, in particular, illustrate the compounded effects of informal urban growth and geological fragility, as unstable slopes and weak soils heightened structural damage.

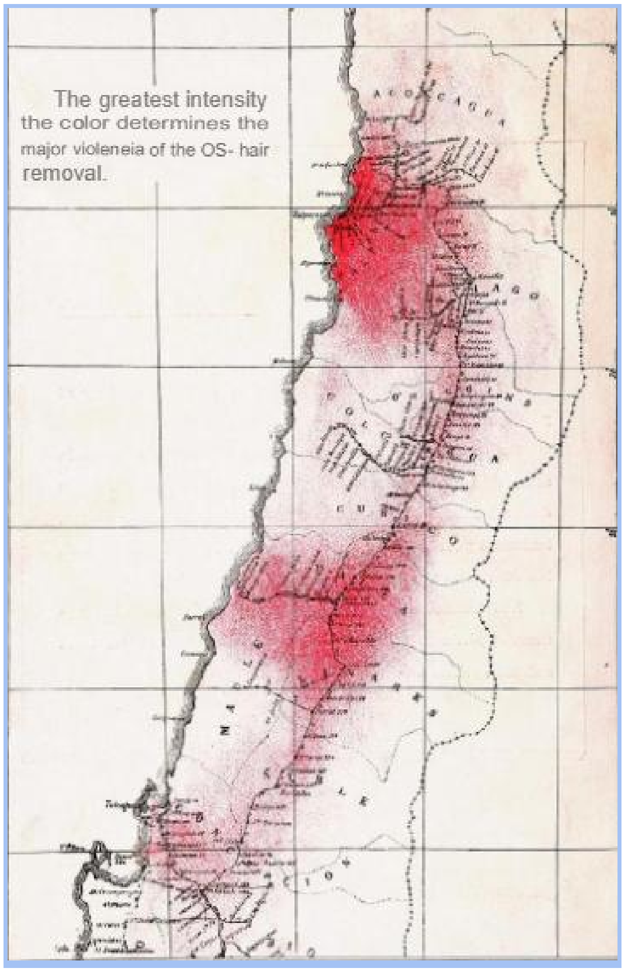


Figure 3: *Seismic Oscillation Intensity Map of Valparaíso During the 1906 Earthquake.*

Note. Darker zones indicate severe shaking, particularly in hillside neighborhoods where informal settlements coincided with geologically unstable slopes. It shows visually how local soil conditions, topography, and unregulated expansion converged to intensify structural failures during the event. Mapping differential shaking provides a spatial explanation for why certain communities experienced more catastrophic outcomes than others.

In line with the representation developed by Maino and Tobriner (2024), a contemporaneous photograph complements this technical record, which documents the collapse of a typical informal dwelling and adds a human dimension to the empirical data (Figure 4). Unlike official engineering reports that emphasize materials or regulatory frameworks, this picture illustrates a direct portrayal of the lived experience of disaster. It captures the fragility of self-built housing and the efforts of residents to reconstruct amid destruction, which reveals how the absence of technical oversight exposed entire communities to structural collapse. In doing so, this figure highlights that vulnerability is produced through both physical limitations and everyday construction practices that are shown in the picture that are shown in the picture such as irregular load paths and brittle joints, and it clarifies why damage became so concentrated in neighborhoods where precarious building methods were widespread.

Figure 4: *Photographic Evidence of Collapsed Informal Housing in Valparaíso, 1906 Earthquake*

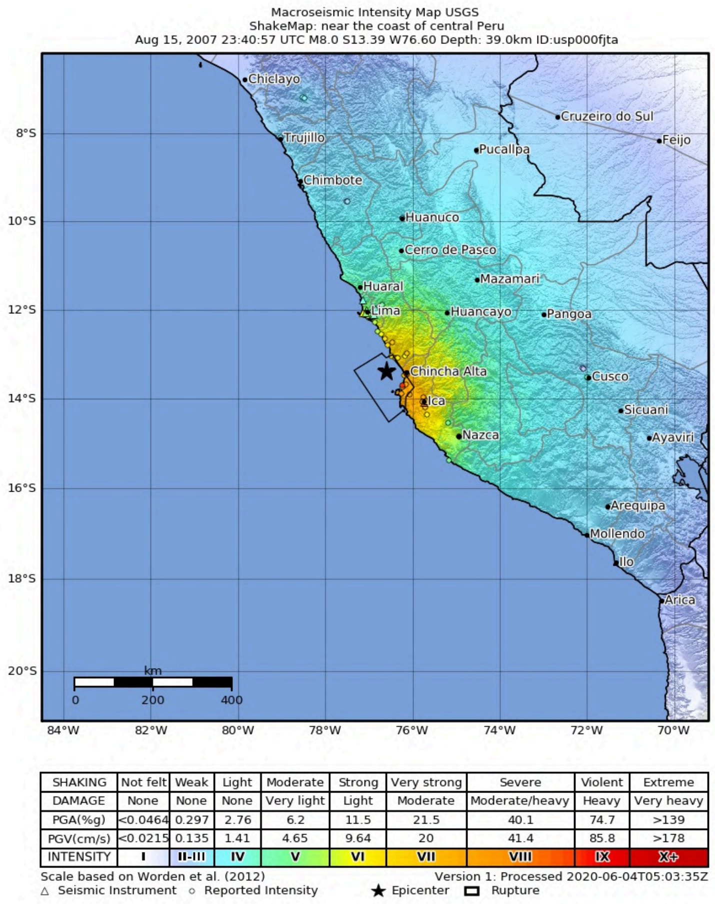
Note. The photograph captures the complete structural failure of a typical self-built home, highlighting brittle connections, and the absence of lateral resistance. It documents the intimate scale of disaster, showing how families faced immediate displacement and were forced to reconstruct with the same precarious methods that had failed in the first place.

Several decades later, the 2007 earthquake in Pisco, Peru, once again exposed the tension between formal engineering codes and the realities of informal construction. According to the NZSEE reconnaissance report (Hopkins et al., 2008), the disaster destroyed more than 38,000 homes, displaced over 100,000 people, and caused nearly 600 fatalities among 70,000 affected families. For instance, the same report from Hopkins et al. (2008) documented the Figure 5, which depicts post-earthquake conditions in Pisco and shows widespread failure of unreinforced masonry and poorly anchored structures, as well as the social trauma that followed across generations. Beyond documenting the physical destruction, the image also reveals how long-standing construction habits shaped the pattern of damage, since layers of incremental additions and limited technical guidance produced structural inconsistencies that intensified collapse across entire neighborhoods.

Figure 5: *Post-Earthquake Building Conditions in Pisco, 2007.*

Note. The figure shows widespread failure of unreinforced masonry, and poorly anchored structural systems typical of incremental informal construction. It also exhibits the social dimension of disaster by depicting households navigating the loss of homes, stability, and inherited building knowledge.

In addition, the macroseismic intensity map (Figure 6) provides visual evidence that seismic impact is not randomly dispersed but spatially patterned, revealing that the darkest intensity zones coincide with low-income and self-built districts (Hopkins et al., 2008). Rather than acting as a simple illustration, the figure shows that extreme shaking clusters directly over areas with pre-existing socioeconomic fragility, which confirms that urban form and inequality shape the geography of disaster itself. This overlap is useful for the argument that earthquakes become social events due to the severity of damage is conditioned by limited access to technical assistance and the concentration of vulnerable housing types in peripheral neighborhoods.



SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	None	None	None	Very light	Light	Moderate	Moderate/heavy	Heavy	Very heavy
PGA(%g)	<0.0464	0.297	2.76	6.2	11.5	21.5	40.1	74.7	>139
PGV(cm/s)	<0.0215	0.135	1.41	4.65	9.64	20	41.4	85.8	>178
INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based on Worden et al. (2012) Version 1: Processed 2020-06-04T05:03:35Z

△ Seismic Instrument ○ Reported Intensity ★ Epicenter ▭ Rupture

Figure 6: *Macroseismic Intensity Map of the 2007 Pisco Earthquake.*

Note. The darkest zones correspond to areas that experienced extreme shaking, many of which were low-income districts with dense informal housing. It conveys how seismic impacts are spatially uneven and correlate strongly with socio-economic marginalization, revealing a pattern in which disadvantaged communities absorb the highest levels of physical and social disruption.

Despite the existence of seismic regulations, enforcement remained inconsistent. Informal areas, where unreinforced masonry and deficient connections were widespread, continued to suffer the most severe losses. The prominent gap between research knowledge and real-world application underscores the persistent disconnect between engineering innovation and self-built housing practices. The prevalence of brittle materials and shallow foundations without lateral resistance forced builders to improvise under precarious conditions.

The Pisco earthquake also revealed the divide between immediate humanitarian response and sustained reconstruction. In many cases, predesigned housing units were imposed without considering local needs or cultural habits, reducing the long-term viability of the recovery process. As a result, numerous houses were abandoned or repurposed. Nevertheless, by 2012, 95.5% of damaged homes were reoccupied, accompanied by significant new construction—over 2,100 new buildings representing 17.6% of total lots—reflecting the persistence of unplanned expansion (Ismail et al., 2017).

Recent data from the INEI (2023), shown in the Figure 7, shed light on the broader structural challenges facing Peru's construction sector today. Both cement usage and public infrastructure investment have declined, with a 7.9% decrease in August and an 8.8% decrease in January of the same year. In that manner, this downward trend reflects three interrelated dimensions. First, the reduction in cement consumption indicates a slowdown in private housing construction, undermining the economic base required to sustain the diffusion of modular technologies. Second, the contraction of public infrastructure projects reveals the state's limited investment capacity, which constrains opportunities to incorporate modular systems into social programs such as educational or affordable housing initiatives. Most importantly, the overall decline in construction activity has weakened investor confidence, as many perceive modular housing as an uncertain or unnecessary innovation amid a shrinking market. Overcoming these challenges demands the stabilization of the construction sector and the development of fiscal and regulatory mechanisms capable of ensuring continuity and scalability in the adoption of modular approaches.

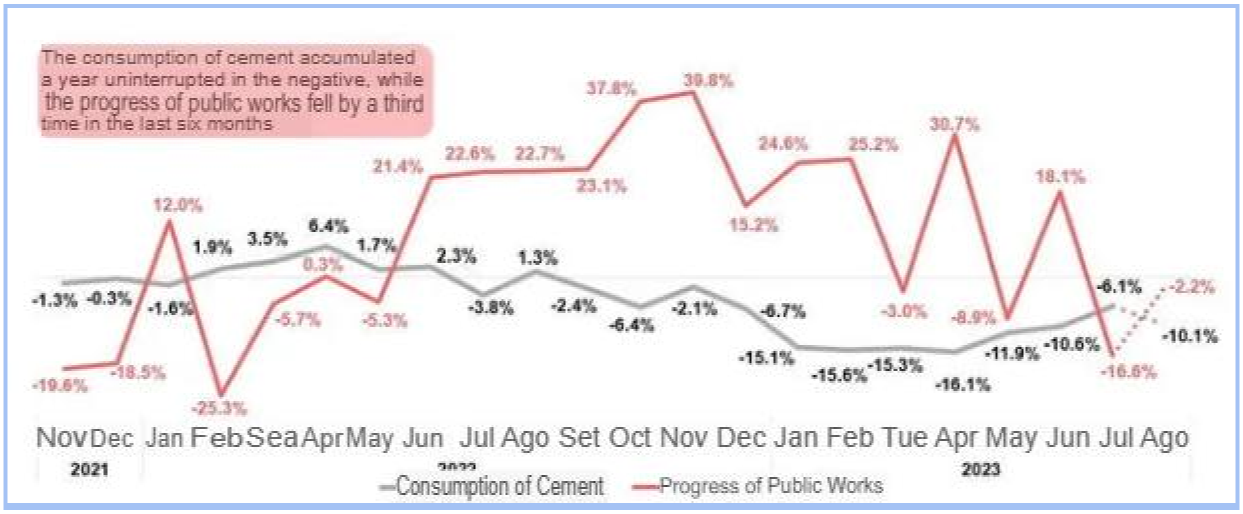
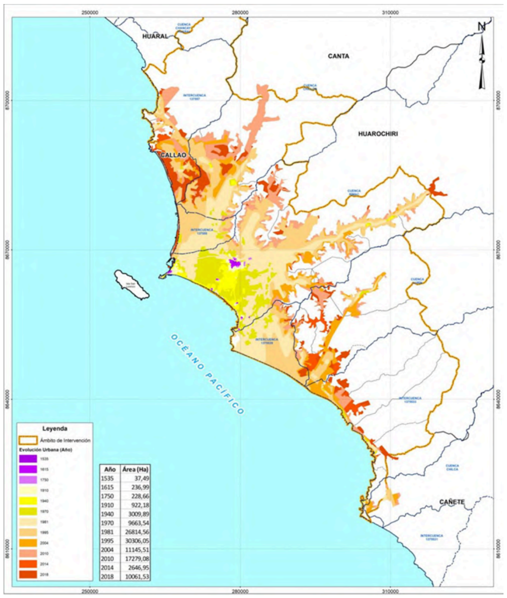


Figure 7: *Trends in cement usage and public infrastructure development in Peru, 2023.*

Note. Both indicators show significant declines, revealing a downturn in the construction sector that constrains the diffusion of innovative technologies such as modular construction. Reduced investment affects the availability of public programs and large-scale procurement processes required to scale affordable modular housing across high-risk regions.

This contemporary decline mirrors the long-term historical pattern in which periods of innovation have often failed to consolidate into lasting resilience frameworks. Across centuries, Latin America's experience has shown that technological progress alone does not guarantee safety in any circumstance. In consequence, seismic resilience must instead be understood as both a physical capacity to absorb shocks and a social capacity to institutionalize and sustain improved building practices over time.

Understanding these continuities becomes even more critical when examining the spatial dynamics of current risk. The expansion of informal settlements into hazardous terrains reveals how historical neglect in planning continues to shape vulnerability today (Sandoval and Sarmiento, 2020). In many Latin American cities, and especially in Peru, rapid urban growth has consistently outpaced formal regulatory frameworks it resulting in extensive peripheral zones where basic infrastructure is either deficient or absent (Sakay et al., 2011). Figure 8 shows that Lima's urban expansion has historically pushed development into peripheral terrains with low geotechnical stability, revealing a long-term pattern in which the city grows faster than planning institutions can regulate. (Equipo Técnico Plan Met 2040, 2020). This map is therefore a visual evidence that vulnerability is produced by the spatial logic of expansion itself, as households settle in environmentally fragile areas that magnify seismic and hydrological risks.



Año	Área (Ha)
1535	37,49
1615	236,99
1750	228,66
1910	922,18
1940	3009,89
1970	9663,54
1981	26814,56
1995	30306,05
2004	11145,51
2010	17279,08
2014	2646,95
2018	10061,53

Figure 8: *Urban growth map of Metropolitan Lima (1535–2018).*

Note. This map shows how the city expanded progressively into peripheral areas with low geotechnical stability, limited infrastructure, and high exposure to natural hazards. As urban growth outpaced planning, these zones became concentrated pockets of informal settlement and cumulative environmental risk.

It is important to note that geotechnical assessments reinforce this spatial inequality. While coarse alluvial soils in central valleys can support up to 4 kg/cm², fine sands and silts, common in peripheral settlements, sustain less than 1 kg/cm², and this makes them highly susceptible to liquefaction and collapse during seismic events (Gutiérrez et al., 2020). Also, when combined with the absence of professional guidance in self-built housing, these conditions amplify structural fragility at a high level.

Moreover, GIS analyses demonstrate that many of Lima's informal districts overlap with seismic amplification zones. Figure 9 makes this convergence particularly visible by mapping dense clusters of self-built housing directly onto areas characterized by unconsolidated soils and deep alluvial deposits (INEI, 2007). Instead of merely locating informal settlements, the figure exposes how urban growth interacts with geological conditions to intensify risk, revealing that the most disadvantaged groups inhabit precisely the environments where ground motion is most likely to be amplified. Indeed, areas characterized by unconsolidated sediments and deep alluvial deposits intensify ground motion during earthquakes, generating localized peaks in shaking intensity. It is important to add the fact that current surveys show that more than 60% of residents in high-risk areas have never received earthquake preparedness training, and over 40% are unaware of evacuation routes, even while living in seismically active zones (Quesada-Román, 2022).

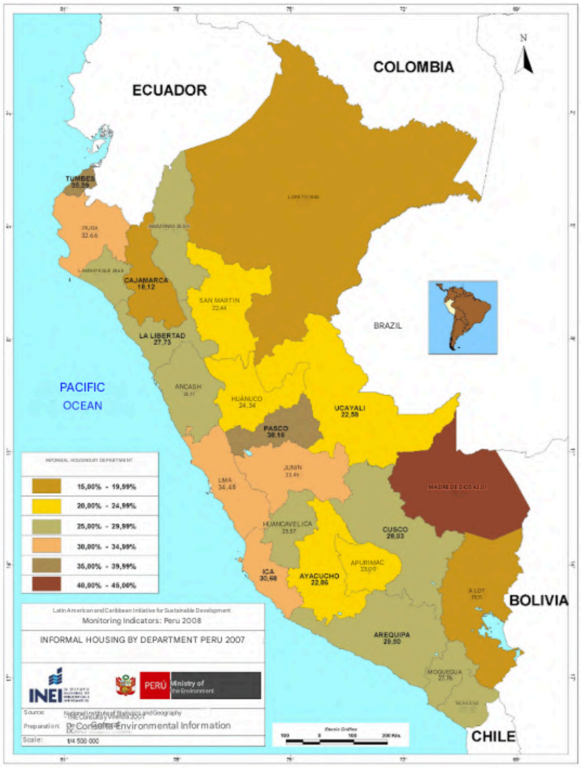


Figure 9: *Distribution of informal settlements in Lima.*

Note. The brown clusters indicate areas with high concentrations of informal housing, many of which overlap with zones of amplified ground motion and poor soil conditions. It shows a persistent pattern whereby the most vulnerable groups occupy the most hazardous environments.

Madre de Dios, Pasco, Tumbes, and Lima are the districts with the highest concentrations of informal settlements, which means that these areas have an emergency response capacity that is further constrained by narrow streets and overcrowded conditions. Adding to this, population density exceeds 1,000 inhabitants per hectare, and combustible materials such as timber and cardboard are used in over 70% of dwellings. As a result, household fires occur two to three times more frequently than in planned neighborhoods, with emergency response delays reaching 40 minutes or more (Ismail et al., 2017). That is to say that these factors heighten seismic risk and compound exposure to secondary hazards.

Although this configuration is characteristic of many Latin American cities, similar processes are evident elsewhere. To illustrate this point, in Warsaw, Poland, inadequate remediation of nearly 300 contaminated industrial sites disproportionately endangers low-income populations, which reveals how socio-spatial inequality perpetuates environmental vulnerability (Maciejewska and Ulanicka-Raczyńska, 2023). In addition, in Lima, the concentration of risk in marginal zones reflects the persistent failures of centralized governance and continues to push low-income households into unstable terrains.

To integrate these findings, these contemporary dynamics extend the historical trajectory traced throughout this section. From colonial-era collapses to modern construction downturns, seismic vulnerability in Latin America has remained closely tied to structural inequality and the uneven diffusion of technical knowledge. In the same way, these takeaways from past and present events emphasize the urgent need for new housing paradigms that combine structural innovation with social participation, objectives that modular construction, when properly adapted, has the potential to fulfill.

Examining these dimensions, we can see that the evolution of seismic adaptation across Latin America embodies the fact that resilience is associated with a socio-structural process shaped by history, inequality, and institutional capacity. Hence, each precedent reveals how progress in engineering has repeatedly faltered when disconnected from local realities and social participation.

Engineering Aspects of Modular Construction

Modular construction is a building method that employs prefabricated components and efficient on-site assembly, which has progressively evolved into an optimal strategy for improving structural safety in vulnerable settings. More precisely, this approach involves the design and partial or complete fabrication of structural modules in controlled environments. Over time, modular construction must be viewed as the continuation of prefabrication practices that date back to monumental works of antiquity and later reappeared during the British colonization, the California Gold Rush, and both World Wars (Smith, 2010). Moreover, technological advances such as robotic manufacturing and specialized transportation systems have refined these methods to achieve high standards of quality control and efficiency rarely matched by conventional construction (AlDairi, 2021).

This historical continuum elucidates essential implications for structural systems. In contrast with informal housing that grows through unregulated additions (Green, 2008), modular systems depend on standardized dimensions and precisely engineered joints that ensure predictable behavior under load (Lawson & Richards, 2010). As shown in Figure 10, the detailing of a typical modular structural joint substantiates how these components maintain continuity of forces throughout the system. Along similar lines, Figure 11 shows the optimal depiction of the different gusset plate configurations—double-hole for external joints, single-hole for corner joints, and four-hole for internal joints—that promote consistent load transfer and minimize weak points. Distinctly, this engineered coherence is sharply different from the irregular load paths found in self-built dwellings. Complementarily, modular systems are compatible with the incremental building logic often observed in low-income contexts, as individual modules can be manufactured and added over time without compromising global stability (Fernández-Maldonado & Bredenoord, 2010). This compatibility drives the whole scenario to a distant level of technical, it is now urbanistic, since it provides a controlled alternative to the incremental growth patterns that shape much of Latin America's peripheral urban form. In this regard, the reconstruction of Valparaíso after the 1906 earthquake evidenced this progression by showing how seismic disasters have repeatedly triggered transitions from empirical to engineering-based construction approaches (Maino & Tobriner, 2024). The visual evidence provided by Figures 10 and 11, therefore, helps address a major issue that is that modular design operationalizes lessons historically learned after major disasters by embedding seismic logic directly into the joints and incremental assembly processes that define how cities in high-risk regions continue to expand.

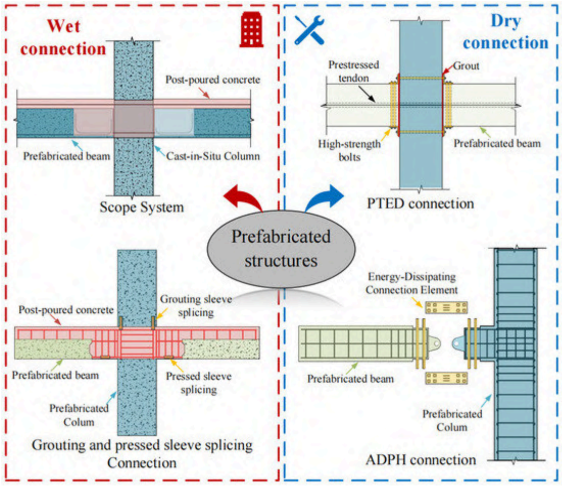


Figure 10: *Structural joint diagram in modular construction systems.*

Note. Illustrates engineered load paths that maintain force continuity across modules, ensuring predictable behavior under seismic loads.

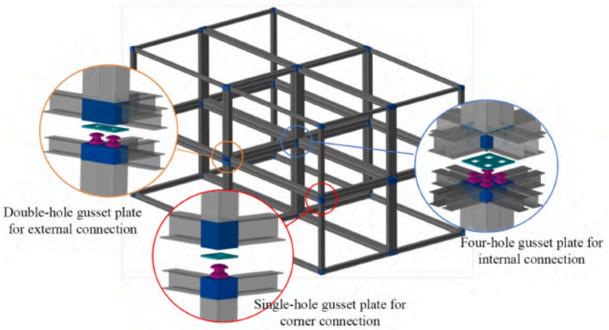


Figure 11: *Connection types in modular housing assemblies.*

Note. Shows connection types that minimize stress concentration and enable consistent energy dissipation.

Considering that structural logic, the connection systems stand out as the critical determinants of seismic resilience. Notably, both inter-module and intra-module joints are designed to optimize robustness and energy dissipation under extreme loading. The most common arrangements include tie rods with shear keys, bolted plates, VectorBloc connectors, and welded cover plates. Furthermore, each configuration directly affects lateral-force resistance and inter-story drift, defining the building's overall ductility (Ginigaddara et al., 2023).

Against this backdrop, Figure 12 offers a representative example of these mechanics by depicting a bolted plate connection that enhances deformation capacity while ensuring efficient load transfer across prefabricated assemblies. As the diagram shows, such systems can accommodate considerable displacement demands without compromising structural integrity, thereby lowering the likelihood of abrupt failure. Consequently, this type of connection underscores that modular construction is not merely a substitute for conventional methods; rather, it constitutes a structurally rigorous strategy capable of meeting the specific performance requirements of high-risk seismic environments.

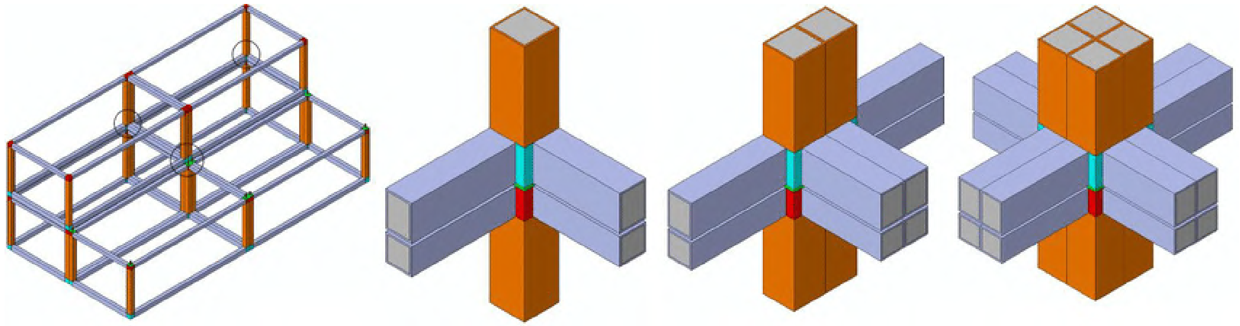


Figure 12: *Detail of bolted plate modular connection.*

Note. Demonstrates how prefabricated joint systems achieve ductility and reduce failure risks.

Transitioning from theoretical modeling to experimental validation, Figure 13 is a crucial link between conceptual seismic mechanisms and their behavior under dynamic conditions. The scaled modular tower tested by Sheng Li et al. (2022) incorporates a superelastic tendon system that enables controlled rocking while preserving the building's ability to re-center after strong ground motions. Concurrently, this detailed diagram highlights the placement of rotation sensors, strain gauges, and acceleration monitors, which together reveal how the tendon redistributes seismic demands away from brittle connections and toward components capable of sustaining large, recoverable deformations. Through shaker table tests, the authors compared fixed-base, and tendon-restrained configurations subjected to identical near-fault impulses. By extention, the tendon-restrained model reduced internal forces by 36 percent and rocking rotations by 61 percent relative to the other two systems. By visualizing how the tendon anchors the upper module and restricts excessive rotation, the figure clarifies why this mechanism is effective in preventing catastrophic joint failures, one of the most persistent weaknesses in modular construction. In consequence, the experimental evidence demonstrates that integrating superelastic NiTi tendons can significantly strengthen modular high-rise structures while preserving the fabrication efficiency that defines industrialized building methods.

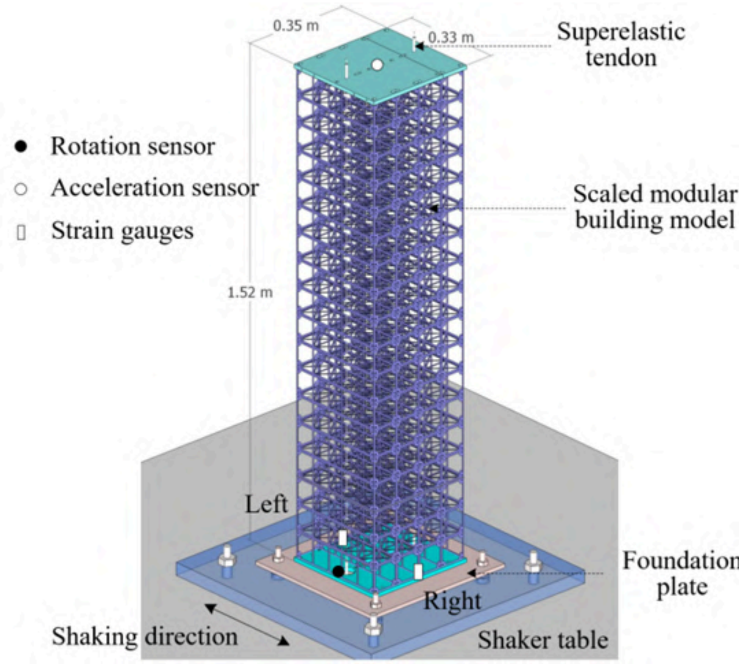


Figure 13: *Scaled modular building model with superelastic tendon system and test set-up.*

Note. The tendon mechanism restricts rocking motion and reduces internal forces during near-fault excitations, demonstrating how advanced seismic technologies can be integrated into modular typologies without compromising prefabrication efficiency.

A practical reference for the implementation of modular systems in Latin America can be observed in Peru. In substantive terms, Figure 14 presents the ALQUIMODUL SAC construction model, which assembles prefabricated concrete and steel components produced in controlled factory environments. Rather than simply illustrating the pieces involved, the image delineates how insulation layers, gypsum boards, galvanized profiles, and phenolic plywood panels are arranged to create a thermally efficient and structurally stable envelope. This configuration shows that locally manufactured components can achieve the precision and material continuity required for seismic reliability, contradicting the assumption that advanced prefabrication is unattainable in low- and middle-income economies. The figure also attests to that modular construction reduces on-site variability, since dimensional accuracy and quality control occur upstream during fabrication. Nevertheless, the long-term success of these systems depends on the development of specialized training programs and alignment with local construction practices so that factory-based production can scale beyond prototype deployments and become a sustainable alternative to informal urban expansion.

Figure 14: *Advanced Modular Concrete Construction System in Peru, 2012.*

Note. This diagram is the main representation of prefabricated wall panels, insulation layers, and structural frames manufactured under controlled conditions. It exemplifies how national industries can produce modular components that bring seismic reliability within reach for low-income populations.

Beyond seismic performance, modular construction has proven adaptable to multiple hazards such as cyclones, floods, pandemics, and fires. In areas exposed to strong winds, for example, reinforced interconnections and fatigue-resistant joints are necessary to counteract high lateral pressures and debris impacts (Di Sarno & Forgione, 2024). Figure 15 presents a hurricane-resistant modular housing design that integrates aerodynamic geometry and improved panel anchoring. Similarly, Figure 16 showcases amphibious pavilion systems and floating foundations, which exemplify how modular structures can adapt to recurrent flooding and changing hydrological conditions (Abdur Rehman, 2024). During the COVID-19 emergency, this flexibility was demonstrated by rapidly constructed modular medical facilities such as the Leishenshan Hospital (Ismail et al., 2017). Nevertheless, significant research gaps remain concerning large-scale tests for combined hazards and fire performance (Bhandari et al., 2023). Figure 17, a rendered model of a modular housing unit, represents the integration of structural resilience with aesthetic and spatial considerations, demonstrating that functionality and design innovation can coexist within resilient architecture.

Figure 15: *Hurricane-Proof Houses: Designs, Costs, and Construction Methods.*

Note. Shows aerodynamic profiles and reinforced anchoring systems developed for cyclonic regions.

Figure 16: *Multi-Hazard Resilient Modular Building Design Example at Leishenshan Hospital.*

Note. Depicts floating or amphibious modules designed for recurrent flooding scenarios.

Figure 17: *Rendered Model of a Modular Housing Unit.*

Note. Illustrates how structural resilience and architectural quality can coexist in modular design.

Considering these perspectives, modular construction can be recognized as one of the most viable strategies for enhancing safety, efficiency, and quality in high-risk environments. Prefabrication enables continuous testing of materials and load-bearing assemblies before installation, minimizing the likelihood of design flaws or assembly errors (Sandoval & Sarmiento, 2020). Furthermore, its modular logic facilitates post-disaster recovery, allowing damaged units to be replaced individually without dismantling the rest of the structure (Eren, 2012). However, achieving adaptive capacity requires more than technical precision. It demands the incorporation of modular construction within broader disaster management frameworks and its adaptation to the cultural, environmental, and economic realities of each territory (Hussainzad & Gou, 2024). When these conditions are met, modular construction ceases to be a mere technological alternative and becomes a holistic tool for safety and inclusive urban development.

When viewed collectively, the engineering perspective on modular construction highlights that adaptive capacity is not achieved solely through stronger materials or advanced joints but through replicability. As a whole, the previous examples and analyses demonstrate how modular systems can balance technical rigor with flexibility, allowing buildings to be assembled and repaired efficiently in hazard-prone settings. By standardizing structural components while accommodating incremental growth, modularity offers a structural language that can be transferred into informal contexts.

Social and Participatory Frameworks

Social structures depend fundamentally on the participation and agency of communities. Engagement from residents, when combined with incremental building strategies, can strengthen both social cohesion and structural resilience in informal settlements. Along those lines, self-managed and incremental construction has been viewed over time as a community-shaped practice, one that intertwines building decisions with everyday forms of cooperation and adaptation. As Fernández-Maldonado and Bredenoord (2010) argue, progressive housing works precisely due to the fact that it mirrors the temporal rhythms of low-income households. Their perspective is pivotal for the hybrid model proposed here, in which community agency functions as a structural driver of safety, in order to enable housing to evolve without compromising local decision-making.

Research derived from participatory approaches portrays the advantages of collaboration in achieving better results. Gavin's (2011) Project-Based Learning study at University College Dublin, though situated in education, is a valuable parallel: 90% of surveyed students reported improved comprehension through collective problem-solving, with group quality (23%) and individual skill (21%) shaping performance. In this regard, the challenges he identifies, such as imbalanced contributions and heavy time demands, share the realities of community-led construction. That is how they highlight that participation requires facilitation and shared responsibility, conditions essential for incremental housing processes.

At the same time, the application of Quality Function Deployment in the construction industry has revealed how integrating user needs early can reduce costly design modifications and accelerate project completion. Abdul-Rahman et al. (1999) show that QFD can cut engineering revisions and design durations by about 50%, decrease startup costs by 20-60%, and reduce warranty claims by 20-50%. Although derived from formal construction sectors, the underlying principle is strongly linked with informal housing as it underscores that residents (who are both users and builders) can shape decisions from the outset and transform interventions in an efficient way.

These insights connect with broader demographic and social shifts. Nguyen and Levasseur's (2023) review of 46 studies demonstrates a growing need for flexible and supportive living arrangements. Consistent with this, retirement communities represented 15% of cases, assisted living frameworks 39%, and cohousing models 24%, with 76% of participants being women and half reporting health challenges. Those findings emphasize that access to services and social support improves well-being. While the context differs, the underlying logic applies to younger and low-income populations in informal settlements: participatory spaces enable residents to reshape their environments as life circumstances change, reinforcing the long-term adaptability central to incremental construction.

Additionally, variations in how cities use space since COVID-19 began have provided more opportunities for development and adaptation. In other words, urban transformations following COVID-19 further illustrate how spatial conditions influence housing possibilities. Remote work in the European Union peaked at 37%, contributing to office occupancy rates falling to around 10%, while vacancy rates in Sydney's central business district increased to 10-11%. In that sense, these trends contrast sharply with pre-pandemic occupancies of 60-70%. For cities facing land scarcity, the reactivation of underused space offers new possibilities for incremental solutions, especially when repurposing occurs through participatory decision-making that attends to local needs and constraints. At the same time, climate-related events add urgency to this discussion. The 2019-2020 Australian bushfires destroyed 3,000 homes across 30 million hectares, while the 1960 Chilean tsunami affected four nations within 12–20 hours. These past events underscore the vulnerability of built environments. Yet, innovative responses-like the Nature Urbaine rooftop garden in Paris, which produces 200 kilograms of food daily across 14,000 square meters, or the relocation of Kiruna in Sweden, involving 6,000 residents and 39 historic buildings—show how participatory and flexible approaches can strengthen sustainability and social cohesion (Anguelovski et al., 2016). Although geographically distant, these cases reinforce principles that directly support that adaptation works best when communities remain central actors.

It is theoretically true that the integration of modular construction, participatory design, and incremental housing may represent one of the most effective strategies for strengthening seismic safety and multi-hazard adaptability in vulnerable environments. This approach draws on vernacular knowledge and participatory governance structures (Tähtinen, 2024), ensuring that innovation remains grounded in local realities rather than imposed through rigid top-down models. As Nguyen and Levasseur (2023) also suggest, adaptability improves when housing is able to evolve with residents' changing needs in a way that we can preserve affordability and reduce long-term vulnerability.

The convergence of evidence from diverse cases strongly supports this synthesis. In rural Colima, Mexico, the adaptation of traditional wattle-and-daub into geodesic domes demonstrated exceptional seismic performance, climatic suitability, affordability, and compatibility with community-led construction (Ismail et al., 2017). In Pakistan, modular flat-pack homes constructed from cold-formed steel and fiber-cement boards enabled rapid and low-cost reconstruction after disasters (Abdur Rehman, 2024). Additional cases from British Columbia's critical infrastructure projects and Cape Town's flood management strategies show that technical solutions are more effective when validated through participatory methods and multi-institutional coordination (Genik & Chouinard, 2015). It is noticeable that, across all examples, innovation succeeds when local governance and environmental demands are met.

It is worth highlighting that these examples reveal a broader concept: resilience must always be adapted to local hazards and governance systems. Whether considering the thermal performance of Colima's earth constructions, Pakistan's flood-resistant modular units, or urban models like the Inner City Suburbia framework (Kotila, 2010), effective strategies merge technological advancement with social and environmental adaptation (Green, 2008). Experimental methodologies such as Stickbot prototyping and interdependency mapping in Canada further illustrate that design improves through iterative, real-world testing rather than abstract planning (Carroll et al., 2023). Resilience is therefore dynamic, continually shaped by both technical progress and community practice.

For Latin America, the conclusions are explicit. Hazard-resistant housing should combine traditional low-carbon materials with contemporary seismic engineering (Ye et al., 2025), incorporate co-design from the earliest stages, and understand modularity and incremental development as proactive rather than reactive strategies (Lawson & Richards, 2010). Pilot projects must operate as living laboratories for technical validation and policy alignment (Varela et al., 2022). The continuity between local innovation and scientific validation can ensure that resilience becomes embedded in both construction practices and institutional frameworks. Even if it appears repetitive, resilience should always be perceived as a dynamic capability fostered through the integration of technical knowledge, social participation, and long-term cultural learning.

Viewed in aggregate, the evidence drawn from participatory frameworks indicates that adaptive capacity depends as much on collective engagement as on construction technology. When a local agency aligns with technical precision, modular and incremental methods evolve into dynamic systems of adaptation rather than static housing products. Within such frameworks, residents shift from passive recipients to active co-designers of safety and continuity. In this configuration, the interaction among participatory governance, modular engineering, and historical awareness thus defines a new paradigm in which resilience is sustained through cooperation and long-term cultural learning.

Conclusion

The evidence analyzed in this study shows that conflating modular construction, participatory design, and incremental housing can constitute a viable pathway in terms of seismic resilience in informal settlements. This combined approach capitalizes on the structural reliability of prefabricated systems while remaining consistent with the incremental and adaptive construction practices characteristic of resource-constrained communities. Actually, resilience must therefore be conceived as a dynamic capacity, reinforced through the continuous interaction between governance and community engagement equally.

For Latin America, the adoption of hybrid modular-incremental models needs more than the replication of technical prototypes. In reality, and even if it takes a long time, it necessitates the institutionalization of participatory frameworks within official planning processes and the development of financing mechanisms that simultaneously address structural safety and social stability.

Truly, future research is obliged to evaluate hybrid housing communities longitudinally in post-disaster contexts and compare their structural and social performance with conventional approaches. It is also worth mentioning the exploration of accessible training programs for informal labor networks, the incorporation of digital tools such as participatory mapping and GIS-based hazard modeling, and the alignment of seismic design with climate adaptation strategies in dual-hazard regions. That is how we, as a society that has actually learned something from the past catastrophes, must advance seismic safety in informal urban areas demands recognition of resilience as both an engineering challenge and a socio-political endeavor; one that needs deliberate coordination between technical excellence, community capacity, and institutional support to maintain the cities in a stable condition.

Acknowledgements

The author extends a huge gratitude to Dr. Devin Carroll, whose mentorship and feedback shaped the analytical depth of this work, and to Kieran Tait, whose constructive critique and constant follow-up of the paper brought motivation at every stage. In addition, I wanted to thank my family since they have always supported this journey related to positively improving the construction world.

Above all, the deepest respect is reserved for the communities living each day under seismic risk around the globe. Their resilience in transforming limited resources into enduring solutions embodies the conviction that guides this study: true safety surfaces when technical knowledge is interwoven with collective agency and rooted in local wisdom.

Bibliography

1. Abdul-Rahman, H., Kwan, C. L., & Woods, P. C. (1999). Quality function deployment in construction design: Application in low-cost housing design. International Journal of Quality & Reliability Management, 16(6), 591–605. https://doi.org/10.1108/02656719910268198
2. Abdur Rehman, Z. (2024). Modular emergency relief: A proposal for integrating modular buildings into post-flood reconstruction and recovery. https://www.theseus.fi/handle/10024/868097
3. AlDairi, S. (2021). Modular construction in the civil engineering industry [Master's thesis, Stevens Institute of Technology]. ProQuest. https://search.proquest.com/openview/21cf00c2a57b6ad03ed474d4fdbff151/1?pq-origsite=gscholar&cbl=18750&diss=y
4. Anguelovski, I., Shi, L., Chu, E., Gallagher, D., Goh, K., Lamb, Z., Reeve, K., & Teicher, H. (2016). Equity impacts of urban land use planning for climate adaptation: Critical perspectives from the Global North and South. Journal of Planning Education and Research, 36(3), 333–348. https://doi.org/10.1177/0739456X16645166
5. Bhandari, S., Riggio, M., Jahedi, S., Fischer, E. C., Muszynski, L., & Luo, Z. (2023). A review of modular cross-laminated timber construction: Implications for temporary housing in seismic areas. Journal of Building Engineering, 63, 105485. https://doi.org/10.1016/j.jobe.2022.105485

6. Calderon, C. (2008). Learning from slum upgrading and participation: A case study of participatory slum upgrading in the emergence of new governance in the city of Medellín, Colombia. https://www.diva-portal.org/smash/record.jsf?pid=diva2:126733
7. Carroll, D., Ang, V., & Yim, M. (2023). StickBot: A methodology for building robots and other functional elements from tree branches and string. https://doi.org/10.1115/DETC2023-109541
8. Di Sarno, L., & Forgione, R. (2024). Innovative steel modular housing system for multiple natural hazard mitigation. International Journal of Disaster Risk Reduction, 111, 104734. https://doi.org/10.1016/j.ijdrr.2024.104734
9. Eren, O. (2012). A proposal for sustainable temporary housing applications in earthquake zones in Turkey: Modular box system applications. Gazi University Journal of Science, 25(1), 269–288.
10. Fernández-Maldonado, A. M., & Bredenoord, J. (2010). Progressive housing approaches in the current Peruvian policies. Habitat International, 34(3), 342–350. https://doi.org/10.1016/j.habitatint.2009.11.018
11. Gavin, K. (2011). Case study of a project-based learning course in civil engineering design. European Journal of Engineering Education, 36(6), 547–558. https://doi.org/10.1080/03043797.2011.624173
12. Genik, L., & Chouinard, P. (2015). An overview of pilot projects in support of critical infrastructure resilience. https://apps.dtic.mil/sti/html/tr/AD1004218/
13. Ginigaddara, T., Ekanayake, C., Gunawardena, T., & Mendis, P. (2023). Resilience and performance of prefabricated modular buildings against natural disasters. Electronic Journal of Structural Engineering, 23(4), 85–92.
14. Green, R. (2008). Informal settlements and natural hazard vulnerability in rapid growth cities. En J. J. Pinkham & R. Green (Eds.), Hazards and the built environment (pp. 218–237). Routledge. https://www.taylorfrancis.com/chapters/edit/10.4324/9780203938720-14
15. Gutiérrez, R. M., Esenarro, D., Pingo, P. A., & Rodriguez, C. R. (2020). Vulnerability of the soils of Metropolitan Lima and their relationship with urban sustainability. 3C Tecnología: Glosas de Innovación Aplicadas a La Pyme, 9(1), 161–177.
16. Hussainzad, E. A., & Gou, Z. (2024). Climate risk and vulnerability assessment in informal settlements of the Global South: A critical review. Land, 13(9), 1357.
17. Ismail, F. Z., Halog, A., & Smith, C. (2017). How sustainable is disaster resilience? An overview of sustainable construction approach in post-disaster housing reconstruction. International

Journal of Disaster Resilience in the Built Environment, 8(5), 555–572. https://doi.org/10.1108/IJDRBE-07-2016-0028

18. Kechebour, B. E. (2015). Relation between stability of slope and the urban density: Case study. Procedia Engineering, 114, 824–831.
19. Khan, R. M. A. H., Mubin, S., & Masood, R. (2025). Land-sharing hybrid models for low-cost housing. International Journal of Housing Markets and Analysis. https://doi.org/10.1108/IJHMA-02-2025-0045
20. Kotila, R. (2010). Inner city suburbia: A hybrid solution to sustainable urban middle-income housing [Master's thesis, University of Cincinnati]. https://rave.ohiolink.edu/etdc/view?acc_num=ucin1274195125
21. Lawson, R. M., & Richards, J. (2010). Modular design for high-rise buildings. Proceedings of the Institution of Civil Engineers – Structures and Buildings, 163(3), 151–164. https://doi.org/10.1680/stbu.2010.163.3.151
22. Maciejewska, A., & Ulanicka-Raczyńska, M. (2023). Lack of spatial planning as a cause of environmental injustice in the context of the provision of health safety to urban residents based on the example of Warsaw. Sustainability, 15(3), 2521. https://doi.org/10.3390/su15032521
23. Maino, S., & Tobriner, S. (2024). The search for earthquake-resistant construction systems in Chile after the 1906 Valparaíso earthquake. Construction History – International Journal of the Construction History Society, 39(2). https://www.researchgate.net/publication/389893944
24. Mehrotra, S., Bardhan, R., & Ramamritham, K. (2018). Urban informal housing and surface urban heat island intensity: Exploring spatial association in the city of Mumbai. Environment and Urbanization ASIA, 9(2), 158–177. https://doi.org/10.1177/0975425318783548
25. Moya, L., Vilela, M., Jaimes, J., Espinoza, B., Pajuelo, J., Tarque, N., Santa-Cruz, S., Vega-Centeno, P., & Yamazaki, F. (2024). Vulnerabilities and exposure of recent informal urban areas in Lima, Peru. Progress in Disaster Science, 23, 100345. https://doi.org/10.1016/j.pdisas.2024.100345
26. Murao, O., Hoshi, T., Estrada, M., Sugiyasu, K., Matsuoka, M., & Yamazaki, F. (2013). Urban recovery process in Pisco after the 2007 Peru earthquake. Journal of Disaster Research, 8(2), 356–364.
27. Nguyen, T. H. T., & Levasseur, M. (2023). How does community-based housing foster social participation in older adults: Importance of well-designed common space, proximity to

resources, flexible rules and policies, and benevolent communities. Journal of Gerontological Social Work, 66(1), 103–133. https://doi.org/10.1080/01634372.2022.2133199

28. Oliver-Smith, A. (1999). Peru's five-hundred-year earthquake: Vulnerability in historical context. En A. Oliver-Smith & S. Hoffman (Eds.), The angry earth (pp. 88–102). Routledge. https://doi.org/10.4324/9780203821190-13
29. Quesada-Román, A. (2022). Disaster risk assessment of informal settlements in the Global South. Sustainability, 14(16), 10261.
30. Qin, J., Tan, P., Cai, G., Zhou, C., Mi, P., Tang, M., & Zhou, F. (2025). Seismic performance investigation on simplified modular loading-bearing and energy-dissipating joints for modular steel buildings. Structures, 79, 109409. https://doi.org/10.1016/j.istruc.2025.109409
31. Rashidfarokhi, A. (2024). Resilience by whom and for whom? Empowering local communities for community-led resilience-building. En Real Estate and Sustainable Crisis Management in Urban Environments: Challenges and Solutions for Resilient Cities (pp. 39-56). Routledge. https://doi.org/10.1201/9781003474586-3
32. Sakay, C., Sanoni, P., & Deng, T. H. (2011). Rural to urban squatter settlements: The micro model of generational self-help housing in Lima-Peru. Procedia Engineering, 21, 473–480. https://doi.org/10.1016/j.proeng.2011.11.2040
33. Sandoval, V., & Sarmiento, J. P. (2020). A neglected issue: Informal settlements, urban development, and disaster risk reduction in Latin America and the Caribbean. Disaster Prevention and Management: An International Journal, 29(5), 731–745.
34. Smith, R. E. (2010). Prefab architecture: A guide to modular design and construction. John Wiley & Sons.
35. Unger, E.-M., Zevenbergen, J., Bennett, R., & Lemmen, C. (2019). Application of LADM for disaster prone areas and communities. Land Use Policy, 80, 118–126. https://doi.org/10.1016/j.landusepol.2018.10.012
36. Varela, S. L., Moncagatta, A. R., & Huamán, C. O. T. (2022). Blue and green infrastructure as public spaces: Five proposals for resilient urban development and social integration in Peru. In Handbook of waterfront cities and urbanism. Routledge. https://cris.pucp.edu.pe/en/publications
37. Walker, C. F. (2003). The upper classes and their upper stories: Architecture and the aftermath of the Lima earthquake of 1746. Hispanic American Historical Review, 83(1), 53–82.
38. Ye, Z., Bu, H., Liu, Z., Lu, D., Min, D., & Shan, H. (2025). Seismic resilience design of prefabricated modular pressurized buildings. Resilient Cities and Structures, 4(1), 53–70.

39. Zeballos-Velarde, C. (2021). Urban linkages: A methodological framework for improving resilience in peripheral areas: The case of Arequipa, Peru. En J. Martinez, C. A. Mikkelsen, & R. Phillips (Eds.), Handbook of quality of life and sustainability (pp. 533–550). Springer. https://doi.org/10.1007/978-3-030-50540-0_27
40. Zohourian, M., Pamidimukkala, A., Kermanshachi, S., & Almaskati, D. (2025). Modular construction: A comprehensive review. Buildings, 15(12), 2020.
41. Hopkins, D., Bell, D., Benites, R., Burr, J., Hamilton, C., & Kotze, R. (2008). The Pisco (Peru) earthquake of 15 August 2007: NZSEE reconnaissance report, June 2008. Bulletin of the New Zealand Society for Earthquake Engineering, 41(3), 109–192. https://doi.org/10.5459/bnzsee.41.3.109-192
42. National Centers for Environmental Information (NCEI). (2023, January 1). NCEI Hazard Earthquake Information. https://www.ngdc.noaa.gov/hazel/view/hazards/earthquake/event-more-info/1295
43. Colajanni, Piero & D'Anna, Jennifer. (2023). Seismic risk assessment of residential buildings by the Heuristic vulnerability model: influence of fragility curve models and inventory scale. Bulletin of Earthquake Engineering. 22. 1-34. 10.1007/s10518-023-01801-z.
44. Li, S., Lam, N., & Tsang, H.-H. (2022). Engineering modular building towers for improving earthquake safety. In Proceedings of the Australian Earthquake Engineering Society 2022 National Conference (pp. 1–6). Mount Macedon, Victoria, Australia.

Response for Reviewers

Dear Reviewers,

Thank you very much for the time and care invested in evaluating my manuscript, **"Safe Housing in Seismic Zones: The Modular Path."** I deeply appreciate the thoughtful feedback. Below, **I provide a point-by-point response to all comments.** All revisions mentioned below have been incorporated into the updated manuscript and are visible in the tracked changes file.

*The revisions that follow both reviewers' recommendations are highlighted in **yellow.**

*The personal corrections or addons are highlighted in **red.**

Reviewer 1: The revisions or addons were highlighted in **purple.**

I would like to preface by saying that the paper takes on a very timely and pressing question that applies to many regions beyond Latin America: how informal settlements often built under precarious conditions might be made more resilient to earthquakes through modular construction. This is already an ambitious undertaking, and what I appreciate most is the way the author tries to hold together several different kinds of evidence and perspectives. Weaving together historical case studies with engineering concepts like modular jointing systems and seismic fragility curves, and then social frameworks (which are often harder to pin down in technical writing!), the paper shows real intellectual courage. It could feel as though the argument is moving on three tracks at once, but the interdisciplinarity of the project is refreshing.

✉ Thank you very much for these generous and encouraging remarks! I sincerely appreciate your recognition of the interdisciplinary effort behind the manuscript and your thoughtful acknowledgment of all the elements I attempted to integrate.

The historical examples are particularly strong. They ground the argument in moments when disasters forced societies to rethink how they built, and they remind us that innovation has often been reactive. The section on quincha in eighteenth-century Peru was particularly vivid in showing how vernacular techniques anticipated modern engineering principles. I can also commend the use of a wide range of visual material, which is impressive for a student paper and gives a strong sense of how lived environments have been reshaped by disaster.

✉ Thank you very much for these generous comments. I truly appreciate your recognition of the historical cases and the way they help frame the evolution of building practices after major disasters.

Where the paper could most improve is in clarifying the through-line of the argument. At the moment, there is so much fascinating material that the central claim about modularity sometimes gets a little buried. One way forward might be to structure the essay more explicitly in three parts: historical precedents, then the engineering aspects of modular construction, and finally the social and participatory frameworks. Each section should end with a short synthesis paragraph that builds momentum toward the next. That would allow the reader to see more clearly how the pieces fit together.

✉ Thank you for this helpful structural recommendation! I implemented a full reorganization of the manuscript into the three-part sequence you suggested. Each major part now ends with a short synthesis paragraph that explicitly links the section to the central claim on modularity. Additionally, I consolidated the previously dispersed thematic material into these three unified sections (Historical Precedents, Engineering Aspects of Modular Construction, and Social and Participatory Frameworks), since these subsections were fundamentally related and benefited from being integrated into a coherent triad.

The bibliography is wide-ranging, which is excellent, but the engagement with it sometimes feels a bit quick. I would encourage the author to slow down at key points and draw out what individual thinkers are contributing. For example, Fernández-Maldonado and Bredenoord's work on progressive housing (or Oliver-Smith on vulnerability), could be tied more directly to the hybrid model the author is proposing. This would strengthen the scholarly voice and show how the author is participating in existing debates, not just reporting them.

✉ Thank you! I expanded the conceptual engagement throughout the revised section Social and Participatory Frameworks. Now, Fernández-Maldonado & Bredenoord (2010) are now explicitly tied to the logic of progressive housing as the foundation for the modular-incremental hybrid, as well as other citations. Also, Oliver-Smith's vulnerability framework is also integrated in the discussion on community agency and governance.

The figures, too, could do more argumentative work (they are not mere illustrations, but visual evidence!) Rather than only describing them, the author might explain what they reveal about urban form, resilience, or vulnerability. For example, the map of Callao after the 1746 earthquake could be used to underscore how disasters completely reconfigure the spatial order of cities, which in turn supports the case for adaptable systems like modular housing.

✉ Thank you! All figure captions have been rewritten to clarify their argumentative function. In that way, in the revised manuscript, the narrative surrounding figures has been strengthened accordingly.

Overall, this is a very promising and ambitious paper. It shows strong initiative and maturity in drawing connections across disciplines. With restructuring, deeper engagement with sources, and tighter analysis of the figures, it has real potential. **My recommendation is to accept it with major revisions**.

Review 2: The revisions or addons were highlighted in blue.

This paper looks into improving seismic safety in the informal settlements of Latin America by using modular construction and participatory design. The paper's main strength lies in its central claim: that a hybrid approach combining the technical rigor of modular systems with the local agency of community-led, incremental building practices is essential for true resilience. The paper also nicely incorporates historical case studies from Lima, Valparaíso, and Pisco effectively. Those cases help establish the recurring patterns of vulnerability and the limitations of top-down technical solutions. That said, the manuscript in its current form requires major revisions before it can be considered for publication. The central idea and chosen topic are strong, but the paper suffers from significant structural disorganization in the later sections, poor integration and presentation of its many figures, and overall issues with flow. These issues collectively obscure writing and make the paper difficult to follow. The author should address the following comments:

(1) **Organization.** The section "Participatory Design and Incremental Housing" is highly disorganized. It presents a collection of disparate statistics on topics ranging from student learning in Dublin and remote work after COVID-19 to retirement communities and Australian bushfires. While these points touch on collaboration or housing, their direct relevance to modular construction in Latin American informal settlements is not established. Please rewrite this section and focus on the central topic. Instead of citing general studies on collaboration, the author should seek out and synthesize literature that deals specifically with participatory planning and incremental building within informal housing contexts, preferably in Latin America or other relevant areas of the Global South.

✉ Thank you for this observation. I rewrote the section to improve coherence and removed unrelated material. Moreover, the COVID-19 example is now clearly justified as an analogy for collaborative learning.

(2) Figures. The paper has many figures, which is great but they have several issues with numbering. For example, Figure 4 is missing. The text on page 6 refers to "Figure 12" when discussing cement usage, but the corresponding figure is labeled Figure 9. Moreover, several figures contain untranslated Spanish text like figure 1 and figure 5. For an English-language publication, all text within figures must be translated or explained. The captions often simply state what the image is, without explaining its relevance to the argument. Please revise the issues with the figures.

✉ Thank you for your feedback! I understand that there were some disorganized figures and lack of translation in some of them as well. So, all figure-related issues have been corrected in the revised version:

- ❖ Renumbered all figures consistently.
- ❖ Ensured all referenced figures exist in sequence.
- ❖ Translated all text in figures originally in Spanish within figures or added explanatory notes when translation within the graphic was not possible.
- ❖ Expanded captions so that each figure now explains its relevance to the argument, rather than functioning as a simple description.

(3) Literature. Right now, the literature reads like disconnected facts. It would make the paper much stronger if the sources could be merged and flow better together to build a clean argument.

✉ Thank you! You're right, that is why sources are now woven into a single argumentative thread rather than listed sequentially. Also, each reference is tied to a specific conceptual or methodological point. In addition, the new structure (Historical → Engineering → Social/Participatory) naturally supports better cohesion.

Given the above comments and the paper's inherent strengths, it has the potential to be published. I recommend that the author undergo **major revisions** of the paper so it can be worthy of publication.

It is clear that the student has responded very well to the requested revisions and responded to all of them substantively. They have gone above and beyond what was initially expected and requested. They responded to all structural and organizational critiques, with a substantial reorganization of the paper as suggested by Reviewer 1. There is considerably deeper conceptual engagement, especially with key theorists on vulnerability and progressive housing. They have rewritten and pruned the participatory frameworks section favorably, and also corrected many of the issues with the figures.

However, in my view, several things could be improved that would raise the paper from just satisfying revisions and being a "strong student work that satisfies the initial reviewer concerns" to "publishable quality."

- Overall, **less description and more analysis.** You have some great ideas; right now, they are being drowned out by descriptions and summaries.
- The paper is trying too hard to be both a review/position paper and an applied research article. However, given where it currently stands, I would say it is a lot closer to being a review, but that should be better clarified. You should explicitly frame this as being an integrative review and reduce all empirical claims unless you have original data and analysis to support it (and of course, if that data/analysis comes from a different work, then that would still be a review, albeit valuable to include nonetheless).
    - On that note, you should bring greater emphasis to your own, personal, novel interpretations and syntheses of the literature rather than just accumulating examples.
    - E.g., add a short paragraph or a few sentences in the introduction that explicitly state what your paper is trying to accomplish: "This paper is a conceptual synthesis and interdisciplinary review that integrates historical evidence, engineering research, and planning literature to propose a modular framework for seismic resilience."
- Your paper is still far too expansive and tries, in my opinion, to accomplish too much. You should cut and compress anything that seems to deviate from your main arguments. E.g., I would cut or further summarize some of the COVID remote work statistics, retirement housing demographics, and bushfire information. It should all stay consistently focused on modular-incremental housing models. I get that some of this demographic and work data might be *important*, but sometimes it does not need to be said; rather, you could refer the reader to certain works that contain this data if they are interested.
    - A scholarly, cohesive review or position paper does not try to explain *everything* about a subject—that is what a good textbook is for. 🙂 It provides original perspectives, syntheses, and insights, and gives people teasers as to where they can find some more of the side details.
- Your thesis is persuasive, but can be better fleshed out. If you are going to include such an expansive and wide range of perspectives and topics, your thesis should also reflect that same level of complexity. "Modular + participatory + incremental systems => better resilience" is good. "Hybrid modular incremental housing systems outperform purely top-down modular systems in informal seismic zones by improving structural

predictability, adoption longevity, and post-disaster adaptability" is better. See what I mean?

  - You should, in particular, more clearly identify specific mechanisms where modularity helps, failure modes without introducing hybrid modularity (e.g., for purely technical solutions), and potential conditions where a hybrid model could fail or would fail
- Let your figures do more of the speaking; a lot of your paragraphs restate what the figures already show. Instead of restating, use the figures to make statements about the literature. What new inferences do the figures allow? What claims are bolstered or contradicted by the figures?

I get that a lot of the critiques above are a bit general, but what I would do is read through the paper and ask yourself: What am I mainly trying to say, what does the paper currently say, and what do I need to change to ensure that my point is clear? I think your paper is trying to tell too much; you should focus on what story **you** are trying to tell.