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Safe Housing in Seismic Zones: The Modular Path

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Abstract

Informal settlements in seismically active regions face disproportionately high levels of structural risk due to incremental construction practices, limited institutional oversight, and exclusion from formal planning systems. While earthquakes are often framed as sudden natural events, their impacts in informal contexts are largely shaped by historically produced social, spatial, and technical conditions. This paper presents an integrative and interdisciplinary review that synthesizes engineering research, planning literature, and historical evidence to examine how modular construction can contribute to seismic resilience when combined with participatory design and incremental housing logics.

Drawing on case studies and experimental research from Latin America and comparable contexts, the paper argues that modular systems outperform purely top-down or purely informal approaches when they operate as hybrid socio-technical frameworks. Specifically, hybrid modular-incremental housing models improve structural predictability, adoption longevity, and post-disaster adaptability by standardizing critical load-bearing components while allowing incremental growth shaped by community agency. The analysis identifies key mechanisms through which modularity enhances seismic performance, as well as conditions under which such systems may fail, particularly in the absence of institutional support and local capacity building.

By reframing modular construction as a transferable structural language rather than a fixed technological solution, this paper contributes a conceptual framework for integrating engineering precision with participatory governance. The findings suggest that seismic resilience in informal settlements emerges not from technical innovation alone, but from the alignment of modular design, incremental development, and social participation within context-sensitive planning frameworks.

Keywords: earthquake engineering, seismic resilience, informal settlements, modular construction, incremental housing, disaster risk reduction, participatory design, Latin America

1. Introduction

Informal settlements in seismically active regions often emerge under conditions of urgency, exclusion, and limited institutional oversight. These environments are shaped primarily by necessity rather than regulation, resulting in housing that lacks the structural capacity to withstand seismic forces. While earthquakes may appear as sudden or coincidental events, the scale of their impact in informal areas is the outcome of systemic conditions in which immediate shelter needs consistently outweigh long-term structural safety. Housing in these contexts is commonly produced through self-initiated construction, usually without professional supervision and frequently using recycled or low-quality materials. As dwellings expand incrementally, load paths become irregular and structural connections remain poorly defined, which significantly increases vulnerability during seismic events. These dynamics align with Ginigaddara's (2023) observation that informal construction, shaped by socioeconomic constraints rather than technical guidance, inherently amplifies seismic risk.

Geological conditions further intensify this vulnerability. In Lima, informal settlements are frequently located on sandy soils or steep hillsides where seismic waves are amplified, while in Valparaíso, hillside communities reflect the cumulative effects of precarious construction practices and exclusionary urban policies. In both cases, physical instability intersects with social and institutional fragility, producing environments in which even moderate earthquakes can lead to severe damage. This pattern is consistent with regional evidence demonstrating that spatial injustice and environmental degradation have systematically concentrated vulnerable populations in geotechnically unstable areas (Maciejewska and Ulanicka-Raczyńska, 2023).

Although seismic disasters have historically prompted advances in construction techniques, responses have remained largely reactive. The 1906 Valparaíso earthquake, for example, led to the introduction of seismic regulations and improved building practices within formal construction sectors. However, these measures were not adopted uniformly. While regulated housing benefited from new materials and standards, informal dwellings continued to evolve through household-level decisions made in the absence of technical support. In that way, damage in informal areas during subsequent earthquakes has remained disproportionately severe, underscoring the limitations of purely technical progress. These recurring disparities suggest that engineering innovation alone is insufficient and that effective solutions must bridge technical knowledge with the lived realities of informal builders (Rashidfarokhi, 2024).

Recent literature indicates that modular construction systems offer promising opportunities in this regard. Reviews of cross-laminated timber systems show that modular approaches can significantly reduce construction time while maintaining strong seismic performance, making them suitable for rapid deployment in earthquake-prone regions (Bhandari et al., 2023). In a similar way, experimental studies on full-scale modular steel prototypes demonstrate that standardized connections can sustain seismic demands under multi-hazard conditions, supporting the structural reliability and repeatability of modular systems (Di Sarno and Forgione, 2024). Together, these findings suggest that modular construction can enhance seismic resilience by delivering structural consistency through prefabricated components and controlled connections. However, evidence also indicates that modularity alone does not guarantee resilience in informal contexts, particularly when introduced as a purely technical solution detached from incremental building practices and local construction knowledge. In that line, this paper advances a conceptual synthesis that examines how modular construction, when integrated with participatory design and incremental development, can contribute to seismic resilience and social sustainability in Latin America's informal settlements. Rather than presenting original empirical data, the paper positions itself as an integrative review that emphasizes novel interpretations and syntheses of existing literature, focusing on the specific mechanisms through which hybrid modular-incremental systems improve structural predictability, long-term adaptability, and post-disaster repair capacity while remaining aligned with community agency.

2. 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 while also revealing deeper limitations embedded within building cultures, institutional frameworks, and technical practices (Oliver-Smith, 1999). In other words, seismic disasters operate as moments of forced institutional and social reflection, particularly in contexts where widespread destruction compels societies to reassess dominant construction logics. As Walker (2003) observes, the collapse of elite housing during major seismic events contrasts with Oliver-Smith's broader interpretation of vulnerability in Peru's seismic history, illustrating that earthquakes disrupt social hierarchies while still producing uneven patterns of loss.

Understanding this dynamic requires acknowledging that earthquakes function as both physical phenomena and social processes. From a geological standpoint, earthquakes result from sudden movement along faults within the Earth, releasing stored 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 remain especially prone to collapse, particularly within informal settlements where construction evolves incrementally, and technical oversight is limited. In this sense, seismic vulnerability emerges as a historically accumulated condition produced through urbanization practices rather than as an isolated natural event.

By way of illustration, the 1746 Lima earthquake offers a foundational example of these processes. Nearly all of Lima's approximately 3,000 buildings collapsed, with only about 25 remaining standing, while the associated tsunami destroyed the port of Callao, killing around 6,000 inhabitants and leaving only 200 survivors. In Lima itself, approximately 1,141 people died out of an estimated population of 60,000, while the combined earthquake and tsunami death toll exceeded 5,900 (NCEI, 2023). Walker's (2003) seismic coupling analysis of the event, shown in Figure 1, demonstrates that destruction followed spatially uneven patterns of ground motion rather than being uniformly distributed across the city. By visualizing concentrated zones of seismic energy release, Figure 1 supports the argument that earthquakes reshape urban form by creating corridors of extreme impact that align with pre-existing geotechnical and morphological conditions.

This spatial unevenness has direct implications for housing systems. When seismic energy varies sharply across short distances, construction approaches driven by ad hoc and incremental decisions generate high levels of structural uncertainty. In contrast, modular systems introduce repeatable structural logics and clearer load paths, which support more predictable performance under irregular seismic demands. The relevance of modularity in this context lies in its capacity to preserve structural coherence despite territorial variability.

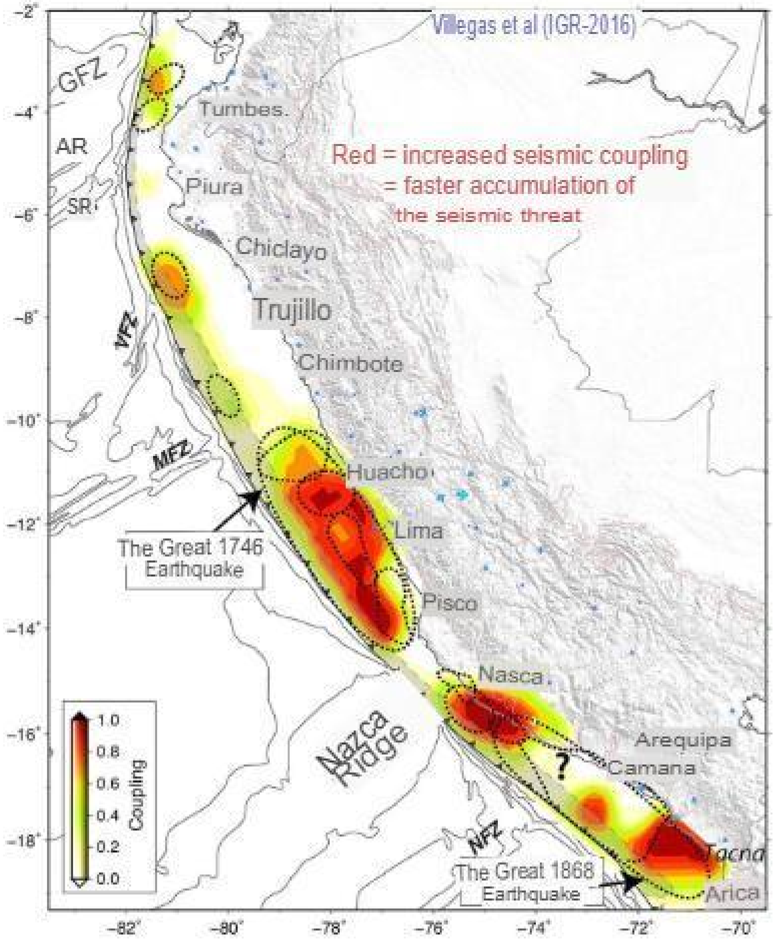


Figure 1: Seismic coupling map showing zones of low to high ground motion during the 1746 Lima earthquake.

Note: The map visualizes the spatial distribution of seismic energy accumulation and release, illustrating how zones of high coupling correspond to areas that experienced the most severe destruction. The figure reveals that vulnerability is conditioned by pre-existing geotechnical and morphological factors rather than being uniformly distributed.

A complementary perspective emerges from Walker's historical mapping of Callao before and after the 1746 event, presented in Figure 2. The comparison reveals that entire neighborhoods disappeared, coastlines receded, and previously inhabited zones became permanently uninhabitable. These territorial transformations demonstrate that resilience operates simultaneously at structural and spatial scales. Disasters damage buildings while also rendering existing urban configurations obsolete. Modular housing aligns with this condition insofar as its disassemblable and relocatable components allow post-disaster reoccupation and spatial reorganization in landscapes that have undergone irreversible change, as occurred in Callao.

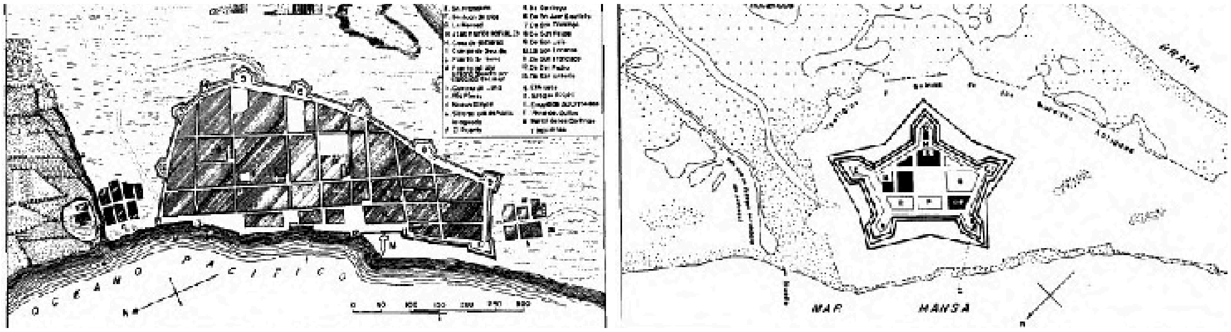


Figure 2: Historical Map of Callao District Before and After the 1746 Earthquake

Note: The juxtaposition reveals the scale of territorial transformation produced by the disaster. Entire neighborhoods disappeared, the coastline receded, and previously inhabited areas became permanently uninhabitable, illustrating how seismic events can irreversibly reorganize urban space.

The transformation of Callao also exposed institutional weaknesses. The disappearance of the port was related not only to geographic exposure but also to the absence of anticipatory planning and adaptive construction practices. In the aftermath, Peruvian authorities promoted quincha, a traditional construction system based on timber framing infilled with cane and mud plaster, to improve energy dissipation during earthquakes (Vergara, 2014). Quincha functioned as an early form of ductile construction, allowing buildings to deform rather than collapse. Although the technique preceded formal seismic theory, it represented a decisive shift toward flexibility as a resilience strategy. Nonetheless, centralized enforcement mechanisms and limited technical outreach constrained its diffusion, resulting in uneven adoption across expanding urban peripheries (Fernández-Maldonado and Bredenoord, 2010). As a result, access to safer construction methods remained conditioned by social and spatial inequality.

Years later, a comparable pattern emerged in Valparaíso, Chile, following the 1906 earthquake. Hillside neighborhoods that had developed informally and with limited engineering guidance experienced disproportionate damage, echoing challenges previously observed in Callao. Accordingly, this event became a critical moment in Chilean engineering history, prompting institutions and professionals to reconsider dominant materials and structural systems. The adoption of reinforced concrete, along with the formalization of seismic codes and the incorporation of structural dynamics into engineering education, marked the professionalization of earthquake engineering in the country (Maino and Tobriner, 2024). Over time, these developments positioned Chile as a global reference in seismic design.

Despite these advances, most improvements remained concentrated within formal sectors of the city. Informal hillside neighborhoods continued to expand with minimal institutional support. Seismic oscillation intensity mapping of Valparaíso, shown in Figure 3, reveals that ground shaking followed patterns shaped by topography, soil conditions, and the spatial logic of urban expansion. In that matter, a recurring mechanism becomes visible. Informal growth on unstable slopes magnified seismic effects and transformed specific sectors into concentrated zones of structural failure, particularly within hillside areas.

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

Note: Darker zones indicate severe shaking, particularly in hillside areas where informal settlements overlapped with unstable slopes. The figure highlights how local soil conditions, topography, and unregulated expansion converged to intensify damage.

This mechanism becomes clearer when examined alongside contemporaneous photographic documentation of collapsed informal dwellings, presented in Figure 4. Unlike engineering reports that emphasize regulatory frameworks or material specifications, the photograph captures the lived experience of disaster. It reveals how irregular load paths, brittle joints, and the absence of lateral resistance translated into total structural failure. Figure 4, therefore, clarifies that vulnerability is produced through the interaction between physical limitations and everyday construction practices shaped by necessity and constrained access to technical knowledge.

Figure 4: Photographic Evidence of Collapsed Informal Housing in Valparaíso after the 1906 Earthquake.

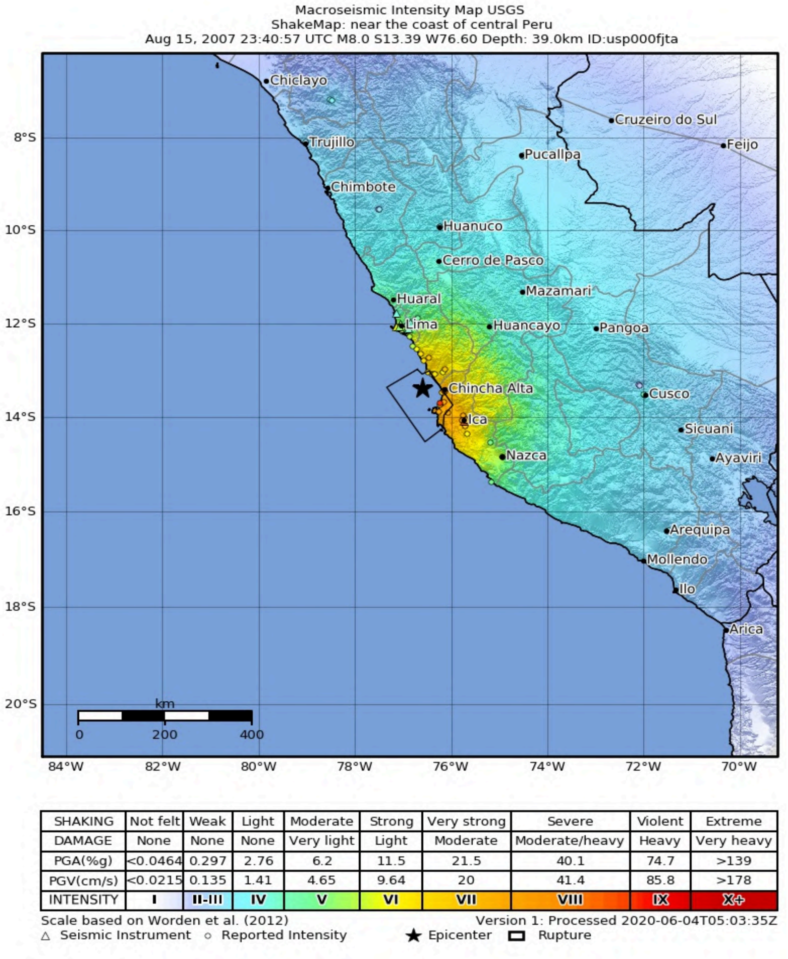
Note: The photograph shows brittle connections, irregular load paths, and the absence of lateral resistance, which illustrate why damage became concentrated in neighborhoods shaped by precarious construction practices.

Several decades later, the 2007 earthquake in Pisco, Peru, once again exposed the persistent gap between formal engineering standards and informal construction realities. According to the NZSEE reconnaissance report, the disaster destroyed more than 38,000 homes, displaced over 100,000 people, and caused nearly 600 fatalities among approximately 70,000 affected families (Hopkins et al., 2008)—post-earthquake conditions documented in Figure 5 show widespread failure of unreinforced masonry and poorly anchored structures. Beyond physical destruction, the figure reveals how incremental additions and limited technical guidance produced structural inconsistencies that amplified 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 deficient connections typical of informal incremental construction.

Macroseismic intensity mapping of the event, shown in Figure 6, further demonstrates that seismic impacts followed spatial patterns rather than random distributions. The darkest intensity zones align with low-income districts dominated by self-built housing, confirming that socioeconomic marginalization shapes the geography of disaster. This overlap supports the argument that earthquakes become social events, as damage severity is conditioned by unequal access to technical assistance and the concentration of vulnerable housing typologies.



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+

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 characterized by brittle materials, shallow foundations, and deficient connections continued to experience the most severe losses. The Pisco earthquake also revealed the limitations of reconstruction strategies based on standardized housing units imposed without sufficient consideration of local practices. Many such units were later abandoned or repurposed, undermining long-term resilience. Nevertheless, by 2012, 95.5% of damaged homes were reoccupied, accompanied by over 2,100 new constructions representing 17.6% of total lots, reflecting the persistence of unplanned expansion rather than the consolidation of safer building practices (Ismail et al., 2017).

Recent data from the INEI (2023), shown in Figure 7, situate these historical patterns within contemporary structural constraints. Cement consumption declined by 7.9% in August 2023, while public infrastructure investment fell by 8.8% in January of the same year. In that manner, these figures signal more than a temporary slowdown. They reflect a contraction that limits the institutional and financial capacity required to scale modular housing systems. Reduced private construction weakens material supply chains, declining public investment constrains pilot programs, and overall sectoral contraction discourages innovation at a moment when resilience-oriented approaches are increasingly necessary.

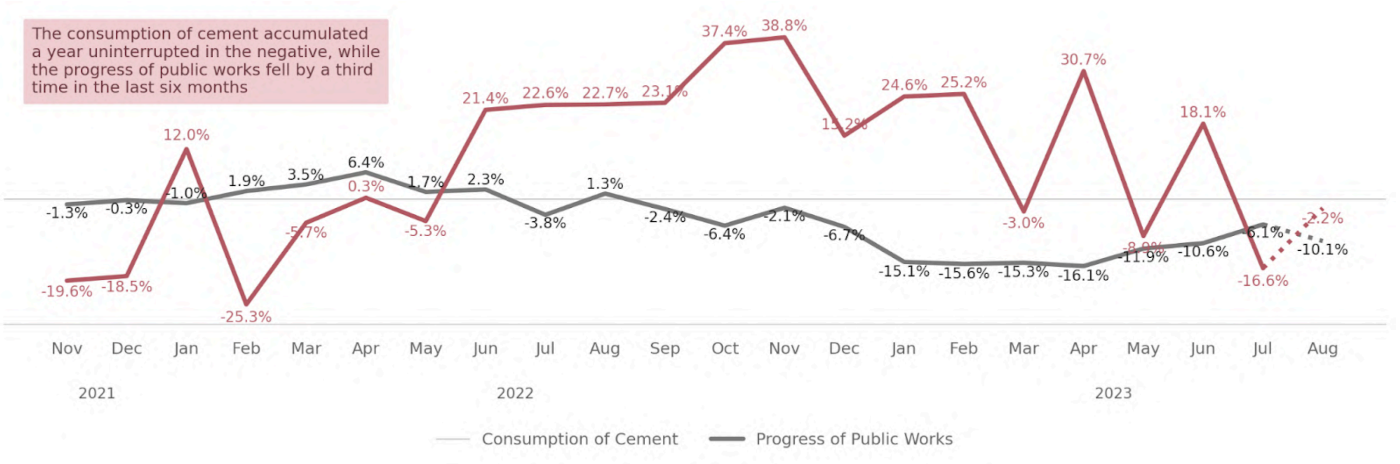


Figure 7: Trends in cement usage and public infrastructure development in Peru, 2023.

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. Plot created using ChatGPT and matplotlib in Python.

These continuities become particularly evident when examining current spatial dynamics of risk. The expansion of informal settlements into hazardous terrains reflects 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, resulting in extensive peripheral zones where infrastructure remains deficient or absent (Sakay et al., 2011). Long-term urban growth patterns in Lima, shown in Figure 8, reveal how development progressively moved into areas with low geotechnical stability, exposing a structural mismatch between urban expansion and institutional capacity (Equipo Técnico Plan Met 2040, 2020).

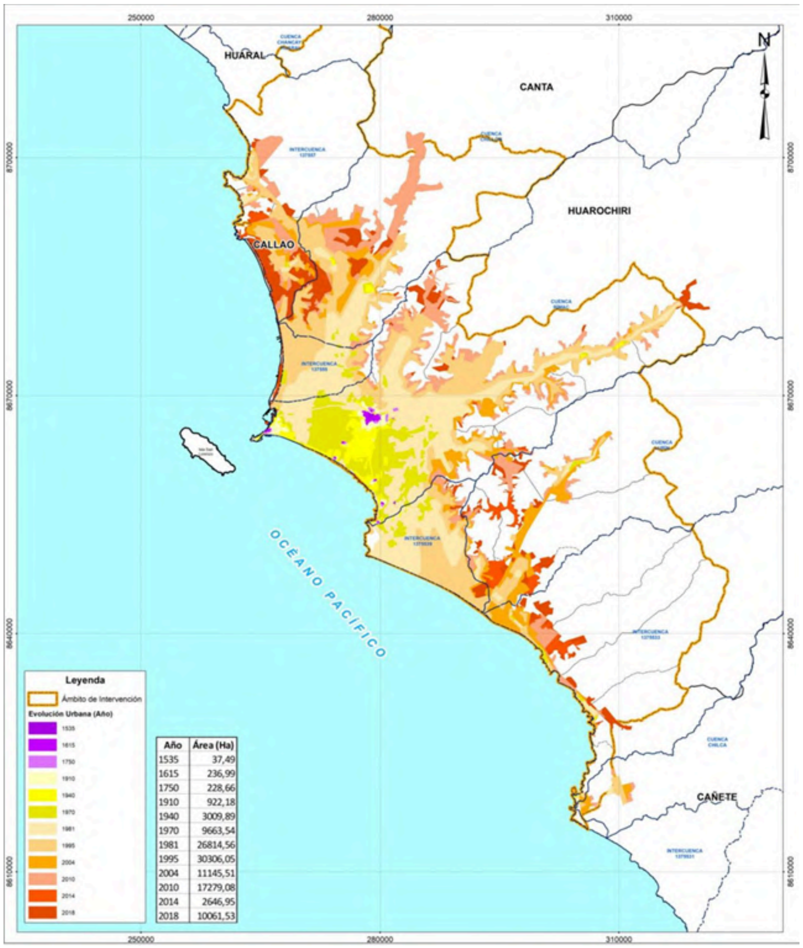


Figure 8: Urban growth map of Metropolitan Lima (1535–2018).

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.

Geotechnical assessments reinforce this spatial inequality. While coarse alluvial soils in central valleys support up to 4 kg/cm², fine sands and silts common in peripheral settlements sustain less than 1 kg/cm², which makes them highly susceptible to liquefaction and collapse during seismic events (Gutiérrez et al., 2020). When combined with self-built housing and limited professional guidance, these conditions significantly amplify structural fragility.

GIS analyses further demonstrate that many informal districts overlap with seismic amplification zones, as illustrated in Figure 9 (INEI, 2007). This convergence reveals that the most disadvantaged groups inhabit environments where ground motion is most likely to intensify. Current surveys indicate that more than 60% of residents in high-risk areas have never received earthquake preparedness training, and over 40% remain unaware of evacuation routes, despite living in seismically active zones (Quesada-Román, 2022). In districts such as Madre de Dios, Pasco, Tumbes, and Lima, population densities exceed 1,000 inhabitants per hectare, combustible materials appear in over 70% of dwellings, and emergency response delays reach 40 minutes, compounding seismic exposure with secondary hazards such as fire (Ismail et al., 2017).

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.

To integrate these findings, historical and contemporary evidence reveals a consistent pattern. Seismic vulnerability in Latin America emerges as a cumulative socio-structural process shaped by inequality, informal urbanization, and uneven access to technical knowledge. Each precedent shows that engineering advances falter when disconnected from local realities and participatory processes. In the same way, these historical trajectories underscore the need for housing paradigms that combine structural predictability with adaptability and social participation, conditions that modular construction, when properly adapted, is uniquely positioned to address.

3. Engineering Aspects of Modular Construction

Modular construction refers to a building approach that employs prefabricated components assembled through coordinated on-site processes. Over time, it has evolved into a strategy with the potential to address structural vulnerability in high-risk environments, particularly where conventional construction struggles to ensure consistent quality. More precisely, this approach involves the partial or complete fabrication of structural modules in controlled settings, where material properties, tolerances, and connection behavior can be verified prior to installation. Within the scope of this paper, modular construction is examined not as a disruptive alternative to vernacular practices but as part of a longer lineage of prefabrication logics that extend from monumental construction in antiquity to British colonial expansion, the California Gold Rush, and the industrial mobilization of both World Wars (Smith, 2010). Recent advances in robotic manufacturing, digital modeling, and specialized transport systems intensify these historical tendencies by enabling higher levels of repeatability and quality control than those typically achieved through site-based construction alone (AlDairi, 2021).

This historical continuity carries direct implications for contemporary structural performance. In contrast to informal housing systems that expand through unregulated, and structurally incompatible additions (Green, 2008), modular systems rely on standardized dimensions and deliberately engineered joints that establish predictable load paths and deformation mechanisms (Lawson and Richards, 2010). As shown in Figure 10, a typical modular structural joint is designed to maintain force continuity across adjacent modules, reducing uncertainty in load transmission during seismic excitation. Figure 11 further illustrates distinct gusset plate configurations, including double-hole plates for external joints, single-hole plates for corner joints, and four-hole plates for internal joints. Each configuration reflects a calibrated response to stress distribution requirements, highlighting how connection typologies function as structural regulators rather than secondary detailing elements.

This engineered coherence contrasts sharply with the irregular load paths characteristic of self-built dwellings, where incremental growth frequently disrupts structural continuity and introduces hidden failure mechanisms. At the same time, modular construction remains compatible with incremental development when expansion is anticipated within the connection logic. Individual modules can be manufactured and added over time without undermining global stability, provided that joints and load paths are designed to accommodate future vertical or horizontal growth (Fernández-Maldonado and Bredenoord, 2010). This capacity elevates modular construction from a purely technical system to an urbanistic one, offering a structurally controlled alternative to the incremental growth patterns that dominate peripheral urbanization in Latin America. In this context, the reconstruction of Valparaíso after the 1906 earthquake illustrates how seismic disasters have historically prompted shifts toward engineering-based construction practices, even though such transitions have rarely been institutionalized across all social sectors (Maino and Tobriner, 2024). Figures 10 and 11 both support a broader inference. Modular design embeds seismic logic directly into joints and assembly sequences, operationalizing lessons that have repeatedly emerged after major disasters but often failed to consolidate into long-term practice.

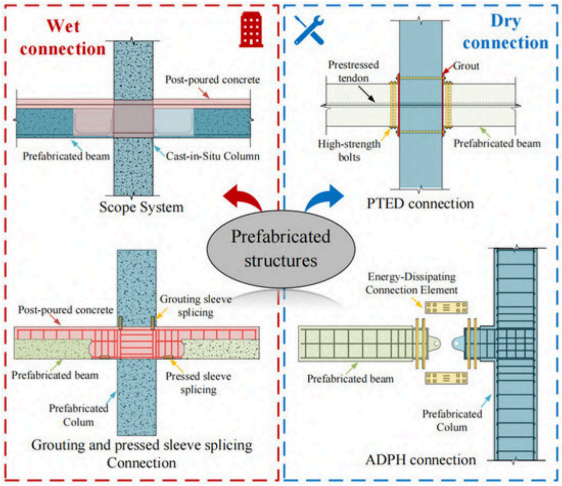


Figure 10: Structural joint diagram in modular construction systems.

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

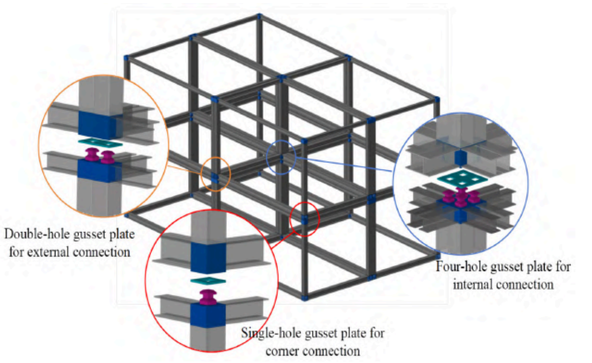


Figure 11: Structural joint diagram in modular construction systems.

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

From a structural perspective, connection systems emerge as the critical determinants of seismic performance in modular construction. Both inter-module and intra-module joints are designed to balance robustness with controlled energy dissipation under extreme loading. Common configurations include tie rods combined with shear keys, bolted steel plates, VectorBloc connectors, and welded cover plates. Each configuration directly influences lateral-force resistance, inter-story drift, and ductility capacity (Ginigaddara et al., 2023). In this sense, the effectiveness of modular systems lies less in the modules themselves than in the way seismic forces are redistributed across interfaces during ground motion.

Figure 12 illustrates this principle through a bolted plate connection engineered to enhance deformation capacity while preserving efficient load transfer across prefabricated assemblies. Beyond confirming structural adequacy, the figure supports a more analytical inference. Such connections accommodate significant displacement demands while maintaining continuity in force transmission, thereby reducing the likelihood of brittle failure. This behavior directly addresses a recurring weakness observed in both informal construction and poorly detailed prefabricated systems. In this sense, the figure reinforces the argument that modular construction can serve as a structurally rigorous strategy for high-risk seismic environments when joint behavior is treated as a primary design variable rather than secondary detailing.

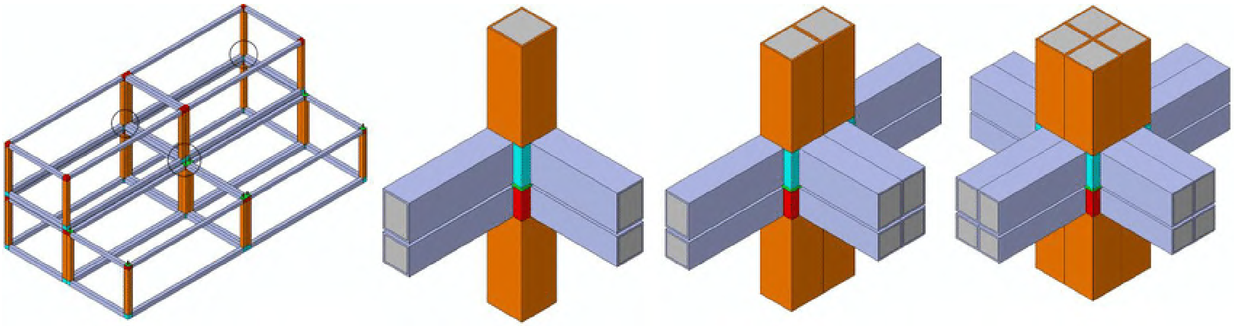


Figure 12: Detail of bolted plate modular connection.

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

Experimental research further clarifies these mechanisms. Figure 13 presents a scaled modular tower tested by Sheng Li et al. (2022), incorporating a superelastic NiTi tendon system that enables controlled rocking while preserving re-centering capacity after strong ground motions. The test setup highlights the placement of rotation sensors, strain gauges, and acceleration monitors, which together reveal how seismic demand is redirected away from brittle joints toward components capable of sustaining large, recoverable deformations. Under identical near-fault excitations, the tendon-restrained configuration reduced internal forces by 36% and rocking rotations by 61% relative to fixed-base alternatives. By visualizing how the tendon anchors the upper module and limits excessive rotation, Figure 13 clarifies the mechanism through which advanced seismic technologies enhance modular performance without compromising prefabrication efficiency.

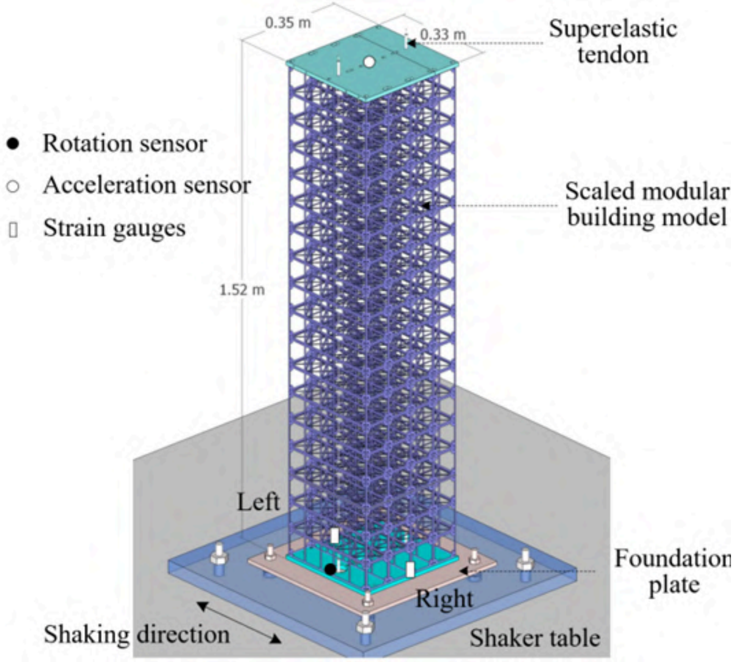


Figure 13: Scaled modular building model with superelastic tendon system and test set-up.

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 within the Latin American context can be observed in Peru. Figure 14 presents the ALQUIMODUL SAC construction model, which assembles prefabricated concrete and steel components manufactured in controlled factory environments. Rather than cataloging individual materials, the figure illustrates how insulation layers, gypsum boards, galvanized profiles, and phenolic plywood panels are organized to produce a structurally continuous and thermally efficient envelope. This configuration demonstrates that locally manufactured components can achieve the dimensional accuracy and material continuity required for seismic reliability, thereby challenging assumptions that advanced prefabrication remains unattainable in low- and middle-income contexts. At the same time, the figure exposes a critical limitation. Although factory-based quality control reduces on-site variability, long-term performance remains contingent on workforce training and alignment with local construction practices. Without sustained institutional support, such systems risk remaining isolated demonstrations rather than scalable alternatives to informal urban expansion.

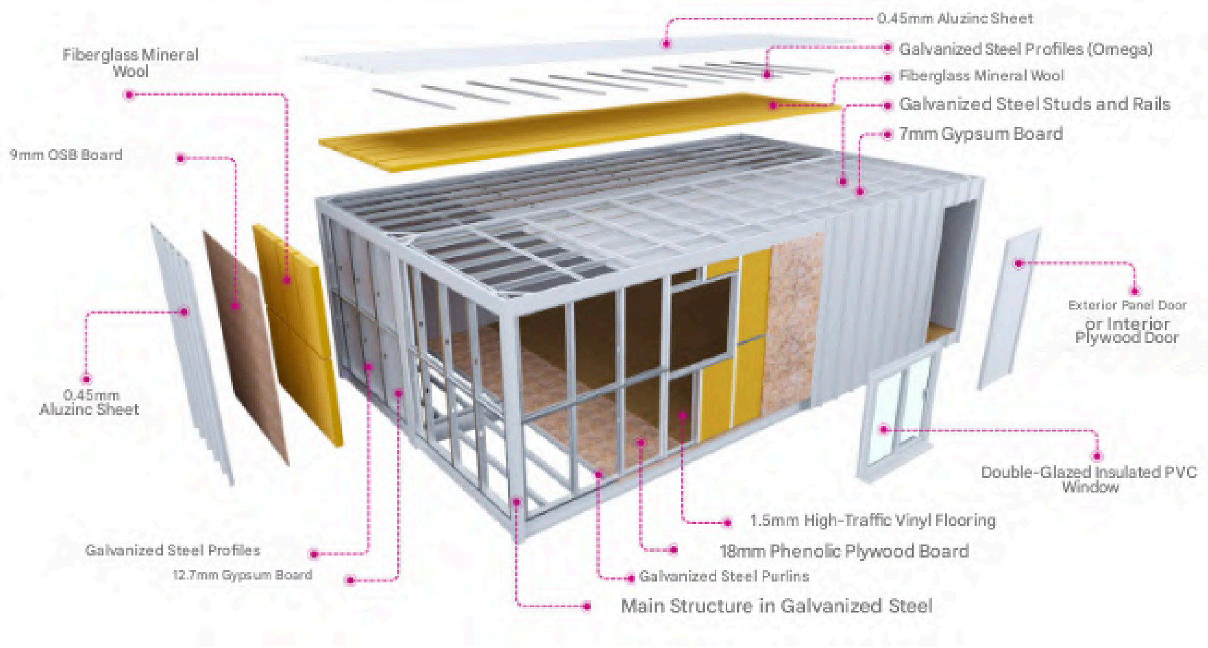


Figure 14: Advanced Modular Concrete Construction System in Peru, 2012.

Note: The diagram presents prefabricated wall panels, insulation layers, and structural frames manufactured under controlled conditions. It exemplifies how national industries can deliver modular components that support seismic reliability in low-income contexts.

Beyond seismic performance, modular construction has also been adapted to address other hazard conditions, although empirical validation remains uneven. In high-wind regions, reinforced interconnections and fatigue-resistant joints are required to resist lateral pressures and debris impact (Di Sarno and Forgione, 2024). Figure 15 illustrates hurricane-resistant modular housing designs that combine aerodynamic geometry with enhanced anchoring systems. Figure 16 presents modular typologies developed for flooding contexts, including amphibious configurations and floating foundations (Abdur Rehman, 2024). During the COVID-19 emergency, modular flexibility was further demonstrated through the rapid deployment of facilities such as the Leishenshan Hospital (Ismail et al., 2017). These cases situate modular construction within broader multi-hazard debates rather than extending the core argument of this paper. At the same time, research gaps persist, particularly in relation to combined hazard scenarios and fire performance, which remain insufficiently addressed in current modular studies (Bhandari et al., 2023). Figure 17 synthesizes these tensions by illustrating how structural resilience, spatial quality, and architectural expression can converge, while also revealing the uneven translation of such integration into built practice.

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 the potential convergence of structural resilience and architectural quality within modular design, serving as a conceptual synthesis rather than an empirical demonstration.

Considering these perspectives, modular construction emerges as one of the most viable strategies for enhancing safety, efficiency, and construction quality in hazard-prone environments, particularly where informal building practices generate high levels of structural uncertainty. Prefabrication enables continuous testing of materials and assemblies before installation, which reduces design inconsistencies and limits the propagation of construction errors across entire housing systems (Sandoval and Sarmiento, 2020). In addition, modular logic facilitates post-disaster recovery by allowing damaged units to be replaced individually without dismantling entire structures, a property that directly supports rapid reoccupation and incremental repair (Eren, 2012). At the same time, adaptive capacity does not emerge from technical precision alone. It depends on the integration of modular systems within broader disaster management frameworks and on their calibration to local cultural practices, environmental constraints, and economic conditions (Hussainzad and Gou, 2024).

When viewed collectively, the engineering evidence reviewed in this section suggests that resilience is produced less by isolated material strength than by replicability combined with controlled flexibility. The cases discussed demonstrate that modular systems perform most effectively when standardized structural components establish predictable load paths, while allowing incremental growth and modification without compromising global stability. This balance enables buildings to be assembled, adapted, and repaired efficiently in hazard-prone settings. At the same time, the evidence also indicates clear limitations. Modular systems risk underperforming when introduced without institutional support, workforce training, or alignment with local construction logics. In this sense, modular construction offers a transferable structural language for informal contexts only when its technical logic operates in dialogue with social practices and governance capacity, rather than as a purely top-down solution.

4. Social and Participatory Frameworks

Social structures depend fundamentally on participation and community agency, particularly in contexts where housing evolves incrementally under conditions of uncertainty. In informal settlements, resident engagement operates not merely as a social attribute but as a structural mechanism that directly shapes how buildings grow, adapt, and retain stability over time. Along those lines, self-managed construction has long been understood as a community-shaped practice that embeds technical decisions within everyday routines of cooperation, negotiation, and adaptation. As Fernández-Maldonado and Bredenoord (2010) argue, progressive housing functions precisely because it aligns construction processes with the temporal rhythms and economic constraints of low-income households. This observation is central to the hybrid model advanced in this paper, in which community agency functions as an internal driver of structural safety rather than as a social layer appended after technical design choices have already been fixed.

At the same time, participatory processes do not automatically improve outcomes. Research grounded in participatory approaches consistently indicates that collaboration enhances performance only when it is deliberately structured. Gavin's (2011) Project-Based Learning study at University College Dublin, although developed within an educational setting, provides a useful analytical parallel. His findings indicate that 90% of participants reported improved comprehension through collective problem-solving, while group quality accounted for 23% of performance variance and individual skill for 21%. In that sense, the limitations identified in the study, including uneven contributions and coordination demands, closely resemble the challenges observed in community-led construction. These results clarify a condition often under-theorized in participatory housing discourse. Participation generates resilience only when supported by facilitation, accountability, and shared responsibility, without which incremental processes risk producing cumulative structural inconsistency over time.

Evidence from formal construction management frameworks further strengthens this interpretation. The application of Quality Function Deployment demonstrates that early integration of user input can substantially reduce inefficiencies and downstream corrections. Abdul-Rahman et al. (1999) report reductions of approximately 50% in engineering revisions and design duration, alongside startup cost reductions ranging from 20% to 60% and warranty claim reductions of 20% to 50%. Although derived from formal construction environments, the underlying mechanism is directly transferable to informal housing contexts, where residents simultaneously occupy the roles of users, builders, and long-term maintainers. In such settings, early participation narrows the gap between design intent and lived use, thereby limiting the need for structurally disruptive modifications during incremental expansion.

These dynamics become more visible when situated within broader social and demographic transformations that intensify demand for adaptable housing. Nguyen and Levasseur's (2023) review of 46 studies highlights a growing emphasis on flexibility across assisted living, cohousing, and retirement models. While the demographic context differs from informal settlements, the underlying logic remains consistent. Housing systems that allow occupants to modify space as life circumstances evolve tend to exhibit greater long-term viability. In this regard, participatory environments reinforce adaptability not as an architectural preference but as a resilience requirement embedded in everyday use and long-term occupancy.

Recent shifts in urban spatial use following COVID-19 further underscore this point. Increased remote work and declining office occupancy rates revealed substantial reserves of underutilized urban space. For cities facing land scarcity, these dynamics suggest opportunities for incremental and modular interventions when repurposing is guided by participatory decision-making rather than centralized redevelopment alone. Similarly, large-scale climate disasters expose the limitations of rigid housing systems. Events such as the 2019 to 2020 Australian bushfires or the 1960 Chilean tsunami illustrate how inflexible construction amplifies displacement. In contrast, participatory responses, including community-driven relocation and adaptive reuse initiatives, demonstrate how social involvement can preserve continuity under conditions of extreme disruption (Anguelovski et al., 2016).

Within this context, integrating modular construction with participatory design and incremental development emerges not as an abstract normative claim but as a conditional strategy for resilience. 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. Adaptability strengthens when housing systems evolve alongside residents' changing needs while preserving affordability and reducing long-term vulnerability (Nguyen and Levasseur, 2023).

The convergence of evidence from diverse contexts supports this synthesis. In rural Colima, Mexico, the adaptation of traditional wattle-and-daub construction into geodesic dome configurations combined seismic performance with climatic suitability and community-led building practices (Ismail et al., 2017). In Pakistan, flat-pack modular housing systems constructed from cold-formed steel and fiber-cement boards enabled rapid post-disaster reconstruction while remaining compatible with local labor capacities (Abdur Rehman, 2024). Additional cases from British Columbia and Cape Town indicate that technical interventions achieve greater effectiveness when validated through participatory processes and multi-institutional coordination (Genik and Chouinard, 2015). Across these examples, innovation succeeds not because of technology alone but because governance structures, environmental constraints, and local agency operate in alignment.

Taken together, these cases point toward a broader conceptual insight. Resilience is inherently contextual, shaped by local hazards, institutional capacity, and cultural practices. Effective strategies merge technological development with social and environmental adaptation rather than treating them as separate domains (Green, 2008). Experimental approaches such as iterative prototyping and interdependency mapping further show that resilience emerges through feedback and learning over time rather than through static planning models (Carroll et al., 2023).

For Latin America, the implications are explicit. Hazard-resistant housing must integrate locally available materials with contemporary seismic engineering (Ye et al., 2025), incorporate co-design from the earliest project stages, and treat modularity and incremental development as proactive strategies rather than reactive responses (Lawson and Richards, 2010). Pilot projects should function as living laboratories that support both technical validation and institutional learning (Varela et al., 2022). Through this continuity between local innovation and scientific assessment, resilience can become embedded not only in construction practices but also within governance frameworks.

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 systems evolve into dynamic processes of adaptation rather than static housing products. In this sense, the interaction among participatory governance, modular engineering, and historical awareness defines a resilience paradigm sustained through cooperation, learning, and institutional embedding.

5. Conclusion

The evidence analyzed in this study indicates that the integration of modular construction, participatory design, and incremental housing constitutes a viable pathway for enhancing seismic resilience in informal settlements. This combined approach leverages the structural reliability of prefabricated systems while remaining compatible with the adaptive and incremental construction practices characteristic of resource-constrained communities. From this perspective, resilience must be understood as a dynamic capacity, reinforced through sustained interaction among governance structures, technical systems, and community engagement.

For Latin America, the adoption of hybrid modular–incremental models requires more than the replication of technical prototypes. It demands the institutionalization of participatory frameworks within formal planning processes, alongside the development of financing mechanisms capable of addressing structural safety and social stability simultaneously. Without this institutional embedding, modular innovations risk remaining isolated interventions rather than contributing to systemic risk reduction.

Future research should therefore evaluate hybrid housing communities longitudinally in post-disaster contexts and compare their structural and social performance with conventional reconstruction approaches. Priority areas include the assessment of accessible training programs for informal labor networks, the integration of digital tools such as participatory mapping and GIS-based hazard modeling, and the coordination of seismic design with climate adaptation strategies in multi-hazard regions. Advancing seismic safety in informal urban areas ultimately requires recognizing resilience as both an engineering challenge and a socio-political process, one that depends on deliberate coordination among technical expertise, community capacity, and institutional support to sustain urban stability over time.

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Author Biography

Cinthya Ariana Perez Cornejo is a Peruvian student researcher from Lima, Peru, and an IRIS NextGen Scholar, selected with a full scholarship to the Engineering cohort of Indigo Research. She completed her high school education at Innova Schools, where she developed a strong interest in applying engineering and STEM education to address structural and social challenges in vulnerable urban contexts. Her academic work focuses on modular and resilient housing systems, disaster risk reduction, and the intersection of engineering design with community-based solutions. In alignment with this research, she was recognized as a Young Planet Leaders scholarship recipient for projects advancing climate action and accessible engineering solutions in Latin America. She is also affiliated with the Intinauta Research Center, where she contributes to research on analog habitats, integrating architectural design with mechanical and aerospace principles to study human habitation in extreme and extraterrestrial environments. Through her projects and leadership initiatives, she seeks to bridge technical innovation with inclusive development and long-term urban resilience.

Mentor Contribution Statement

Dr. Devin Carroll served as the author's mentor during the six-week Indigo Research Intensive (IRIS) Engineering cohort in which this manuscript was developed. As part of the program, he delivered instructional sessions on how to approach an engineering research project, including how to analyze peer-reviewed literature and identify a coherent research focus. These sessions included guided discussions on reading and synthesizing academic papers across engineering and interdisciplinary contexts. In addition to group instruction, Dr. Carroll met with the author in limited individual meetings to provide feedback on the emerging research topic and overall direction of the paper. During these meetings, he offered recommendations on how to relate modular construction systems to observed vulnerability patterns in seismic zones in the author's home country, helping to clarify the conceptual linkage between engineering systems and social risk contexts. At the end of the cohort, Dr. Carroll offered high-level comments on the near-final draft, focusing on structure and conceptual clarity. All research decisions and written content reflect the author's independent work.

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