AN ARCHITECTURAL AND STRUCTURAL FRAMEWORK FOR INCREMENTAL HOUSING IN POST-EARTHQUAKE RECONSTRUCTION

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Abstract. Treating emergency shelter and permanent housing as separate operations after natural disasters creates problems related to cost, time, logistics, and household needs. This study examines the incremental housing model from architectural and structural perspectives in earthquake-prone regions. Its theoretical framework draws on John F. C. Turner's conception of housing as a process and N. John Habraken's theories of Open Building and Supports. In view of the risks associated with uncontrolled self-construction in seismic regions, the principle of providing "half of a good house" is reconsidered in relation to technical safety and phased occupancy.

The model combines an engineered core with lightweight, dry-assembled expansion areas that can be completed over time. Basic infrastructure and wet-area connections are incorporated into the core from the outset. The production strategy comprises three stages: an emergency living core, transitional or interim housing, and a permanent dwelling enlarged under controlled conditions. Because the model has not yet been tested in the field, the printing and construction durations stated in this paper are design targets rather than measured results. Safe expansion depends on defining the limits of the structural system at the outset, designing the directions of growth, and regulating user-led modifications through technical guidelines.

Keywords: incremental housing, post-disaster shelter, transitional shelter, three-dimensional concrete printing (3DCP), construction building.

1. Introduction and Theoretical Framework

Providing shelter for large numbers of households within a short period is one of the central challenges of disaster management after major earthquakes (Galindo & Batta 2013; Yonetani 2015). A common sequence begins with tents or tarpaulins, continues with temporary container settlements, and ends with the construction of permanent housing (Bashawri et al. 2014; Bolin & Stanford 1991). Because resources invested in temporary shelter cannot readily be transferred to permanent housing, this linear sequence may duplicate expenditure and delay

integration with permanent reconstruction (Johnson 2007; International Organization for Migration [IOM] 2012). Transporting containers and prefabricated units can be costly. Waste generated after use and prolonged stays in temporary settlements may also hinder recovery (Arslan & Cosgun 2008; Johnson 2007).

The transitional shelter approach anticipates that a unit used during the emergency phase will either become part of a permanent dwelling or be reused elsewhere (IOM 2012). Incremental housing manages this transition by allowing the initial unit to grow according to predefined rules. Turner (1972, 1976) defines housing as a process shaped by residents over time rather than as a finished product. This approach enables households to participate in housing production, but in earthquake-prone areas such participation must proceed under engineering supervision (Greene & Rojas 2008; Mota 2021).

The structural division within incremental housing can be explained through Habraken's theories of Open Building and Supports (Habraken 1972, 2021). In this framework, the dwelling consists of two layers:

The support structure, or primary structure, is the engineered system that defines property boundaries and the principal spatial arrangement, carries service lines, and provides structural safety.

The infill, or secondary system, comprises lightweight partitions and supplementary components that occupants can alter in response to their needs and financial means (Habraken 1972, 2021; Jokar & Khakzand 2026; Türkmen & Yıldız 2026).

Brand's (1994) concept of building layers with different service lives, together with Schneider and Till's (2007) distinction between fixed structural and service components and adaptable partitions, can be used to define the limits of incremental growth. In seismic regions, the primary structure should determine the location of subsequent additions and their load paths. Machado's (1976) distinction between a host structure and added components provides a further framework for understanding this relationship (Jokar & Khakzand 2026; Türkmen & Yıldız 2026).

Accordingly, the theoretical framework establishes that post-earthquake incremental housing should be conceived not as a sequence of disposable shelters but as a controlled process in which a permanent structural core supports safe, user-led adaptation over time.

2. Architectural Organization and Built Examples of Post-Disaster Incremental Housing

Incremental housing does not mean delivering a fully finished small dwelling that can simply be enlarged later (Wainer et al. 2016). Under the "half of a good house" approach, the

initial investment is directed toward components that residents cannot safely construct on their own, including site infrastructure, the earthquake-resistant primary structure, vertical circulation, and service shafts (Aravena & Iacobelli 2012; Boano & Vergara Perucich 2016; Türkmen & Yıldız 2026). The process includes land acquisition, construction of the initial core, and planned stages of expansion (Marinovic 2020a 2020b).

The initial core contains a kitchen, bathroom, and minimum living or sleeping space (Azizibabani & Bemanian 2019; Greene & Rojas 2008; Marinovic 2020a; Türkmen & Yıldız 2026; Wainer et al. 2016). Arranging wet areas around a shared shaft or back-to-back in adjoining units can reduce service runs and related costs (Wainer et al. 2016). The relationship between this arrangement and the structural system must be resolved for each project.

Expansion voids are volumes defined in the initial design that establish the location and dimensions of future additions (Türkmen & Yıldız 2026). At Quinta Monroy, these voids were left between masonry or reinforced-concrete boundaries and floor lines. Additions could therefore occur within designated volumes rather than spreading beyond the plot (Türkmen & Yıldız 2026).

An incremental dwelling can expand inward, outward, or upward. Inward expansion occurs when an initially unfinished volume is completed later; outward expansion occupies a predefined area beside or behind the dwelling; upward expansion adds one or more storeys (Kamalipour & Dovey 2020). The suitability of each strategy depends on plot dimensions, density, structural capacity, access, daylight, ventilation, fire safety, and escape routes (Alexander et al. 1985; Greene & Rojas 2008; Türkmen & Yıldız 2026).

2.1. International Examples of Incremental Housing

PREVI Experimental Housing

PREVI Lima was an experimental housing program conducted by the United Nations and the Government of Peru between 1968 and 1975. As an alternative to high-rise mass housing, the program developed a low-rise, high-density settlement pattern. The structural system and service infrastructure were installed at the outset, while courtyards and growth areas were reserved for later horizontal and vertical additions. Pedestrian routes, shared open spaces, and graded privacy within the plots formed part of the settlement layout. The subsequent transformation of PREVI provides evidence for examining how effectively the original design guided user-led modifications (Aravena & Iacobelli 2012; Greene & Rojas 2008).

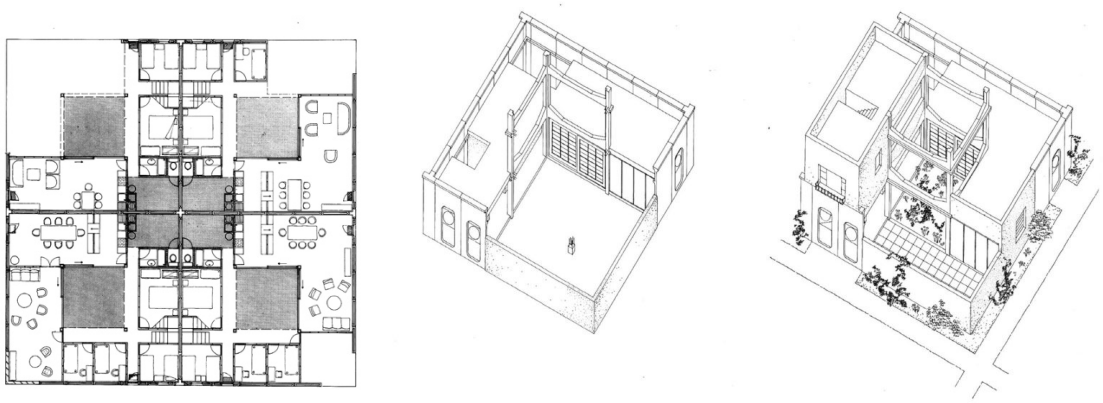


Fig. 1-2-PREVI Incremental Housing. Source: https://hiddenarchitecture.net/previ-low-cost-housing-i/

Belapur Incremental Housing

Designed by Charles Correa in Navi Mumbai between 1983 and 1986, the Belapur settlement consists of low-rise, high-density housing clusters. Each household plot permits horizontal or vertical expansion without encroaching on adjacent properties. The relationship between the dwelling, courtyard, terrace, and veranda establishes a sequence of open spaces extending from the private family courtyard to a shared space enclosed by seven or eight dwellings and then to the main pedestrian spine. The use of accessible techniques, including local brick, render, and traditional roof construction, made it easier for households to undertake later additions. For the present study, Belapur is significant because it integrates the right to expand with the design of shared open spaces (Azizibabani & Bemanian 2019).

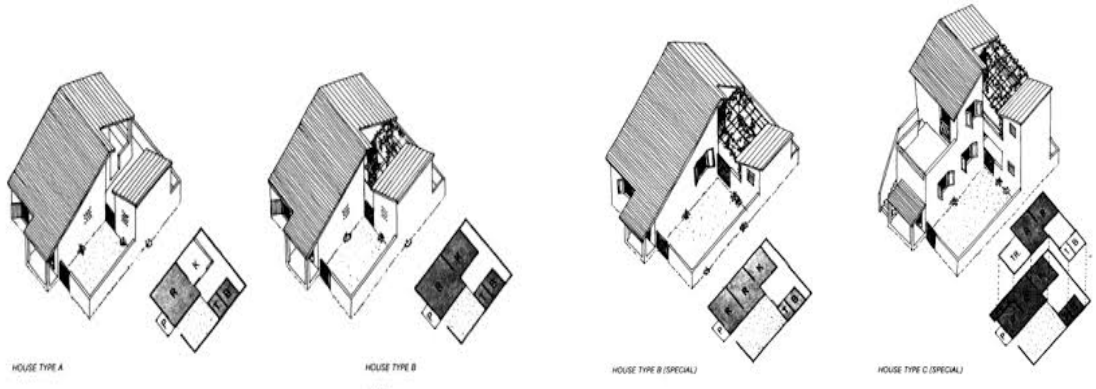


Fig. 3- Belapur Incremental Housing Project (https://hiddenarchitecture.net/belapur-housing/)

Quinta Monroy

Quinta Monroy, completed by Elemental in Iquique, Chile, in 2003-2004, sought to rehouse inner-city households on the same site with limited public funding. Rather than financing a complete but very small dwelling, the budget was directed toward technical components such as the structural system, service core, roof, and vertical circulation. Defined voids for later construction were left beside the ground-floor units and upper-level duplexes. Residents were expected to build their additions within these areas. The project's transformation over time permits examination of both controlled growth and problems associated with overbuilding and construction oversight (Aravena & Iacobelli 2012; O'Brien et al. 2020).



Fig. 4-5-6- Quinta Monroy Project (https://www.archdaily.com/10775/quinta-monroy-elemental)

Villa Verde Post-Disaster Reconstruction

Villa Verde was designed by Elemental in Constitución, Chile, after the 2010 earthquake and tsunami and was completed in 2013. Units delivered at approximately 57 m² were designed to expand to about 85 m² by occupying a reserved volume. The shared roof and structural bays were built during the first phase, and user-led additions were confined within these limits. The project used timber framing and dry-construction components. Villa Verde is a built example through which the technical relationship between the initial structure and later household additions can be examined in post-disaster housing (Carrasco & O'Brien 2022; O'Brien et al. 2020).



Fig.7-8 Villa Verde Project https://www.re-thinkingthefuture.com/case-studies/a7429-villa-verde-project-by-alejandro-aravena-low-cost-housing/

2.2. Rapid and Robotic Production of Post-Disaster Cores

Three-dimensional printing projects associated with post-disaster shelter have reached different levels of development. Some are completed dwellings, while others remain designs or prototypes for emergency shelter. An industry report published in 2015 stated that INNOprint 3D aimed to print an emergency shelter measuring approximately 3 x 3 x 3 m in 20-30 minutes (www.3DPrint.com, 2015; Nantes Université, 2015). The report does not establish that the structure was deployed at a disaster site or that its insulation and occupancy conditions were validated. The stated duration also concerns printing alone. Foundations, reinforcement, roofing, openings, insulation, services, curing, and site infrastructure must be added when calculating total delivery time.

The Serendix Sphere prototype developed in Japan has an area of approximately 10 m². Designboom reported that production and assembly were completed in 23 hours and 12 minutes at a cost of approximately JPY 3 million, or USD 25,000 at the time (Neira, 2022).These figures concern a rapid-production experiment. They do not demonstrate that the prototype was used for post-disaster emergency shelter or that independent testing verified the seismic and wind performance attributed to its spherical form.



Fig. 9- Serendix Sphere (https://cloudsao.com/SERENDIX-SPHERE)

In the Nacajuca project in Tabasco, Mexico, it was used in an affordable housing program developed with New Story and local partners. Approximately 24 hours of active machine time was reported for printing the walls of each unit, which has an area of about 46.5 m² (Subramanya & Kermanshachi 2022). This figure is not the total construction period, because it excludes the foundation, roof, doors and windows, services, and finishes. Nacajuca is a completed social housing project; it was not classified as an emergency settlement erected immediately after a specific disaster.



Fig.10 World Housing. 3D Home Community, Nacajuca, Mexico.
(https://worldhousing.org/communities/3d-home-community-nacajuca-mexico/)

Taken together, the cases show that neither incremental precedents nor rapid-printing demonstrations constitute ready-made post-disaster solutions; their transferable value lies in defining a serviced initial core, reserved growth zones, and verifiable limits for later additions

3. Structural and Technical Design Principles for Seismic Regions

In post-disaster reconstruction, adopting an incremental housing strategy in seismic zones necessitates reconciling two conflicting dynamics: accommodating the architectural flexibility of phased occupant growth while maintaining uncompromised structural integrity under cyclic earthquake loads. Unregulated self-construction in earthquake-prone regions typically results in severe structural deficiencies, including undersized column sections, omitted tie beams, soft-storey formations, and unengineered vertical additions that drastically compromise structural ductility. To prevent incremental modifications from escalating into cumulative seismic vulnerabilities, the primary load-bearing infrastructure—the "support" or "host" core—must be rigorously decoupled from subsequent secondary additions through predefined engineering boundaries and tectonic hierarchies. Within this framework, seismic resilience is governed by the structural hierarchy established between the core and the infill: the initial foundation and core must be engineered to withstand the gravity and lateral load combinations of the fully expanded building, horizontal growth patterns must be prioritized to avoid torsional irregularities, and subsequent domestic infill must rely strictly on lightweight, dry-assembly construction methods. Accordingly, the following subsections delineate the technical criteria for integrating advanced on-site production, geometric growth limitations, and seismic-resistant material systems into an incremental post-disaster framework.

In uncontrolled additions in earthquake-prone areas, inadequate foundations, undersized columns, missing tie beams, and later vertical extensions increase structural risk (Greene & Rojas 2008; Jokar & Khakzand 2026; SPARC 2013). Applying incremental housing therefore requires the limits of the initial structural system and subsequent additions to be defined through architectural and earthquake-engineering criteria.

3.1. Robotic and Extrusion-Based On-Site Systems

Containerized or mobile three-dimensional printing systems allow printing equipment to be transported to a disaster area (Hager et al. 2016; Subramanya & Kermanshachi 2022). On-site production speed nevertheless depends on access to energy and water, mix constituents, technical personnel, foundation preparation, climate, and transport conditions (Le et al. 2012;

Subramanya & Kermanshachi 2022). Portability alone does not establish that a structure can be made ready for occupancy within a short period.

Serendix and the Almaty house are completed examples of three-dimensional printed housing. Nacajuca is a settlement project implemented as social housing. Together, these cases show that printing technology can be used at different scales. Post-disaster delivery time, seismic safety, and suitability for incremental expansion require separate technical testing and occupancy data for each project.

Alongside cement-based printable mortars, researchers are investigating printable cob and other earth-based mixtures containing fibrous constituents (Gomaa et al. 2021; Perrot et al. 2018). Existing studies do not by themselves establish comparative advantages in cost, carbon impact, or structural safety for post-disaster housing. A mixture intended for disaster housing should be selected on the basis of printability, strength, water and fire performance, local availability, and test results.

3.2. Structural Limits of Horizontal and Vertical Growth

Horizontal additions generally introduce less additional mass than adding a storey to the structural system. Their position may nevertheless alter the centers of mass and stiffness, so torsional irregularity must be checked in the structural analysis (Jokar & Khakzand 2026; Türkmen & Yıldız 2026). Low-rise layouts and predefined lateral expansion areas are therefore common in incremental housing projects (Azizibabani & Bemanian 2019; Greene & Rojas 2008).

Vertical expansion can provide additional floor area where land is limited (Nohn & Goethert 2016). Later storeys may, however, exceed the capacity of the existing structure and increase seismic risk (Greene & Rojas 2008). The number of storeys and additional loads should be calculated in the initial design, and lightweight steel, timber, or panel systems should be considered for upper floors (Mota 2021; Türkmen & Yıldız 2026; Wainer et al. 2016). In attached buildings, separate structural grids and adequate joint widths should be determined through engineering calculations that account for pounding risk (Lizarralde 2011).

3.3. Material Selection and Dry Assembly

Light timber, light-gauge steel, and dry-board systems can limit the loads imposed on the existing structure by later additions (Marinovic 2020a; O'Brien et al. 2020). Off-site manufactured modular components can facilitate construction oversight when their connections are defined in advance. The timber frame used at Villa Verde provides field experience of

accommodating user-led additions through a lightweight system. It does not, however, show that every addition built by unskilled labor is safe. Materials, connections, and workmanship require inspection (Carrasco & O'Brien 2022; O'Brien et al. 2020).

In seismic regions, the weight of an infill wall and its connection to the primary structure cannot be separated from material selection. When correctly detailed, interlocking modular blocks and lightweight dry panels may provide alternatives to heavy, uncontrolled masonry additions (Alexander et al. 1985; Türkmen & Yıldız 2026). The combination of steel sections and brick vaults at Narmak is a historical example of a hybrid system (Mota & Haileselassie 2021). The seismic behavior of stabilized earth blocks with reinforced-concrete tie beams must be verified in relation to block strength, tie-beam layout, connections, and construction quality.

The technical analysis therefore indicates that seismic safety depends on treating the printed core, lightweight additions, and their connections as a single engineered system whose geometry, mass distribution, and material performance are verified before construction.

4. An Incremental Housing Production Strategy for Disaster-Affected Areas

This paper uses a three-stage design framework. The first stage is a minimum living core that provides emergency protection. In the second stage, the services and occupancy conditions required for transitional or interim housing are completed. In the third stage, the dwelling expands within predetermined limits in response to household needs. These stages are not universal time categories. Safety, infrastructure, and occupancy criteria must be assessed for each project.

The proposal treats three-dimensional printing as one possible method for producing a service-intensive initial core, not as a means of manufacturing the entire dwelling in a single operation. Limiting the printed portion to a standard module could allow the remaining areas to be completed with lightweight systems suited to local conditions. The proposal has not yet been validated through a prototype, field trial, or comparative cost and time data.

The first stage proposes a core of approximately 28 m². It contains the bathroom, toilet, kitchen connections, and a minimum living area. The 18-24-hour period shown in Table 1 represents the active printing time assumed during preliminary design. It excludes foundations, reinforcement, connections, roofing, openings, services, insulation, and curing. The figure should therefore not be read as the time required to deliver a shelter ready for occupancy and must be tested through prototype production.

Using printable mortar as a structural core depends on verifying the reinforcement layout and wall-to-floor connections through seismic analysis and testing. Constructing later rooms with lightweight timber, light-gauge steel, or panel systems assembled by dry methods is intended to reduce the additional load on the initial structure (Asprone et al. 2018). Connection performance, fire safety, moisture, and maintenance requirements must also be assessed for the selected system.

Anchor pockets or mechanical connection recesses can be formed during printing for lightweight components added later. Their tensile and shear strength, response to cyclic seismic loads, waterproofing, and maintenance requirements must be determined through testing. The connections proposed in this study are subjects for prototype development, not validated standard details (Asprone et al. 2018; Marchment & Sanjayan 2020).

The spatial program should consider both minimum humanitarian standards and the spatial requirements of a dwelling. The Sphere Handbook recommends at least 3.5 m² of covered living space per person, rising to 4.5 m² in cold climates (Sphere Association 2018). For a household of four or five people, this corresponds to 14-17.5 m² and cannot be treated as a permanent housing standard. The 28 m² proposed for Phase 1 is a design decision intended to accommodate living space, wet areas, and circulation within the same core. Adding 16 m² in Phase 2 and 25 m² in Phase 3 to reach a total of 69 m² is also a proposal developed in this study. Neither these areas nor the durations in Table 1 are measured implementation data.

Table 1. Proposed Stages of Incremental Housing Production for Disaster-Affected Areas

Parameter	**PHASE 1**	**PHASE 2**	**PHASE 3**
Area (m²) and typology	Emergency living core 28 m²	44 m² One-bedroom dwelling	69 m² Two-bedroom dwelling
Construction system and material	Three-dimensional concrete printing Proposed core system	Lightweight frame and dry assembly Timber or steel sections and panels	Supervised user-built additions Local materials and lightweight panels
Proposed duration (estimate; active printing stated separately)	Target of 18-24 hours of active printing*	Estimated construction period of 2-3 days*	Estimated construction period of 1-2 weeks*

Spatial and structural function	Wet areas and minimum living space Proposed structural core Connection points for later additions	16 m² additional room Initial area allocated to shared living Greater household privacy	25 m² additional room and veranda Completion of permit and inspection procedures Total area reaches 69 m²

* All durations are estimates within the conceptual production scenario developed in this study; they are neither measured total construction periods nor ready-for-occupancy delivery times.

4.1. User Participation and Construction Oversight

The safety of user-built additions in earthquake-prone areas depends on enforcing throughout construction the rules established at the beginning of the project (Aravena & Iacobelli 2012; Greene & Rojas 2008; Marinovic 2020a 2020b; Türkmen & Yıldız 2026). Oversight can be organized in three areas:

Participatory preliminary design. Before the primary structure and expansion areas are defined, the spatial priorities and financial means of households, together with local labor capacity, should be assessed (Aravena & Iacobelli 2012; Azizibabani & Bemanian 2019).
Construction manual. The technical document supplied with the dwelling should identify the limits of additions, permitted connections, and acceptable materials (Aravena & Iacobelli 2012; Marinovic 2020a 2020b; Türkmen & Yıldız 2026). The templates prepared for Lo Espejo and Las Higueras define dry-assembly components, insulation thickness, and the limits of garden-side expansion (Marinovic 2020a). The manual should also prohibit heavy masonry additions, cutting structural members, and using heavy materials not anticipated in the design (Greene & Rojas 2008; Marinovic 2020b; Türkmen & Yıldız 2026).

Legal and financial arrangements. Planning regulations should define the property boundaries, permit stages, and inspection responsibilities for later additions. Infrastructure investment and microfinance instruments need to be addressed within the same program so that low-income households can complete the planned stages of growth (Greene & Rojas 2008; Türkmen & Yıldız 2026; Wakely & Riley 2011).

4.2. Implementation Constraints

Regulation and oversight. Limited technical knowledge, construction costs, and lengthy permit procedures may lead residents to bypass approval and inspection stages (Asibey et al. 2025).

Loss of open space. Unplanned additions that enclose courtyards and gardens may reduce ventilation and obstruct escape routes, making fire safety and post-earthquake evacuation more difficult (Carrasco & O'Brien 2022; O'Brien et al. 2020).

Multi-storey growth. Upper-floor additions require closer control of materials and workmanship. Alterations made without knowing the capacity of the existing structural system present greater risk than single-storey horizontal additions (Greene & Rojas 2008; Marinovic 2020b).

Economic access. As the Millard Fuller Foundation case in Nigeria demonstrates, formalized incremental housing programs may still fail to reach households with limited ability to pay (Nwachukwu et al. 2025). The cost of the initial unit and the financing of later stages must be considered together.

Land and infrastructure. Incremental housing is not a construction method based solely on household labor. Access to land, finance, infrastructure, material supply, and labor must be addressed within a single implementation program (Friendly 2025; van Noorloos et al. 2020).

The transition from emergency shelter to permanent housing takes time and requires coordination among several institutions (IOM 2012; Subramanya & Kermanshachi 2022). A three-dimensional printed core should therefore not be treated as a ready-made product that resolves this transition on its own. The use of a mobile printer depends on transport, energy, water, materials, specialist personnel, and maintenance capacity. Because these conditions differ between urban and rural settings, the production system should be selected according to local resources (Hager et al. 2016; Subramanya & Kermanshachi 2022). Claims that earth- and fiber-based mixtures offer lower costs or environmental impacts require comparative tests and life-cycle data.

Consequently, the proposed three-stage strategy is feasible only when rapid core production is coupled with predefined expansion rules, lightweight construction, continuous inspection, and coordinated access to land, infrastructure, finance, and skilled support.

Conclusion

The incremental housing model proposed in this study treats the emergency shelter unit as the initial part of a permanent dwelling rather than a structure that will later be abandoned.

The structure and services of the initial core are completed under engineering supervision, while household additions are built within reserved areas and through defined connections. Construction speed is not the model's sole criterion. Structural safety, continuity of water and energy services, oversight of additions, and household access to finance must be secured together.

Three-dimensional printing is one method that may be considered for producing the initial core (Habraken 1972, 2021; Subramanya & Kermanshachi 2022). Active printing time and ready-for-occupancy delivery time must be calculated separately. Structural behavior, material properties, connections, and the post-earthquake operation of services should be measured through prototype and field testing. Lightweight dry-assembly systems may be used in later stages, while the user manual should identify permitted additions and inspection points (Marinovic 2020a; O'Brien et al. 2020). Pilot studies covering different household sizes and local construction conditions are needed to test the model's feasibility.

Ultimately, this study demonstrates that resolving the post-disaster shelter crisis requires moving beyond the false dichotomy between temporary relief and permanent reconstruction. By integrating advanced automated fabrication—such as 3D concrete printing—with participatory, dry-assembly expansion strategies, incremental housing redefines the emergency unit not as disposable building waste, but as the permanent seismic and infrastructural backbone of the home. However, the viability of this model hinges on treating architecture not merely as a formal or technical exercise, but as an integrated socio-spatial and regulatory process. Bridging the gap between technological innovation and grass-roots implementation will necessitate institutional adaptability: local authorities and disaster agencies must enact flexible planning instruments, such as phased permitting and incremental building codes, underpinned by visual, user-oriented construction manuals. Whether deployed in dense urban footprints or distributed rural communities, confining user agency within an unyielding engineering framework provides a viable pathway toward equitable, cost-effective, and seismically resilient post-disaster habitats.

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