Resilient Modular Shelter for a Changing Climate

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Abstract. Climate-driven disasters are increasing in frequency and intensity, underscoring the need for shelters that combine rapid deployability, structural durability, and sustainability. This paper presents a modular shelter system designed for quick deployment and operability across diverse climates. Structural performance is optimized by coupling topology-optimization workflows with additive manufacturing, which simultaneously reduces material usage and component weight. To minimize environmental impact and construction time, the system employs reusable molds in conjunction with locally available construction materials. The shelter's load-bearing capacity and serviceability were evaluated through scaled-prototype experiments that simulated wind and seismic demands. Results confirm adequate strength and stiffness for emergency occupancy while preserving flexibility for post-disaster reconstruction scenarios. The proposed solution advances a climate-adjustable, resource-efficient shelter that integrates emergency response needs with longer-term rebuilding requirements.

Keywords: human shelter, post-disaster, topology optimization, additive manufacturing, mold design

1 Introduction

Over recent decades, the frequency and intensity of climate-driven disasters have escalated, repeatedly triggering large-scale humanitarian crises that disproportionately affect vulnerable populations [1,2]. While access to food, water, healthcare, and psychosocial support can often be scaled through logistics and staffing, shelter remains persistently challenging. Housing responses must negotiate the temporary–permanent continuum, storage and transport constraints, on-site constructability by semi-skilled teams, and stringent sustainability requirements, factors that complicate procurement, deployment, maintenance, and lifecycle performance [3–5]. These pressures are amplified in protracted emergencies, where displacement frequently extends beyond a single season, exposing occupants and structures to multiple hazard cycles (windstorms, aftershocks) and diverse climatic stresses (heat, cold, humidity).

A wide spectrum of shelter modalities exists, family tents, plastic sheeting and kits, prefabricated units and containers, lightweight dwellings, cash/rent support, and rehabilitation programs. Yet solutions optimized primarily for low cost and speed, such as tents, tarpaulins, and basic prefabricated units, frequently underperform on durability and resilience when occupancy extends beyond a year or when exposure to wind and seismic hazards is nontrivial [6–8]. Common gaps include limited structural capacity and stiffness, poor thermal performance leading to heat stress or inadequate winterization, low reparability, and weak pathways for adaptation as needs evolve from emergency relief to early reconstruction.

This paper investigates a rapid-deployment, modular shelter that is climate-adjustable and resource-efficient. The concept couples topology optimization with additive manufacturing (AM) to concentrate material where it carries load, thereby reducing mass and embodied material while preserving or improving structural performance. To minimize environmental impact and construction time, the design integrates reusable molds compatible with locally available materials (e.g., earth- or cement-based mixes, bio-aggregates), enabling on-site casting of standardized components and facilitating repair or replacement with locally sourced inputs. The modular kit supports configuration flexibility (plan expansion, connection details) and climate adjustability through interchangeable elements (vents, shading/baffles, insulation layers) that can be tuned for hot-arid, hot-humid, or cold conditions without replacing the primary structure.

We articulate five design objectives that guide the system: (i) Rapid deployment with minimal tools and training; (ii) Multi-hazard resistance (wind and seismic serviceability/strength for emergency occupancy); (iii) Climate adjustability via passive measures (ventilation, shading, insulation) integrated into the kit-of-parts; (iv) Circularity and material efficiency, achieved by optimization-driven geometry, reusable molds, and local materials; (v) Upgrade path from immediate shelter to early reconstruction, enabling component reuse and incremental improvement of habitability.

This work offers: A modular, climate-adjustable shelter concept integrating topology optimization, AM, and reusable molds into a coherent design-for-deployment workflow; A design-for-fabrication methodology that aligns optimization outputs with moldable geometries and local material constraints to simplify on-site making; Experimental validation through scaled-prototype testing under simulated wind and seismic demands, evidencing adequate strength and stiffness for emergency occupancy; A practical transition strategy that links emergency response to reconstruction by enabling repair, retrofitting, and scaling without discarding core components.

Section 2 presents the architectural concept, the topology-optimization workflow, the structural design and reinforcement strategy, and the mold design. Section 3 details the prototype's design and fabrication, including assembly sequencing and field-relevant logistics. Sections 4 and 5 provide conclusions and discussion, respectively, with reflections on operational deployment, environmental implications, and avenues for future work.

2 Shelter Design Framework

2.1 Concept and Architectural principles

2.1.1 Concept

The shelter system is organized around a modular cubic unit measuring 3.10 × 3.10 × 2.40 m (L×W×H). Units assemble on a 3.10 m orthogonal grid, enabling fast layout decisions, predictable logistics, and clear separation between private (enclosed modules) and shared (inter-module) spaces. At the construction site, 3D-printed molds are fabricated and used to cast standardized components. The molds are stackable and reusable, sized for palletized transport, and designed to nest for compact storage, together enabling rapid deployment and efficient redeployment across sites [9,10].

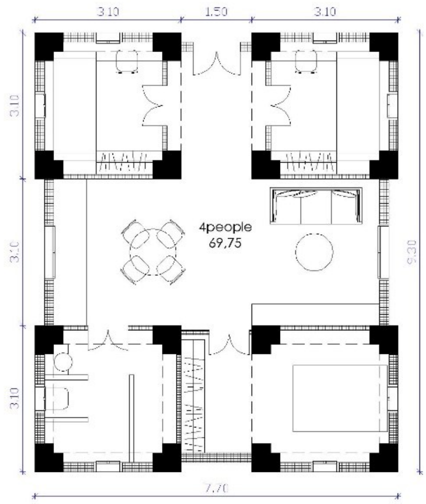

Fig. 1. Four-module shelter unit. Axonometric view: two enclosed bedrooms, one service module, one flexible module; central 3.10 m semi-open bay with shading

2.1.2 Architectural principles

1. **Modularity & scalability.** Modules can be added, subtracted, or re-arranged to respond to changing occupancy and programmatic needs, from nuclear families to community pods (health, education, shared services).
2. **Spatial legibility.** A 3.10 m grid structures both the enclosed volumes and the semi-open interstitial zones (nominally one grid bay), which support day uses (cooking, washing, shaded gathering) while preserving privacy for sleeping and caregiving.
3. **Climate adjustability.** The kit-of-parts includes interchangeable elements, ventilation panels, shading baffles, and insulation layers, that can be tuned for hot-arid, hot-humid, and cold conditions without replacing the primary structure.

4. **Material pragmatism.** Reinforced concrete is selected for its form freedom, robust mechanical performance, and durability under multi-hazard exposure. The system intentionally integrates local materials for roofing, wall infill, and flooring, e.g., timber or light-gauge metal for roof frames, locally sourced aggregates or earthen mixes for infill, and compacted soil or lime-stabilized screeds for floors, thereby lowering cost and environmental footprint while improving repairability [11–13].
5. **Design for deployment.** Molds double as logistical assets: they are dimensioned for standard truck beds and ISO pallets, permit on-site casting with locally available mixes, and can be reused to scale production or fabricate replacement parts, reducing waste across the shelter's lifecycle [9–13].
6. **Hazard-aware geometry.** Module corners and lintels are thickened/filleted to reduce stress concentrations; reinforcement is concentrated at connections and openings identified by the optimization workflow (Section 2.2). The resulting components balance strength-to-weight with constructability.

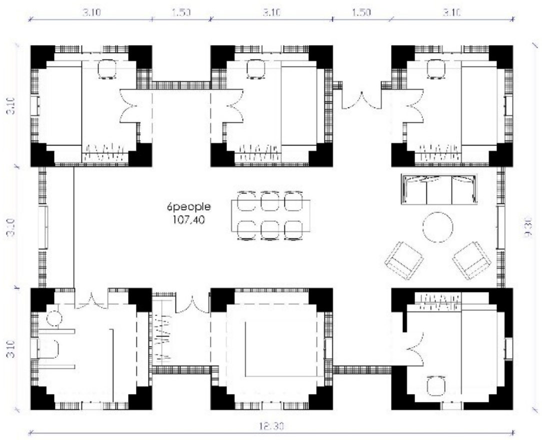

Fig. 2. Six-module family layout. Plan and section showing added living/dining module and improved cross-ventilation paths

2.1.3 Dimensional system

Each unit's plan footprint is $3.10 \times 3.10 = 9.61$ m^2. Assemblies of *N* modules provide an enclosed area $A_{enclosed} \approx 9.61 \times N$ m^2, excluding semi-open bays. Inter-module shared bays are typically one grid square (≈ 9.61 m^2) per gap in the chosen layout, supporting cooking, circulation, and shaded living.

2.1.4 Programmatic configurations

- **Four-module configuration.** Provides two enclosed sleeping modules and two shared/service modules (e.g., storage, hygiene), plus a central/semi-open bay, appropriate for small nuclear families (see Figure 1)

- **Six-module configuration.** Adds enclosed living and service capacity for larger or multi-generational families, improving thermal zoning and privacy (see Figure 2)
- **Eight-module configuration.** Enables specialized zoning for health-care and education pods alongside extended-family living or community support functions; suitable as a neighborhood node (see Figure 3)

Table 1. Typical module configurations and uses (enclosed area only*)

Configuration	**$A_{enclosed}$ (approx.)**	**Typical occupants**	**Primary functions**	**Figure**
Four-module	≈ 38.44 m²	3–5 persons	2 sleeping rooms; storage; hygiene; semi-open day space	1
Six-module	≈ 57.66 m²	5–8 persons	+ living/dining; enhanced privacy; expanded storage	2
Eight-module	≈ 76.88 m²	8–12 persons or community pod	+ clinic/education pod; service core; covered courtyard	3

*Excludes semi-open inter-module bays (≈ 9.61 m² each), which vary by layout

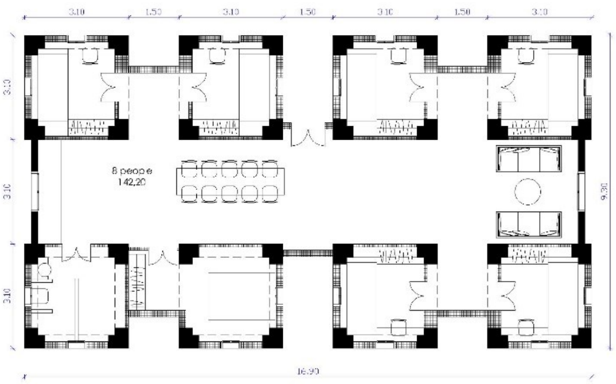

Fig. 3. Eight-module community node. Diagram illustrating healthcare/education pod + extended-family zone, covered courtyard, and circulation

2.2 Topology Optimization

The basic objectives of shelter design can be achieved through topology optimization which simultaneously helps reduce CO2 footprints and reduces costs [14]. Topology optimization uses a process to optimize structural stiffness while reducing the design domain volume. The method works by dividing the design space into elements before performing an iterative process that removes and rearranges materials using an objective function with finite element analysis [15,16]. The procedure stops at a final geometry that shows an unconventional shape which standard construction techniques find difficult to build.

$$\min_{x_i \in \Omega} C = \frac{1}{2} U^T K U$$

$$subject\ to: KU = F$$

$$\sum u_i x_i \leq V^*$$

$$x_i \in [0,1]$$

where C denotes the compliance of the structure, K is the global stiffness matrix, U is the nodal displacement vector, F is the external load vector, xi is the binary design variable indicating the presence (1) or absence (0) of material at element i, vi is the volume of each element, V ∗ is the allowable material volume, and **Ω** is the design domain

To implement this type of optimization as a four-wall structure, with no bottom and top surface, measuring 3100 × 3100 × 2400 mm^3, with 400 mm uniform wall thickness. The Ameba [17] plug-in for Grasshopper [18] was used for topology optimization. Ameba is based on the Bidirectional Evolutionary Structural Optimization (BESO) [19] algorithm, which incrementally evolves the geometry by iteratively removing inefficient material.

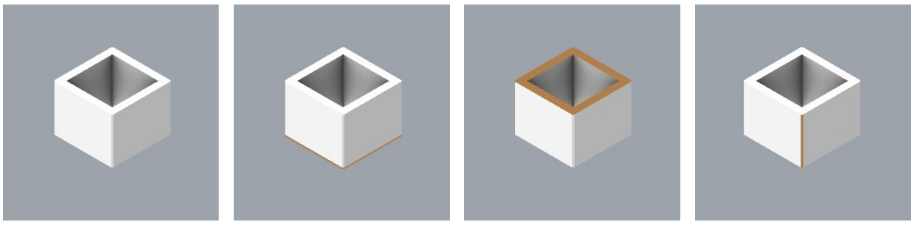

Fig. 4. From left to right: (a) the four-wall design domain, (b) base constraints, (c) linear distributed load, (d) pseudo-static seismic load

The base of the walls was constrained by applying boundary conditions. The simulation involved two load conditions: (1) a uniformly distributed vertical roof load applied across the top edges of the four walls of 2,15 KN/m^2; and (2) a diagonal pseudo-static force mimicking seismic activity applied to a selected edge. Reinforced concrete attributes were assigned as material properties, specifically using appropriate Young's modulus and Poisson's ratio values.

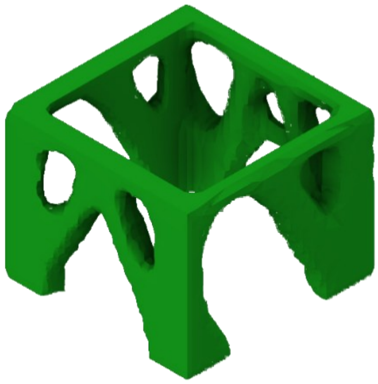

Fig. 5. Optimized Structural Module

The domain received its 3D Delaunay finite element triangulation through 58,277 mesh elements. The algorithm maintained structural significant areas at 40% target volume. Through topology optimization users achieve better structural strength while optimizing material use and design freedom because they can create shapes that traditional construction methods cannot produce.

2.3 Reusable Mold Design: Integrating T.O with Additive Manufacturing

Topology Optimization leads to geometries that are almost impossible to build by conventional means. By integrating the use of topology optimization and additive manufacturing presents substantial opportunities in emergency construction. Topology optimization allows computationally driven material distribution to produce structurally efficient, lightweight forms by eliminating unnecessary material while preserving strength.

Additive manufacturing, which fabricates components layer-by-layer directly from digital models, enables the realization of these complex geometries with minimal waste. The combination of these methods results in significant reductions in raw material usage, energy consumption, labor intensity, and project timelines, offering an innovative, sustainable and cost-effective [20] alternative to conventional construction methods.

In emergency situations, electric power is a valuable resource, making it challenging to 3D print concrete structures directly on-site [21, 22]. To overcome this, we propose using pre-printed molds made from PET-G or PLA materials [23]. These molds are much easier to transport and allow for on-site concrete casting using only human labor. Essentially, rather than printing the final optimized structure, a reusable mold will be printed instead. [24, 25, 26].

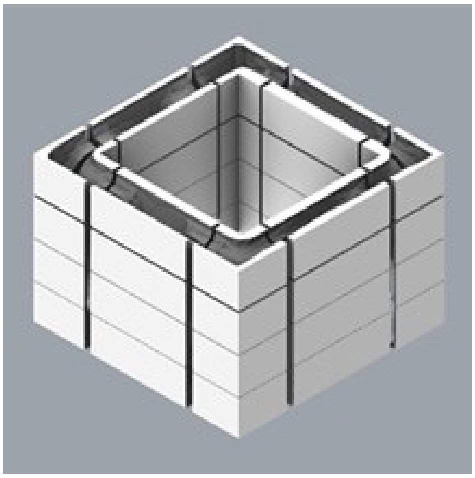

Fig. 6. The designed mold with the vertical and horizontal

The final optimized shape became a mold template which measured 3.30 x 3.30 x 2.40 meters with 0.75 units of consistent thickness. The complex shape underwent horizontal segmentation to produce four separate layers. The eight individual parts consisted of four corner sections together with four middle sections which divided each layer. A sixteen-part mold system needs precise assembly to replicate the optimized geometry of the structure.

The placement of vertical cuts in each layer helped minimize double curvature problems to make manufacturing and construction easier. The system of overlapping overhangs created at vertical and horizontal interfaces ensured accurate shaping and seamless assembly of the mold components. The mold received structural reinforcement through precise design of transverse setscrews and vertical hinges which maintained stability throughout material introduction.

2.4 Structural Analysis

Concrete and its tensile weakness challenge the traditional precast construction methods. This is particularly true for large, unreinforced pieces, where the process of casting horizontally and then flipping vertically is labor-intensive and risky. Even though the module's volume initially implied the necessity of reinforcement, we conducted a Finite Element Analysis (FEA) to understand its stress behavior.

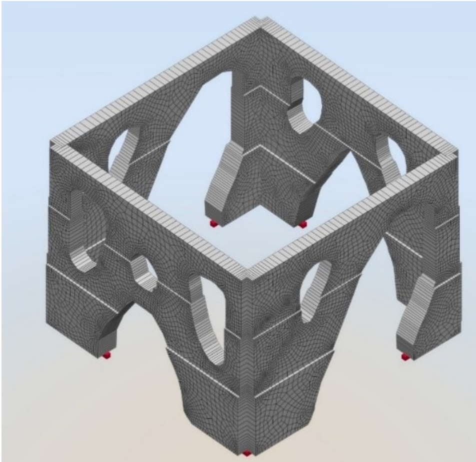

Fig. 7. Model in SOFiSTiK

SOFiSTiK [27] software is used to examine the structural behavior of the optimized geometry. The 3D model of the structure was developed within the Sofiplus graphical environment, utilizing the provided .fbx and .sat geometry files as the basis for model generation. The block was vertically subdivided into three sections, with each level exhibiting a reduction in width from bottom to top to reflect the actual geometry.

The applied loads were defined as follows:

- Dead Load: 1.20 kN/m² (uniformly distributed on the top surface)
- Live Load: 1.55 kN/m² (uniformly distributed on the top surface)
- Seismic Loads: Horizontal seismic actions were considered in both principal directions (EQx and EQy), acting on the lateral faces of the structure

Seismic load calculations and combinations were carried out in accordance with EN 1998-1 (Eurocode 8) [28] for the design of structures for earthquake resistance. The seismic base shear was determined using the general design spectral acceleration expression:

$$\mathrm{Sd(T)} = \mathrm{a} \cdot \gamma\mathrm{I} \cdot \mathrm{S} \cdot \eta \cdot \frac{q}{2.5}$$

Where a=0.16g: design ground acceleration, γ: importance factor (taken as 1.0 unless specified otherwise), S: soil factor (Soil type B), q: behavior factor (1.50), η: damping correction factor (typically 1.0 for 5% damping). Seismic action and load combinations were defined in accordance with EN 1998-1:2004, specifically clause 3.2.4, which governs the combination of seismic actions with other actions. In line with this clause, the seismic design situation was formulated as:

$$\sum Gk + \sum \psi\, E_{,i} \cdot Qk_{,i} + Ed$$

The following figures illustrate the finite element model, principal stress distribution, and crack width results obtained from the nonlinear analysis.

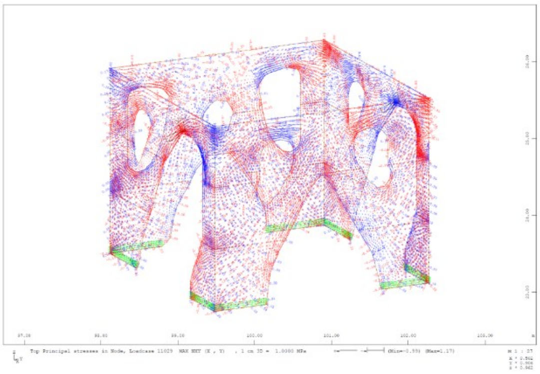

Fig. 8. Structural Analysis Results Principal Stress Distribution

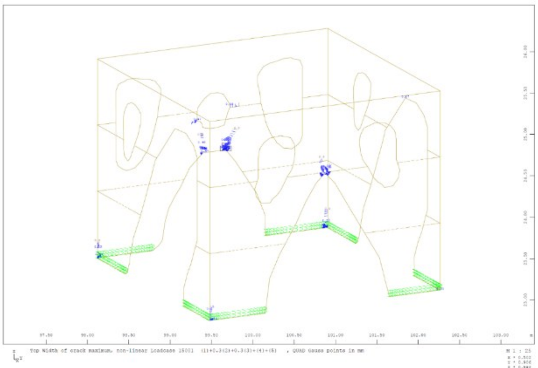

Fig. 9. Structural Analysis Results: Crack Width Results

3 Exploring Feasibility: Scale Model Construction

To understand the proposed structure's geometry and assess its buildability, we constructed a scale model in two phases: a 1:20 scale phase and a 1:10 scale phase. Each phase involved refining the 3D mold design, printing the mold's sixteen pieces, and then casting concrete within it.

3.1 Phase A: 1:20 Scale Model

3.1.1 Design and Printing

We began by designing and printing a 1:20 scale, sixteen-piece "closed" mold for concrete casting. This smaller scale was chosen to efficiently test the mold's behavior while saving time and 3D printing filament. Each 17x17x3 cm layer took about 13.5 hours and 140g of PLA filament to print on an Original Prusa i3 MK3S+ 3D printer, using settings of 0.20mm layer thickness and 15% infill.

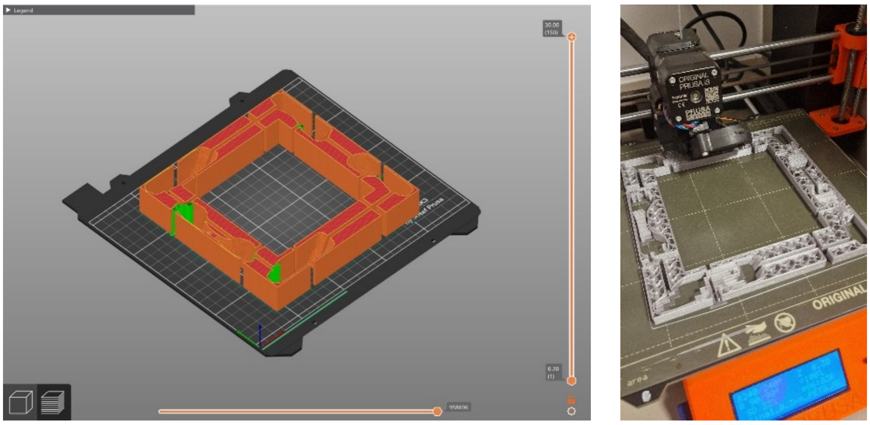

Fig. 10. (left) The designed mold with the vertical and horizontal cutouts; (right) The first layer of the mold

3.1.2 Casting Procedure

After printing, all mold pieces were assembled and secured with tape. We applied petroleum jelly to the interior surfaces as a release agent before casting a white cement-based mortar with high hydration properties, selected for its ability to fill the delicate mold accurately. The model was left to cure for one week.

3.1.3 Unmolding Challenges

During unmolding, the model fractured at each layer, primarily due to the mortar's poor sand quality. The release agent also appeared to have washed away, causing the mold's interior and exterior pieces to bond due to the exothermic reaction of the curing mortar. This made unmolding extremely difficult, almost impossible.

3.1.4 Key Observations from 1:20 Scale

The 1:20 model revealed that while cost-efficient, the mold's small size negatively impacted assembly and casting. We also learned that the casting material and release agent must be carefully chosen to be compatible with concrete. Consequently, we decided to print a portion of the mold at a 1:10 scale to test design refinements. We planned to incorporate an overhang system and engraved numbers on each piece of the 1:10 scale mold to improve assembly.

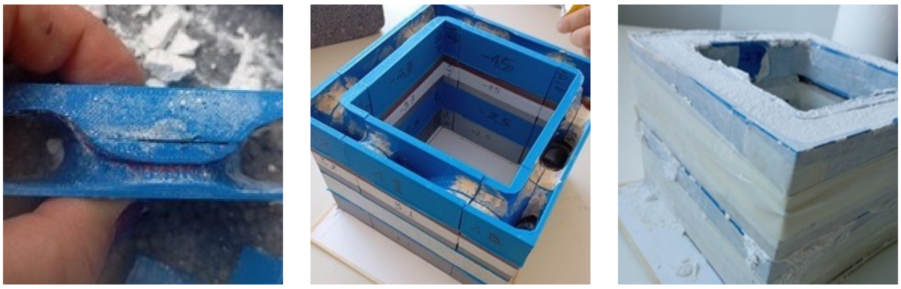

Fig. 11. Assembly and Casting Procedure. (left) view of the interior of the printed mold, (center) the four layers assembled, (left) casting procedure

Fig. 12. Structure's rapture due to poor sand quality

3.2 Phase B: 1:10 Scale Model

3.2.1 Re-Design for Integrity and Assembly

To improve mold integrity and simplify assembly, we redesigned eight mold pieces from the first and second layers. The redesigned molds included:

- **Notched sections:** For secure interlocking of components
- **Overhangs:** Allowing each mold to attach securely to the previous one, with the final mold anchored by a vertical spike
- **Perimeter hanging band:** Ensuring vertical alignment (details in a relevant section)
- **Internal dowel holes:** Specifically engineered in larger inner pieces (4mm at 1:10 scale) for robust internal connections
- **External wings (overhangs):** At the base of each layer for vertical alignment and stability
- **Handholds:** Integrated to facilitate easier dismantling and handling

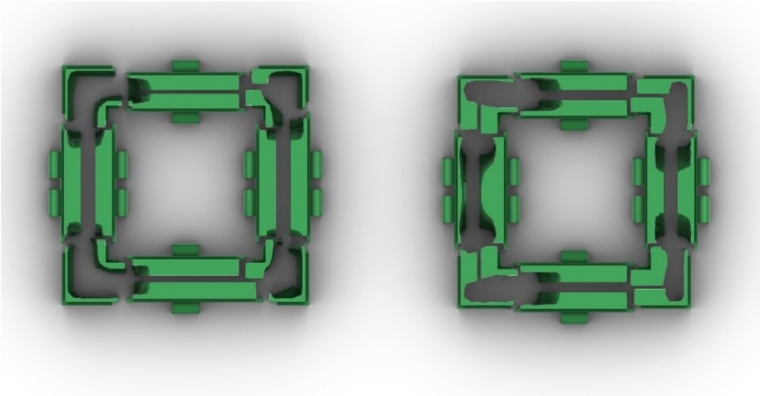

Fig. 13. Redesigned layers one and two with wings and overhangs

3.2.2 Printing and Assembly

Printing the eight redesigned pieces required 33 hours and 400g of PLA filament, using the same 0.20mm thickness and 15% infill density. The assembly process saw significant improvements in both precision and speed.

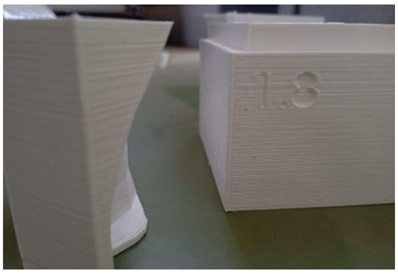

Fig. 14. Assembly and Preparetion Procedure. (left) mold pieces with number engravings (right) the assembled pieces

3.2.3 Casting and Unmolding

After assembly, the mold's interior walls were coated with Sika's separating agent. The casting mixture followed ISO-standards: 1500g cement, 4500g sand, 600g water, and Sika retarder. Unmolding was largely successful, except for some curved sections in the second layer (from the base), where print layers were visible on the concrete surface.

Fig. 15. Unmolding the eight pieces model in 1:10 scale

3.2.4 Key Observations from 1:10 Scale

Fabricating a larger mold helped identify critical areas where mold components completely enclosed the structure, preventing successful unmolding. Despite the overhangs improving assembly speed, it became clear that a dedicated locking system was needed for the interior and exterior mold sections, along with an additional mechanism to secure individual layers.

3.3 Phase C: Further Refinements and Observations

3.3.1 Enhanced Connections

To strengthen connections between layers of the shelter system's molds, we added horizontal 4.5mm holes to accommodate 4mm dowels, securing the exterior and interior molds. Vertical dowels were also incorporated at specific points to ensure stable alignment across all four mold layers. Additionally, a new component, potentially an eave, needs to be designed to connect inner corner pieces using vertical dowels. This will address fit issues within the mold's solid parts and ensure a seamless, robust connection throughout the structure.

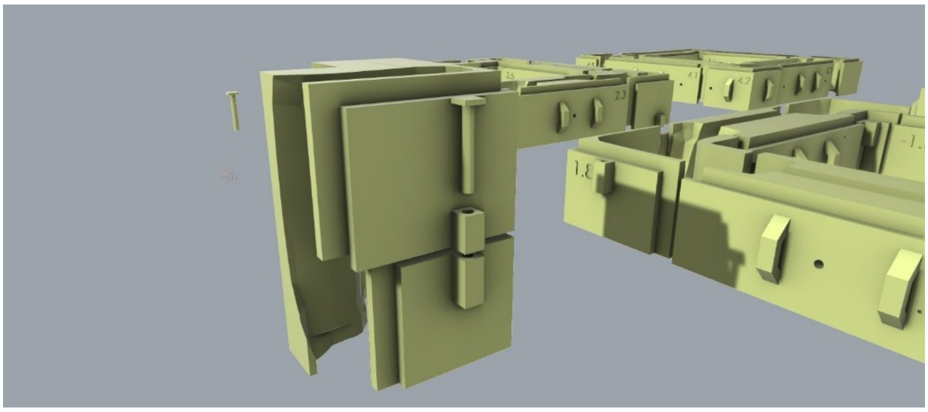

Fig. 16. Improvements in mold Design in 1:10 scale

3.3.2 Casting and Unmolding

The casting procedure in this phase successfully used the refined material recipe from the previous step. The precisely scaled printed mold pieces significantly streamlined both mold assembly and the subsequent casting. However, unmolding revealed inconsistent air gaps across different layers, suggesting potential issues with concrete flow or inadequate mold venting during casting. This critical finding emphasizes the need for further mold design refinements and optimized concrete mix proportions to achieve more consistent and high-quality results in future iterations.

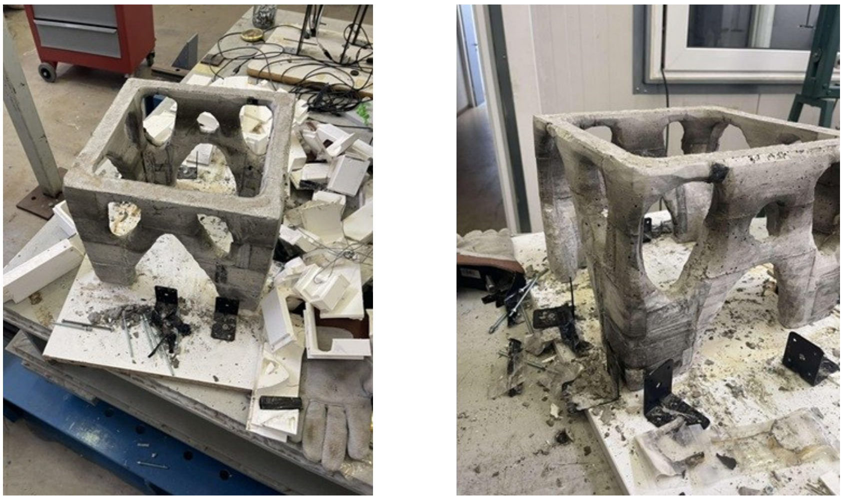

Fig. 17. Final precast model 1:10 scale

4 Conclusions

This study highlights the benefits of combining topology optimization and additive manufacturing for building post-disaster shelters. Our modular concrete system offers several improvements over traditional methods: better structural integrity, less material use, simpler labor, and efficient creation of complex shapes. By using reusable molds and local materials, it's both cost-effective and environmentally friendly. Scaled model tests confirmed the design's feasibility under simulated loads, proving its resilience, especially in earthquake-prone regions. While promising, we identified areas needing refinement: precise mold fabrication, improved joint performance, optimized concrete flow and venting, and better reinforcement integration.

Challenges during larger-scale model reinforcement and unmolding indicate that prototyping needs a more detailed approach. Future research should focus on intermediate-scale models (e.g., 1:5 and 1:2) and explore advanced 3D printing for molds. Testing full-scale prototypes on seismic beds will provide crucial data on performance, durability, and reinforcement interaction. Ultimately, this research moves us closer to developing sustainable, rapidly deployable, and robust housing for disaster-affected communities, showcasing digital fabrication's vital role in humanitarian architecture.

5 Discussion

This modular shelter system is a game-changer, blending technical innovation with environmental sustainability, economic feasibility, and social impact. It's designed to be cost-effective, easily transitioning from immediate emergency housing to more semi-permanent shelter, which fills a crucial gap in disaster recovery.

A major strength of this system is its use of light-reinforced concrete with molds made from either biodegradable PLA or recyclable PET-G [29]. This smart material choice supports both quick deployment and long-term ecological responsibility. Plus, over 70% of the building components are designed to be locally sourced, which drastically cuts down on transportation emissions and boosts local economies.

The reusability and recyclability of the molds offer clear environmental benefits. Once their construction purpose is served, the plastic molds can be ground down and reused. Similarly, the hardened concrete structures can be dismantled and repurposed as concrete blocks, promoting circular construction practices. This makes the system ideal for areas prone to repeated disasters or those with limited access to materials.

However, there are still challenges, especially with concrete curing in less-than-ideal conditions. Using non-potable water, like saline or brackish water, could affect the chemical integrity of reinforced concrete. We need more experimental studies to understand the long-term impact of these interactions on the structure's durability.

From a regulatory standpoint, the anti-seismic design, achieved through computational optimization, makes this module highly adaptable to different regions and building codes. This versatility allows the system to be customized to specific local needs while still adhering to universal design principles.

In short, this paper strongly supports the idea that modular, digitally-fabricated concrete shelters are a practical and scalable answer to global housing crises in disaster-prone areas. With ongoing research and improvements, this system could become a gold standard for resilient and sustainable emergency architecture.

Acknowledgment

Part of this research was supported by the ADAPT4CE project: “Adaptive digital systems for sustainable construction and material management in the circular economy” (No: 101182768) belonging to the Marie Skłodowska-Curie Actions (MSCA) Research and Innovation Staff Exchange HORIZON-MSCA-2023-SE. Their support is highly acknowledged.

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