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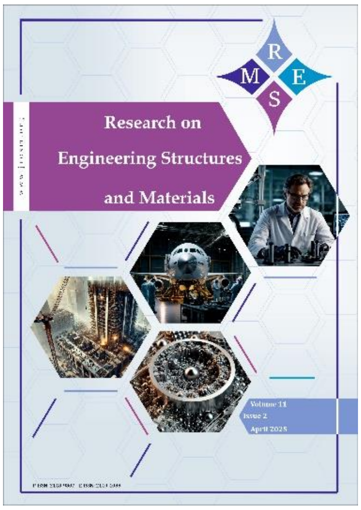

Recent advances in precast and 3D sandwich wall panels

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Review Article

Recent advances in precast and 3D sandwich wall panels

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Abstract

Precast and 3D sandwich wall panels represent a recently developed technology that combines structural efficiency, thermal insulation, and rapid construction performance. These panels consist of two concrete layers separated by a lightweight core such as expanded polystyrene foam, which offers significant thermal insulation and load bearing capacity, especially in connection systems subjected to both lateral and vertical loading. The experimental studies reported that ultra-high performance fiber reinforced concrete (UHPFRC) sandwich panels achieved up to 60% of higher flexural strength and improvement in thermal insulation compared with conventional concrete panels, confirming their thermo - mechanical efficiency. Additionally, the fabrication process has been refined to enable faster production, improved reliability, and adaptable modifications to meet diverse architectural requirements. These enhancements contribute to improved energy efficiency, durability, and overall sustainability in building performance. This review focuses on the integration of high-performance concrete (HPC) and fiber-reinforced polymer (FRP) and explores recently developed construction techniques such as precast fabrication, tilt-up methods, and shotcrete applications, along with their structural performance. Moreover, the paper discusses recent studies where advanced numerical tools such as ANSYS and ABAQUS have been utilized to optimize structural design, evaluate seismic and dynamic response, and assess thermal performance. The review also addresses sustainability, cost-effectiveness, and expanding architectural possibilities allowed by these systems. This study highlights the current challenges and future research directions aimed at enhancing the performance and application of these advanced construction components.

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1. Introduction

The growing demand for faster and more resource-efficient construction has strengthened the importance of precast concrete technology in modern practice. Unlike conventional cast-in-situ methods, precast elements such as slabs, beams, columns, and walls are produced in controlled

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environments and then assembled on-site, ensuring better quality, reduced labor requirements, and quicker project delivery [1]. Recent research further shows that the seismic performance of precast structures is strongly influenced by the quality of their connections. Studies have demonstrated that well-grouted wall–raft joints increased lateral resistance by more than 50%, highlighting the significance of robust joint design in earthquake-prone regions [2]. Historically, the concept of precast construction can be traced back to Roman innovations in early concrete, while its global development was accelerated by the establishment of the Precast Concrete Institute in 1954, which promoted standardization and large-scale adoption. Today, precast methods are widely applied across the world for both infrastructure and building projects, though in India their use remains largely limited to bridges, metro systems, and a few large-scale developments [1]. Broadening their application to residential and commercial buildings could play a key role in meeting the growing demand for speed, sustainability, and structural performance in construction. The main structural components used in precast concrete systems such as slabs, beams, and columns as shown in Fig. 1.

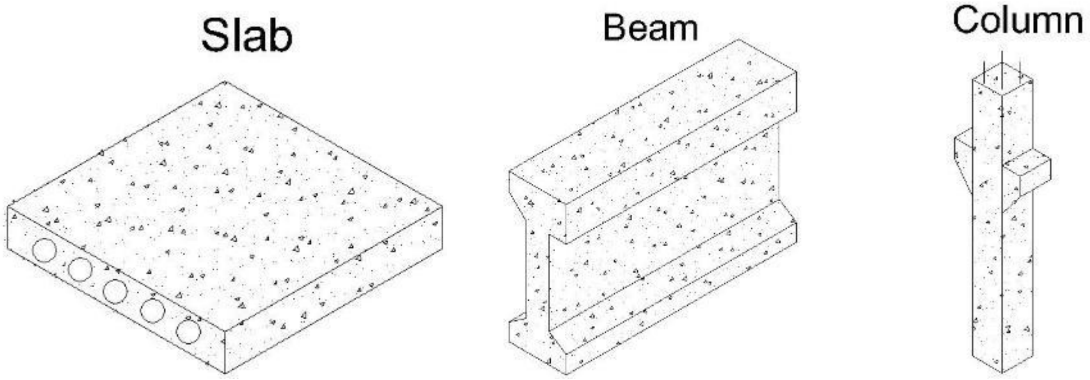


Fig. 1. Typical components of precast concrete (Slab, beam, column)

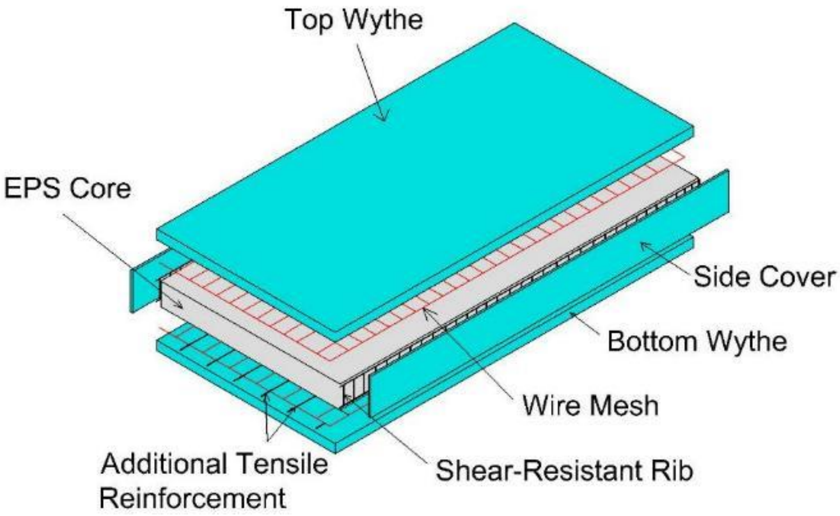


Fig. 2. 3D Sandwich wall

In recent years, 3D sandwich wall panels have attracted wide interest for their thermal insulation, high strength-to-weight ratio, rapid prefabrication, and seismic resistance. A typical configuration of a 3D sandwich wall panel with concrete layers and an insulating core is illustrated in Fig. 2. They are used as external and internal load bearing as well as non-load-bearing walls in building construction [9]. A typical panel consists of two concrete or fiber-reinforced concrete wythes separated by a lightweight insulating core, giving them excellent stiffness-to-weight ratios and energy efficiency [3–5]. Common core materials include expanded polystyrene (EPS), polyurethane (PU) foam, and phase-change materials (PCM), which reduce thermal conductivity and improve energy performance [3]. However, while connectors enhance structural integrity, they may also create thermal bridges that lower insulation efficiency [5]. These panels are subjected to vertical loads from self-weight and gravity, and in-plane loads from wind and seismic forces, and their behavior is best understood through numerical analysis of deformation, failure modes, and load distribution [6–8].

1.1 Importance of Precast Systems in Modern Constructions

Precast systems are increasingly preferred in construction for their ability to deliver projects quickly with less on-site labor [11,12]. Elements such as slabs, walls, and beams are produced in factories under controlled conditions, ensuring dimensional accuracy and reliable quality while avoiding delays from weather disruptions [11]. Within these systems, precast sandwich panels stand out as they combine load-bearing strength with superior thermal insulation, making them suitable for both structural and energy-efficient applications [10]. Ongoing developments in shear connectors, core insulation, and digital fabrication methods have further improved their mechanical performance and sustainability [11,12].

1.2 Classification of 3D Sandwich Wall Panels

The classification of 3D sandwich panels typically considers the type of core (e.g., EPS, PU foam, or lightweight concrete), the facing materials (such as concrete, metal, or fiber-reinforced polymers), and their load-bearing capabilities. Different types of sandwich walls are listed below:

1.2.1 Precast Concrete 3D Sandwich Panels

Precast concrete 3D sandwich panels are made of two layers of reinforced or prestressed concrete enclosing an insulation core, typically expanded polystyrene (EPS), extruded polystyrene (XPS), polyurethane (PU), or mineral wool [13]. Manufactured under controlled factory conditions and assembled on-site, they offer fast construction with consistent quality. Studies indicate that adding longitudinal reinforcement and end stiffeners to slender precast sandwich walls enhances their lateral strength and seismic behavior, making them more effective than conventional reinforced concrete walls [14,15].

1.2.2 Steel or Aluminum Faced 3D Sandwich Panels

3D sandwich panels faced with steel or aluminum are formed by bonding two metal sheets to a lightweight insulating core, resulting in a superior strength-to-weight ratio [16]. They provide fire resistance, long-term durability, and effective thermal and acoustic insulation, making them valuable across construction, transportation, and aerospace industries. The decision to use steel or aluminum typically depends on factors such as structural weight, corrosion resistance, and application needs. Research on double-layer sandwich panels has validated finite element (FE) and two degrees of freedom (TDOF) models, emphasizing the parameters that govern failure behavior and energy absorption [17].

1.2.3 Expanded Polystyrene Core 3D Panels

EPS core 3D panels are constructed by embedding a lightweight expanded polystyrene (EPS) core between galvanized steel meshes, which are then encased in reinforced concrete [18]. These panels are recognized for their thermal insulation, energy efficiency, low cost, and ease of handling, making them well suited for floors, walls, and roofs in residential, commercial, and industrial applications. Beyond these advantages, researchers have noted that the addition of fibers can significantly enhance their structural performance. It was reported that incorporating steel fibers into 3D-printed beams increased flexural strength and reduced brittle cracking, suggesting that similar strategies could benefit EPS-based sandwich panels [20]. Their lightweight configuration not only simplifies transportation and installation but also provides adequate strength, which explains their growing popularity in modern construction [18].

1.2.4 Glass Fiber-Reinforced Polymer (GFRP) Sandwich Panels

Glass Fiber Reinforced Polymer (GFRP) sandwich panels consist of GFRP facings bonded to a lightweight core such as foam or honeycomb, which enhances their strength and durability [13]. These panels reduce construction time and maintenance costs while offering non-conductive and fire-resistant properties, making them suitable for specialized applications like enclosures and transportation systems. In concrete sandwich walls, GFRP shear connectors are often used to improve overall performance [13].

1.3 Construction Procedure of 3D Sandwich Wall Panels

An overview of the installation process of 3D panels is outlined below, along with a step-by-step explanation of their production method, emphasizing the efficiency and practical advantages of this system [19].

1.3.1 Connection to Foundation

The EVG-3D construction system can be installed on any type of foundation, provided that vertical reinforcement bars are anchored according to structural specifications [15]. During installation, panels are aligned with the rebar positioned between the mesh and polystyrene core, ensuring proper wall placement. To enhance durability, a damp-proof layer is applied beneath the wall panels [15]. The detailing of the foundation construction and wall anchorage arrangement is shown in Fig. 3.

Fig. 3. Detailing of foundation construction (JMV) [15]

1.3.2 Erection of Wall Panels

The erection of EVG-3D panels starts from the corners to provide structural rigidity [15]. The erection process of the wall panels, including corner alignment and fastening, is illustrated in Fig. 4. Figure 3 illustrates the panels are joined using splice mesh on both sides and fastened with either manual or pneumatic tools for secure connections [15].

Fig. 4. Erection of wall panels [15]

1.3.3 Reinforcing-Panels Splices

Panel walls are reinforced using splice mesh, especially at corners, panel joints, and openings, to ensure continuous strengthening [15]. At intersections of structural elements, reinforcing ties and bars are added to improve joint performance, while the meshes are securely connected with pneumatic fastening tools [15]. The reinforcement and splice mesh arrangement at panel junctions is shown in Fig. 5.

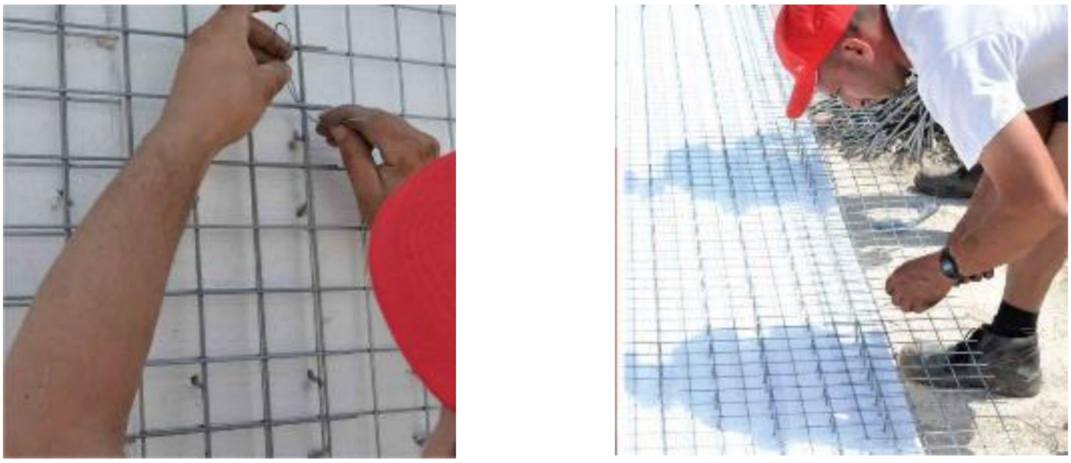


Fig.5. Reinforcing panels splices [15]

1.3.4 Forming Openings

Door and window openings can be cut on-site to the required size using metal cutting tools, starting with an initial hole spaced at least 100 mm apart (Fig. 5). Splice mesh is fixed at corners for stability, while larger openings require additional reinforcement bars to retain strength [1,2]. Accurate cutting minimizes material waste, and where power tools are unavailable, the mesh can be cut with bolt cutters and polystyrene removed using a hand saw [3]. The method used for forming door and window openings on 3D panels is presented in Fig. 6.

Fig. 6. Cutting method of 3D panel [15]

1.3.5 Shoring and Placing of Slabs

The EVG-3D panel system can be effectively used for roofs and intermediate floor slabs, with support provided by adjustable props, tripods, and beams. Slab reinforcement includes bottom rebars, U-bars at supports, and splice mesh between panels [1,2]. Panels are manually lifted and positioned on wall supports, and the system can be integrated with conventional construction techniques [3]. The details of formwork, temporary support, and slab placement are shown in Fig. 7.

Fig. 7. Detailing of Form work and placing of slab [15]

1.3.6 Utilities

Utilities can be routed between the reinforcing mesh and polystyrene once the panels are in place. Additional space can be created by carefully shaping the polystyrene using a propane torch or heat gun [15]. The arrangement of electrical conduits and service openings within the 3D sandwich wall panels is illustrated in Fig. 8.

Fig. 8. Electric conduits provisions [15]

1.3.7 Shotcrete

Shotcrete is applied to walls and slab undersides using manual or mechanical methods (wet or dry) (Fig. 9). Normal-weight concrete should meet IBC Section 1913, achieving 17.2 MPa at 28 days, with aggregates not exceeding 9.5 mm and Gradation No. 1 per ACI 506R-90. It shall also comply with ACI 506R-90 and ACI 318-19 (Section 22.5) for shotcrete design, placement, and strength verification to maintain structural reliability. The material is typically placed in one or two layers, with screed points used to check thickness and alignment, and the final layer hand-trowel to ensure proper finish and surface tolerance. The application of shotcrete during wall finishing is depicted in Fig. 9.

Fig. 9. Shotcrete of mortar/concrete [15]

1.3.8 Finishing

Once the panels are in place, different finishing options can be applied to suit both design and functional needs. These finishes not only improve the look of the structure but also help protect it from weather, moisture, and general wear. Exterior surfaces are commonly treated with plaster, textured coatings, or cladding, depending on design and site conditions. Inside, paint, render, or drywall may be used after preparing the surface. Using the right materials ensures good adhesion, prevents damage like cracking, and results in a durable, professional finish. The various finishing options for both exterior and interior surfaces are illustrated in Fig. 10.

Fig. 10. Finishing [15]

2. Material Innovations

Recent developments in high-performance materials have significantly enhanced the structural efficiency, environmental sustainability and thermal behavior of precast and 3D sandwich panels. This section examines the development of high-performance concrete (HPC), fiber-reinforced polymers (FRP) and novel insulation materials within this context.

2.1 Higher-Performance Concrete (HPC)

Ultra-High-Performance Fiber-Reinforced Concrete (UHPFRC) significantly enhances both the strength and thermal efficiency of sandwich panels. Its dense microstructure and steel fibers boost tensile and compressive strength while enhancing post-crack behavior. When combined with cellular lightweight concrete, panels demonstrate superior mechanical and thermal efficiency. Using post-crack steel bars as shear connectors further ensures excellent composite action and insulation, achieving a thermo-mechanical performance coefficient of 98.8% [21]. As shown in

Table 1, flexural strength was measured under four-point bending, and thermal conductivity was assessed using the transient plane source (TPS) method. Higher composite action ratios indicate better integration between layers.

Table 1. Mechanical and thermal properties of UHPFRC-based sandwich panels [21]

UHPFRC Thickness (mm)	Shear Connector Type	Flexural Strength (kN)	Thermal Conductivity (W/m·K)	Composite Action Ratio (%)	Reference
20	Shear Keys	6.5	0.27	53.2	[21]
20	Steel Bars	7.8	0.28	60.4	[21]
20	Post-Tensioned Steel Bar	8.3	0.29	68.8	[21]
30	Post-Tensioned Steel Bar	9.7	0.29	65.1	[21]
20 (Box, No core)	-	6.1	1.55 (no insulation)	42.0	[21]

UHPFRC panels with post-tensioned steel connectors achieved nearly 68.8 % composite action, indicating a notable quantitative improvement approximately 60 % higher thermo-mechanical efficiency compared with non-insulated panels. Specifically, UHPFRC panels reached 9.7 kN flexural strength versus 6.1 kN for conventional concrete panels, confirming their nearly 60 % higher load capacity and significantly improved thermal insulation (0.29 W/m·K vs. 1.55 W/m·K).

2.2 Fiber-Reinforced Polymer (FRP)

Fiber-reinforced polymers (FRPs), including glass fiber reinforced polymer (GFRP), carbon fiber reinforced polymer (CFRP), and basalt fiber reinforced polymer (BFRP), enhance sandwich panels by improving reinforcement, connectivity, and offering high strength-to-weight ratios, corrosion resistance, and thermal insulation. Studies have observed that while glass fibers increased stiffness, they often led to brittle response, whereas steel fibers provided greater ductility, underscoring the importance of selecting fibers based on structural demand [20]. Basalt FRP (BFRP) provides thermal stability and cost-efficiency, potentially replacing traditional steel connectors. Additive manufacturing enables the production of continuous fiber-reinforced facings and honeycomb cores in a single step, enhancing structural integrity and resistance to delamination [22, 23, 26]. By varying fiber volume and orientation, engineers can tailor stiffness and damping properties to specific requirements [24].

Table 2. Mechanical and thermal properties of FRP types [22, 24]

FRP Type	Elastic Modulus (GPa)	Tensile Strength (MPa)	Density (g/cm^3)	Thermal Conductivity (W/m·K)	Remarks	Reference
GFRP	69-76	600-1200	2.5-2.6	0.3-0.4	Economical, Good Corrosion Resistance	[22]
CFRP	150-600	800-3000	1.4-1.8	0.8-1.5	High stiffness and strength but costly	[24]
BFRP	80-90	1000-1400	2.6-28	0.4-0.6	Superior thermal stability, freeze-thaw durability	[22]

Among the FRP types, CFRP exhibits an elastic modulus of 150–600 GPa, nearly eight times greater than that of GFRP (69–76 GPa). However, its thermal conductivity is roughly twice as high (0.8–1.5 W/m·K vs. 0.3–0.4 W/m·K), illustrating the clear trade-off between stiffness and insulation efficiency. Continuous fiber-reinforced honeycomb panels reached up to 95 MPa flexural strength**,** nearly 30% higher than hybrid natural fiber composites, proving their superior bonding and stiffness.

Table 3. Summary of AM strategies for FRP sandwich panels [23, 25, 26, 30]

Manufacturing Strategy	Fiber Type	Fiber Volume Content (%)	Flexural Strength (MPa)	Remarks on Performance and Bonding	Reference
In-situ Continuous Fiber Placement	E-glass	50	90-110	Enhanced interfacial bonding via surface preheating	[23]
Continuous Fiber-reinforced Honeycomb structures	Glass fiber	40	85-95	Better stiffness at low infill densities	[26]
Sandwich panels with CFRP straps	Carbon fiber	-	130 (tensile bonding)	Strong post-elastic response via double-strap joints	[25]
Hybrid natural fiber/Epoxy skins (3D corrugated)	Cotton fiber	30	70-80	Natural fibers with high energy absorption	[30]

2.3 Novel Insulation Materials

Innovative insulation materials aim to enhance thermal resistance while maintaining mechanical strength. Natural fiber composites (NFCs), such as jute, flax, and hemp, are gaining attention for their renewability, biodegradability, and structural potential, and are used as face sheets and core materials in eco-friendly sandwich panels. Advanced designs, including 3D-printed gyroid topologies, improve load distribution and energy absorption. Panels with polyurethane foam (PUF) cores demonstrated better post-fracture load retention [29], while corrugated cores combined with natural fiber-reinforced skins showed enhanced bending performance and energy absorption [30].

Table 4. Comparison of insulation core types for 3Dsandwich panels [21, 22, 29, 30]

Core Type	Density (kg/m^3)	Thermal Conductivity (W/m·K)	Mechanical Contribution (Flexural/Compressive strength)	Reference
EPS (Expanded Polystyrene)	10-35	0.030-0.040	Low compressive strength, but not suitable for high-load panels	[22]
Cellular lightweight concrete (CLC)	400-1900	0.080-0.30	Moderate, Add compressive stiffness but less ductility	[21]
Polyurethane Foam (PUF)	30-60	0.020-0.025	High energy absorption, improves ductility and deflection capacity	[29]
3D printed Gyroid (Polylactic Acid (PLA)/PUF Hybrid)	300	0.035-0.050	High specific stiffness and core	[29, 30]

PUF cores exhibit nearly three times better thermal insulation than cellular lightweight concrete (CLC), with thermal conductivity of 0.020–0.025 W/m·K compared to 0.080–0.30 W/m·K, representing 70–80 % higher heat resistance. Despite having only one-tenth the density of CLC (30–60 kg/m^3 vs. 400–1900 kg/m^3), PUF cores maintain superior ductility and post-fracture energy absorption, making them particularly efficient for lightweight, energy-saving wall systems.

3. Recent Advances in Precast Wall Panels

The introduction of precast concrete wall panels marked a major advancement in construction efficiency, accuracy, and long-term performance. Wall panels were used mainly for basic functions like cladding, support, and insulation, but with ongoing progress in materials and construction methods, their role has significantly improved construction efficiency and precision, meeting the complex demands of modern buildings. A main motivation for this development is the need for building systems that cut down on time, labor, energy and ecological burden. Incorporation of high-performance materials such as Ultra-High-Performance Concrete (UHPC), GFRP and the newest generation of insulation with newly developed connection methods are some of the established means of ensuring that structures will meet higher safety, thermal and durability requirements.

3.1 New Manufacturing Techniques and Their Benefits

The three main manufacturing innovation techniques in concrete sandwich wall panels (CSWP) are Precast plant fabrication, tilt-up casting and shotcrete panels, three methods are briefly discussed in this section [31].

3.1.1 Precast Fabrication

The variety of concrete sections used as layers include solid concrete panels, hollow-core units, and paired structural elements that can be combined to form precast concrete sandwich systems. A standard configuration typically consists of an external concrete face, an insulation core, and an internal load-bearing layer [32]. Precast panels are usually fabricated in quality controlled prestressed precast plant [42,43]. The panels are then stripped, lifted, warehoused or transported to the erection site after the concrete has gained sufficient strength (see also Figure 11). The step-by-step process of precast concrete sandwich wall panel construction, from factory casting to site installation, is illustrated in Fig. 11.


(a) (b) (c)

Fig. 11. Step-by-step process of precast concrete sandwich wall panel construction: (a) casting the panel in the factory, (b) lifting and handling in the yard, and (c) installation at the construction site [31]

Precast have several advantages over other building methods, including higher flexural strength, a distinctive surface treatment and prestress to resist service cracking. In addition, when loading requirements or architectural reasons require cladding of reduced weight to minimize the seismic weight of the structure, such panels are also produced, using thin (25–50 mm) UHPC wythes as well [33, 44]. But there is not much literature on large scale experiments on realistic size Ultra-High-Performance Concrete (UHPC) panels. It has been found that restrictions on lifting capacity of crane equipment in the plant, truck length and load limits of shipping trucks, and lifting pressures on, for example, lifting devices are all general logistical and design considerations in precast concrete manufacture. To transport precast panels from the plant to the construction site, overhead cranes, moveable gantry cranes (Figure 11b) and derrick cranes (Figure 11c) are often used, which makes the construction of long and heavy panels more complex. This is compared to tilt-up which is built-in place, with just one crane. These panels will have to be designed and constructed considering shipping stresses, imposing additional loads during transportation which can be significant for long panels [45]. Finally, lifting forces are applied to the connectors at picking points, "increasing" the forces on panel design further due to lack of testing-based guidance to account for these forces [37]. The construction equipment used in precast CSWPs can be generally subdivided into three categories which are bracing equipment, lifting equipment and embeds [46,47]. In addition to connecting panels to other panels and to other structural systems such as footings, slabs on ground, joists and girders, embeds are used to assist with lifting (anchors and lifting loops). Lifting gear can include spreader beams, chains and clutches. Because most lifting devices and connectors are proprietary, no research has been done to examine how lifting stresses affect wythe connectors. Finally, bracing tools aid in preserving stability when building the floor and roof components. The impact of interim bracing techniques on the connector's performance is unknown.

3.1.2 Tilt-up Method

Usually a prepared casting slab on-site "Figure 12(a), (b)" and placed into position by using crane (Figure 12c) [48,49]. At that time the document was written, they were only strengthening with mild steel, and the outer side is made up of outer masonry vertical wall, inner masonry vertical wall and an insulating layer. These methods are widely used in commercial, industrial and public buildings due to their cost effectiveness and easy installation [50,51], typically less transportation cost compared to precast methods [52]. However, the tilt-up construction technique may be affected by atmospheric conditions and seasonal weather, and limited production window for a specific period. The advantage of tilt-up method compared to precast method is that the precast elements are cast off-site, and the shipping is more difficult whereas in tilt-up method structural elements are cast on-site. So, the limitation of shipping in precast method is reduced in tilt-up method. The prevention of heavy and bulky precast panels for long distances reduces the transportation expenses and CO2 emissions [53]. There may be a chance of cracking occurring during lifting, since they are non-prestressed [54]. Besides, the tilt-up panels can be customized in terms of architectural and finishes directly on casting surfaces. This method needs extensive site preparation, ensure proper curing and large open areas for casting.

(a) (b) (c)

Fig. 12. Tilt-up CSWP construction process: (a) workers placing insulation with layer connectors, (b) concrete cast on second layer, (c) erecting the panel in place [31]

Tilt-up method has benefits as well as some limitations too, mainly placing and lifting walls on-site [56]. Precast elements are cast on plant environment whereas tilt-up elements are cast on-site, the elements subjected to site conditions like humidity, dry, rain and temperature which affect the quality, curing and finishing. Also, the weight and shape of the panels must be looked at carefully for safe lifting because tilt-up building uses only one crane [54]. The typical tilt-up sandwich wall panel construction sequence, from insulation placement to erection, is shown in Fig. 12. How far the crane can reach can also make the building process harder. This can also decide the size of the panels and the order they are put up.

Additionally, lifting inserts, embeds, and temporary bracing systems are used as essential construction hardware in tilt-up concrete structural wall panels [49, 57]. To facilitate hoisting, lifting inserts including coil inserts, plate anchors, or custom lifting anchors are incorporated into the panels during fabrication. To stabilize tall panels as they are erected and before the structural system gains adequate stability, adjustable temporary bracing systems such as steel braces are vital [58]. Comparable to other precast panels, limited research explores how wythe connectors perform under the stresses of hoisting and early stabilization, particularly for unusually large or complex panels.

3.1.3 In-Plane Sprayed Concrete Wall Panel Construction

Concrete is pneumatically sprayed onto a surface containing reinforcement and insulation, thereby forming shotcrete concrete sandwich wall panels which are cast in-situ [40]. Unlike tilt-up and precast panels that require lifting and transport, shotcrete panels are well-suited for constructing low-rise residential and commercial buildings in locations with restrictions on the movement of large, prefabricated components [59]. The construction procedure involves building a foundation equipped with vertical dowels, setting the panels in place along with rebar and then applying the shotcrete using sprayed concrete until the desired thickness is achieved, encapsulating the internal reinforcement and insulation in a single operation [39].

A pumping system, hoses, and electrical tie-wire guns are some of the essential pieces of equipment needed to manufacture shotcrete CSWPs [41]. However, in some cases alternative reinforcement could be considered to reduce costs and environmental impacts. The integration of wire mesh and rebar increases structural integrity as intended by design codes and standards [60]. There is presently no documented usage of this technology employing fiber-reinforced polymer (FRP) fasteners in lieu of stainless steel wythe connectors which are commonly specified. While code minimums for reinforcement are sensible, further tests on experimental connections using innovative materials not yet standardized could potentially yield benefits with respect to durability, corrosion resistance or whole-life costs if substantiated by appropriate analysis and investigation. These stainless-steel connectors are used to connect the inner and outer wythes (Figure 13a). A high-pressure hose is used to apply the shotcrete to reduce voids and guarantee correct adherence to the insulation and reinforcement, the surface is finished manually (Figure 13b). The construction stages of a shotcrete sandwich wall panel, including setup, first-layer application, and final surface, are presented in Fig. 13.

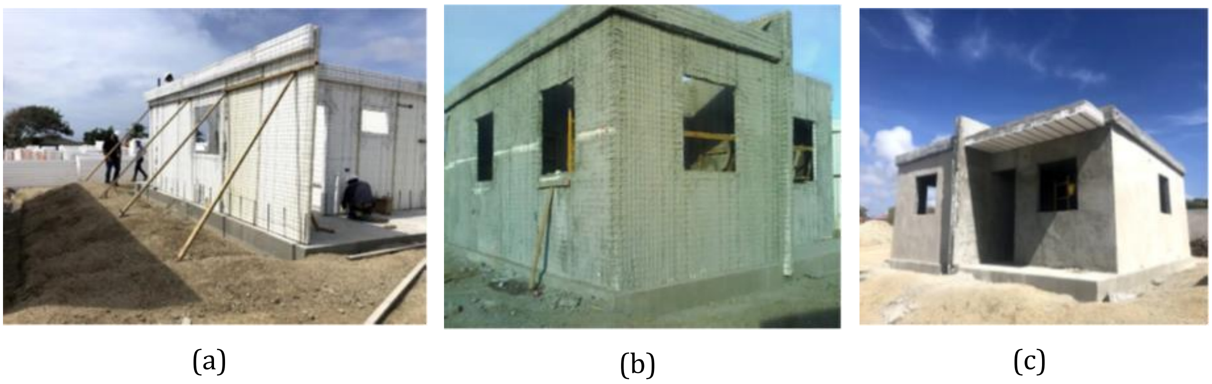
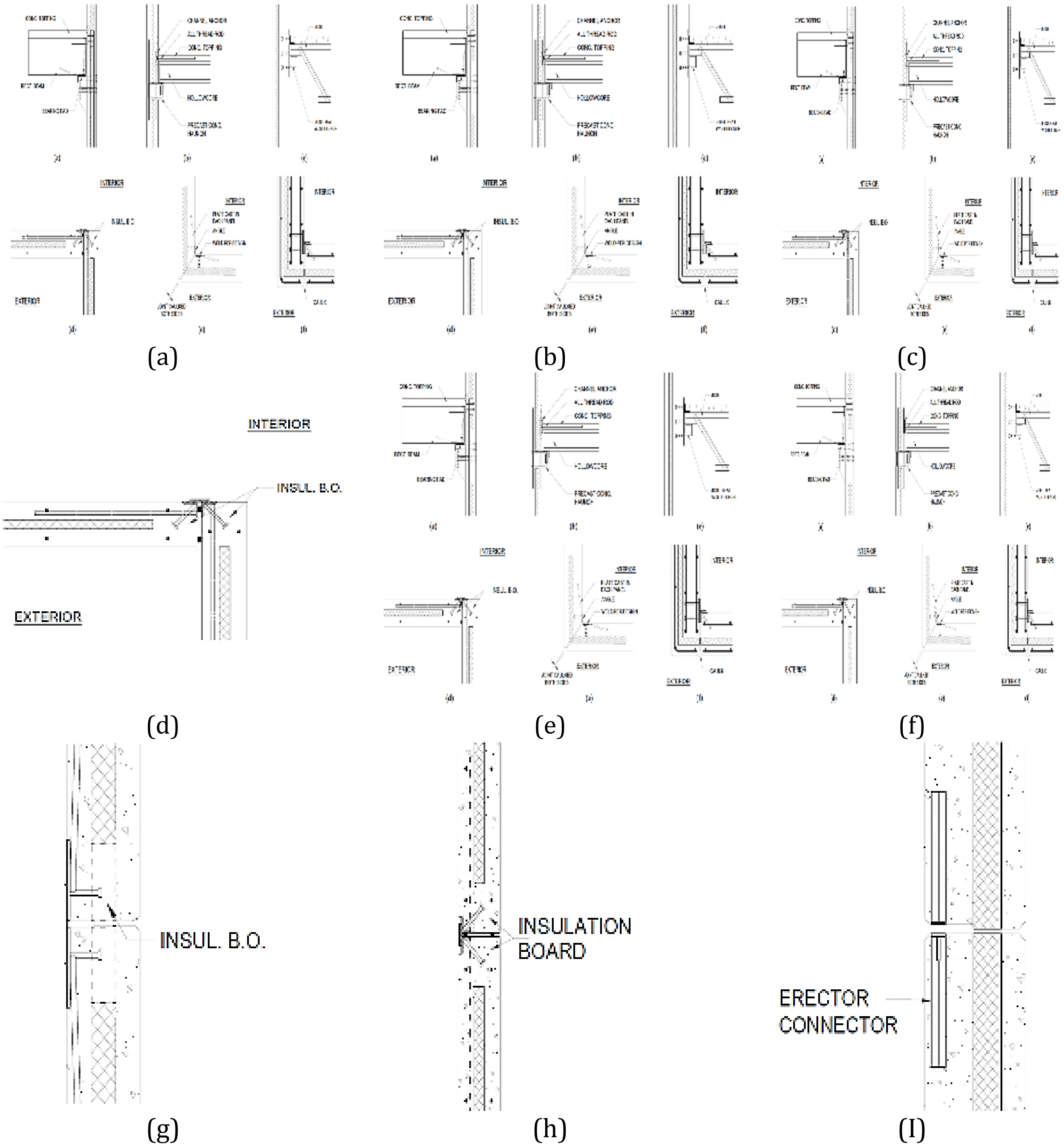

(a) (b) (c)

Fig. 13. Construction steps of a shotcrete sandwich wall panel: (a) panel setup before applying concrete, (b) panel after the first layer of shotcrete, (c) completed surface [31]

The primary benefit of shotcrete panels is their formability and are cast-in-place, which includes curved surfaces. Shotcrete reduces the number of joints and connections and gives a better surface finish. Further, this product reduces the need for uplifting devices and cranes, which increases the finished products cost. Because of this, the panels are an appealing product for homes and partition walls in steel-framed and concrete structures [61]. Although there are certain limitations in this method. Firstly, these panels are limited to more than 4m floor heights and strength less than 35 MPa which is below the tilt-up and precast method. Additionally, the material may differ by mixed design, placement in site and environmental factors which affect the curing and lead to shrinkage cracking that partially reduces the short and long-term performance of the structure [62-64].

3.2 Highlight Advancements in Connection Systems

The design of connections in concrete sandwich panels is complex for some reasons: firstly, panels mostly use concrete wythes 50 to 100 mm thick, which worried practicing engineers. Secondly, the reactions imposed on floors and roofs by lateral loads can be quite substantial and intricate, posing challenges for engineers aiming to conceive designs that venture beyond code minimums relying primarily on educated speculation regarding force transmission paths. In addition, there exists sparse documentation chronicling experimental evaluation of thermally proficient joint configurations within available literature, save for select studies examining corbels [34,38]. This dearth of data renders codification of such connections rather difficult. Among the junctions commonly used in CSWPs are those joining panels to diaphragms, one panel to the next, and panels interfacing with other panels.



(a) (b) (c)

(d) (e) (f)

(g) (h) (I)

Fig. 14. Common examples of thermal efficiency in CSWP construction (a–c) show how beams, slabs, and joists connect to panels; (d–f) illustrate different corner connections between panels; (g–i) show side-by-side panel connections [34, 35, 36]

The techniques used by engineers to address some of these challenges are illustrated in Fig. 14, many of which rely on strategies that alter bending forces and improve thermal transitions across materials. Sorensen [35] suggested several solutions, but widespread application has been constrained by limited experimental validation and insufficient knowledge of long-term performance. According to PCI 150-24 (2024) and Eurocode 2 (EN 1992-1-1, Clause 6.2), connector detailing must satisfy minimum shear-transfer capacity and thermal bridge control limits. Including these clauses clarifies the regulatory framework for modern sandwich-panel design. Others have explored alternative methods to improve joint performance, aiming to maintain mechanical reliability while minimizing thermal bridge through connections. Recent work also emphasizes that connection detailing directly affects seismic safety. For example, studies have demonstrated that larger shear connectors significantly increased lateral strength and energy absorption, underscoring the importance of careful detailing for durable, earthquake-resistant panels [2]. Overall, advancing research at a broader scale is crucial to identifying the most effective and lasting solutions for varying structural and environmental conditions.

4. Review Methodology

A structured and transparent review process was followed to ensure clarity, credibility, and scientific research. Relevant studies on precast and 3D sandwich wall panels were systematically collected, screened, and analyzed.

4.1 Search Strategy

The literature search was carried out using reliable academic databases, including Scopus, ScienceDirect, SpringerLink, and Google Scholar, for the publication period 2015–2025. The main search terms used were “precast sandwich panel,” “3D wall system,” “fiber-reinforced polymer (FRP) connector,” “thermal insulation,” “numerical modeling,” and “composite concrete panel.” To maintain the scientific quality of the review, only peer-reviewed journals, international conference proceedings, and official technical standards (ACI, PCI, Eurocode) were included.

4.2 Screening and Selection

An initial pool of 250 research papers was identified. After removing duplicates and irrelevant works, 180 papers were screened based on title and abstract. Of these, 110 full-text articles were reviewed in detail. Based on the inclusion criteria focus on experimental or numerical analysis of mechanical, thermal, or structural behavior. Finally, 81 studies were retained for detailed evaluation.

4.3 Data Extraction and Synthesis

Each selected study was examined for its panel type, core material, connector system, testing methodology, and principal findings. The final set of reviewed works was summarized in a comparative table to highlight design innovations, material performance, and research gaps in the field. The summary of key studies of different panel types are shown in the Table 5.

Table 5. Summary of key studies highlighting panel types, core materials, connector systems, and key findings

Study / Year	Panel Type	Core Material	Connector System	Key Findings
Ghazy et al. [23]	UHPFRC Sandwich	Lightweight Concrete	Steel Bars	60% higher flexural strength and 3× better insulation.
Pham et al. [20]	3D-Printed	EPS Foam	Steel Fibers	Enhanced ductility and reduced cracking.
Pandey et al. [76]	Honeycomb	Aluminum Core	CFRP Straps	High energy absorption and low weight.
Tawil et al. [81]	Composite Precast	PU Foam	GFRP Rods	Reduced thermal bridging and improved insulation.
Varghese et al. [74]	Sustainable Precast	C&D Waste + Foam	Steel Ties	Strong mechanical performance using recycled core.

4.4 Outcome of the Review

The systematic review shows continuous progress in material innovation, connector design, and manufacturing techniques, enhancing both strength and energy efficiency. However, limited full-scale testing and lack of unified design codes remain major research gaps for future studies.

5. Developments in 3D Sandwich Wall Panels

Three-dimensional sandwich wall panels represent a structural system that combines mechanical strength, thermal control, and material efficiency. These segments usually have two concrete wythes with a light core between, working together composable. Sometimes one wythe is thicker than the other for extra protection. The core transfers loads between the wythes like rebar does in concrete alone. Thinner panels go up faster and need fewer materials but must be very well-fastened. The 3D panels provide cost-effective, energy-efficient building solutions with long-term durability and reduced maintenance demands. While 3D sandwich panels offer notable benefits including load resistance and insulation prowess, recent advances have significantly enhanced panel performance. The clever design of these composites allows withstanding both axial and flexural forces while providing high thermal insulation. This minimizes thermal bridging and overall weight, lessening foundation loads for faster, easier installation. [22,67,73].

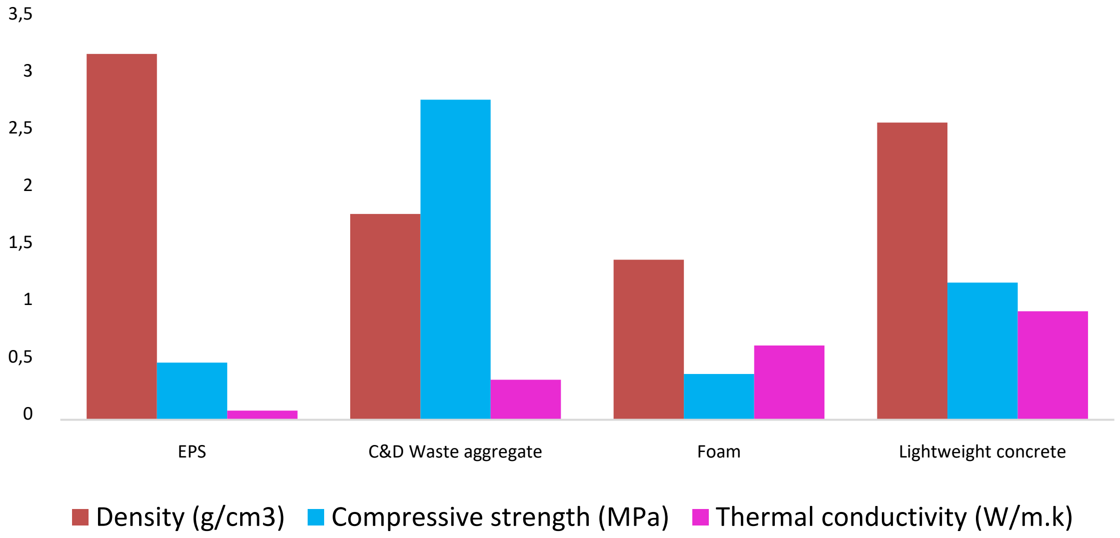


Fig. 15. Comparison of core material properties [71,73,74]

Furthermore, innovative core materials have played a pivotal role in boosting panels' mechanical and heat-related characteristics. For example, expanded polystyrene stays widely used owing to its lightweight, high thermal resistance qualities. Another core material gaining popularity is glass wool for its formidable strength-to-weight ratio and exceptional vibration damping abilities, leading to less sound transmission. Together, these fortified cores continue strengthening panels' capacities in demanding construction projects. A comparison of different insulation core materials and their mechanical properties is shown in Fig. 15. EPS cores and found that - apart from the thermal capabilities such cores can save costs in LCA (life cycle assessment). In addition, researchers have been working on environmentally friendly replacements [73]. C&D waste was utilized as a core material, and the mechanical characteristics anticipated for core material were satisfying and waste recycling was done simultaneously [74]. further investigated response of foam, honeycomb, and lightweight concrete cores under compressive and shear loading and showed the effect of core's stiffness on the strength and deformation response of the panel [71].

Apart from materials, the development of panel geometry and their optimization methods have led to improved share of loads and rate of material usage. They have used topology optimization in designing sandwich panels, leading to lightweight panels with better stress distribution and less materials without reducing structural integrity. Their computational method allows architects and engineers to adjust not only the panel shapes but also the interior structure considering some of the performance demand such as seismic and wind loads responses [68].

And 3D printing technology from the field of manufacturing, when applied to food, is another enormous step. The application of 3D printed concrete in construction, improved accuracy, less material waste and shorter construction periods were reported [69]. Several 3D concrete printing systems have also been reviewed and it has been highlighted that they are adaptable for prefabricated sandwich elements, with possibility of complex geometries and tailor-made voids arrangements for enhanced thermal and structural behavior [70]. the development of sandwich panels via fused deposition modeling (FDM), with improved mechanical performance and geometrical customizability, especially for the cases with continuous and curved sections [72].

The thermal aspect is still a concern for the design of the wall panels. thermal analysis of precast sandwich panels with different insulation types conductive that the insulation continuity and type have a significant impact on the total thermal resistance [67]. Their work paves the way for hybrid insulation layers and embedded phase change materials in future panels. Development in 3D sandwich wall panels, a combination of material innovations, geometry optimization and automated manufacturing. This development contributes thermally superior, structurally efficient, economically, environmentally sustainable.

Table 6. Recent innovations in 3D sandwich panel manufacturing [67- 71, 73, 74]

Innovation area	Description	Reference
Sustainable core materials	Use of C&D waste, foam and recycled materials	[71,74]
3D Concrete printing	Layer-by-layer panel manufacturing, reduced formwork	[69,70]
Geometry optimization	Topology-based design to reduce weight and stress concentration	[68]
Hybrid insulation design	Multi-layered insulation for better thermal resistance	[67,73]

6. Structural Performance

6.1 Load-Bearing Capacity

Strengthening Weakness: A panel's ability to carry vertical or lateral structural loads without failing/having a hole in it. Panels of Precast Hollow-Core Sandwich Panel Wall (PHCSPW) showed higher axial and lateral strengths. From full scale pseudo-static tests, lateral load capacities of 17.49-19.64 kips with a strong post-yield behavior and very little reduction were observed due predominantly to the density of heavy slag concrete and reinforcement detailing [78]. Steel-Foam and Alum-Plywood panels showed equivalent behavior, as the energy absorbing cores facilitated the load transfer mechanisms for compression and flexure [77]. Expanded Polystyrene – High-Performance Expanded Polystyrene Concrete (EPS-HPEPC) resulted in a well performing (normalized score of 0.78) panel that approached lightweight core performance and improved face sheet strength, with reduced stiffness, compared to PHCSPW [76].

6.2 In-Plane Behavior

In-plane behavior assesses the performance of panels under shear forces and axial loads, which is particularly important in the case of lateral load resisting systems. EPS-HPEPC had a maximum scoring (0.82) in that category while benefited by its high flexural, compressive strength and enhanced bonding of the core as for example observed within the edgewise compression tests [76]. Rated by 0.80 and 1.12 respectively, it was because Precast Hollow-Core Sandwich Panel Column (PHCSPC) and PHCSPW exhibited well strain distribution and energy dissipation in simulated earthquake loads [78]. The shear strength of Steel-Foam panels was also demonstrated to be reliable because of the cushioning effect of the foam and the plastic deformation of the steel faces [77]. However, ALUM-Plywood panels, though acceptable, exhibited slight reduced in-plane strength owing to orthotropy of plywood and were thus not as desirable for high axial shear loads.

6.3 Out-of-Plane Behavior

This is what that panel can take without failing "in bending" (loads perpendicular to the panel plane, the way wind or impact would take it). The Alum-Plywood panel performed well (0.88) showing excellent resistance to penetration in high-velocity impact tests which both the aluminum face sheet and wood core absorb the impact. Moreover, Expanded Ultra-Lightweight Reinforced Sandwich Insulated Panel / High-Performance Expanded Polystyrene Concrete (EURSIP/HPEPC) was presented with excellent performance under 4-point bending tests (0.85), and high-flexural stiffness, with its failure mode kept stable (non-delimitative) [76]. Steel-Foam (0.80) and PHCSPW (0.75) panels performed well but were less intended for bending. Steel foam steel sandwich provided consistent and predictable flexural strength, especially in defensive structures [77]. The comparative structural performance of various 3D sandwich panel systems under different loading conditions is illustrated in Fig. 16.

6.4 Seismic Performance

Seismic behavior relies on ductility, energy absorption, and deformation capacity. The PHCSPW system far surpassed others in this area, with an evaluation of 0.90. Its cyclic testing revealed more extensive hysteresis loops and higher ductility. This precast structural wall configuration dissipated energy more effectively than comparable cast-in-place walls due to the component materials and interconnected panels [78]. Research also highlighted how Modular Sandwich Composite Insulated Panel (MSCIP) walls brilliantly mitigated seismic loads through resilient energy dissipation in full-scale simulations. Meanwhile, engineers continuously seek designs with optimal combinations of strength, drift reduction, and damage limitation [75]. Steel-Foam and Alum-Plywood panels are subjected to high impact, perform less energy absorption during cyclic loading and scoring 0.65 and 0.60 respectively [78]. Additionally, its strong behavior, EPS-HPEPC also had a low score of 0.60 and a propensity for stiffness decline after cracking [76].

6.5 Dynamic Performance

Dynamic performance necessitates withstanding high-velocity impact and blast loading with composure. Steel-Foam panels exhibited the most effectual behavior (0.90), remarkably deforming plastically and dissipating energy during explosive overpressure simulations [77], buttressing their excellence. Alum-Plywood constructions demonstrated staunch resistance to impact, uniquely from high-speed projectiles owing to the plywood's compressibility and the aluminum sheet's steadfastness. While achieving moderate success under dynamic stresses (0.70), PHCSPW suits static or quasi-static loads better [78]. EPS-HPEPC, though competent under customary loading, could not hold up when abruptly confronted with dynamic conditions (0.65) and it has a limited resistance under intense strain rates [76].

6.6 Durability and Long-Term Behavior

Durability encompasses aging resistance, fatigue behavior, and environmental degradation. PHCSPW exhibited the greatest resilience, scoring highest with a mark of 0.88 due to defeating chloride attack, surviving freeze-thaw cycles unscathed, and staunching crack propagation. These feats were proven through extensive long-term laboratory simulations and field evaluations that spanned numerous years [78]. Steel-Foam and Alum-Plywood performed well under repeated stress, gaining enhanced fatigue life thanks to their intricate layered structures, though moisture protection is paramount to fend off delamination [77]. Meanwhile, though exhibited diminished segregation and stiff bonding when fabricated under controlled conditions, it remained wanting when faced with harrowing conditions in the real world [76].

7. Design and Modeling Advancements

Advanced developments in the Sandwich composite panels from its design and modeling using Finite Element Modeling (FEM), parametric optimization studies and against international design codes are realized. Commercial software such as ANSYS and ABAQUS have been the key to simulating the complex structural behavior of these panels subjected to dynamic as well as static loads. For instance, Sahu et al. based case study for sensitivities and free vibration of glass fiber-reinforced plastic (GFRP) sandwich composite bridge deck panels using ANSYS, on how changes to the alignment of the stiffener, hole diameter and the property of the face layer affect the natural frequency and dynamic response of the deck panels [75]. Similarly, Tawil et al. employed ABAQUS to perform nonlinear practical push-off tests on precast concrete sandwich panels with S-type shear connectors, and afterwards the performance was evaluated for the shear resistance with preserving the thermal insulation effect through [81]. Figure 17. visually demonstrates the finite element modeling setup for GFRP sandwich bridge deck panels using ANSYS. Including this figure helps readers understand how stiffener orientation affects structural behavior as a core part of your FEM discussion. The finite element modeling setup for GFRP sandwich bridge deck panels analyzed in ANSYS is shown in Fig. 17.

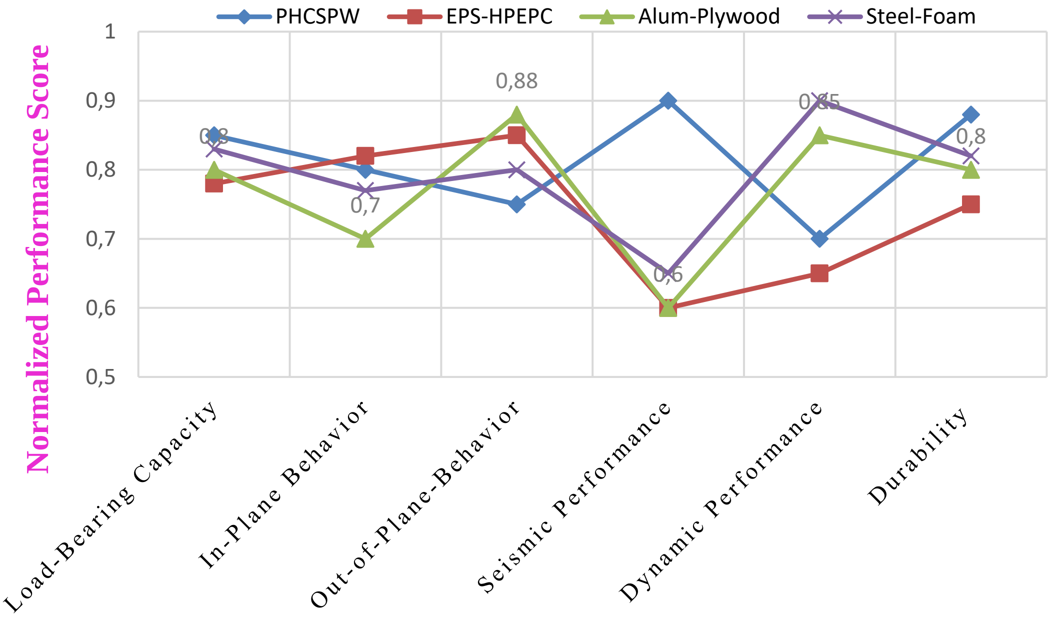


Fig. 16. Comparative Structural Performance of 3D Sandwich Panels (Precast Hollow-Core Sandwich Panel Wall (PHCSPW); Expanded Polystyrene–High-Performance Expanded Polystyrene Concrete (EPS-HPEPC) [76–78]

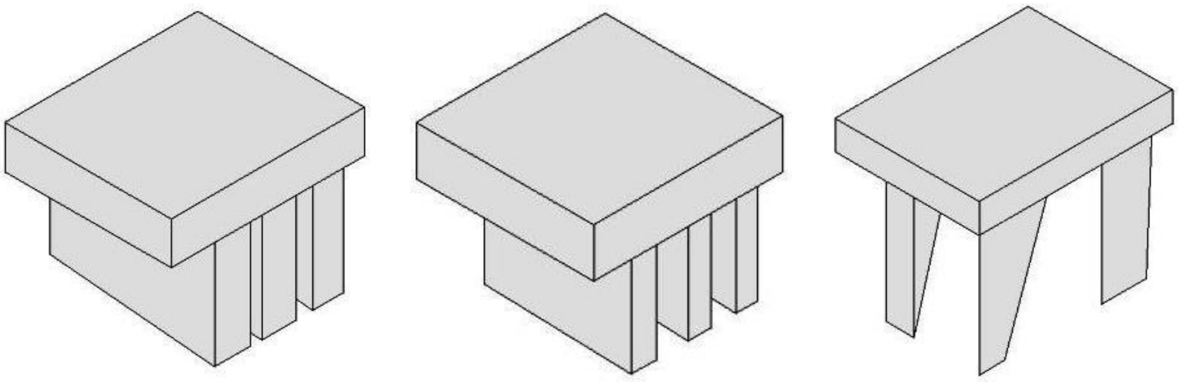


Fig. 17. Typical sandwich composite plate with multiple stiffeners in longitudinal, transverse, and inclined directions [75]

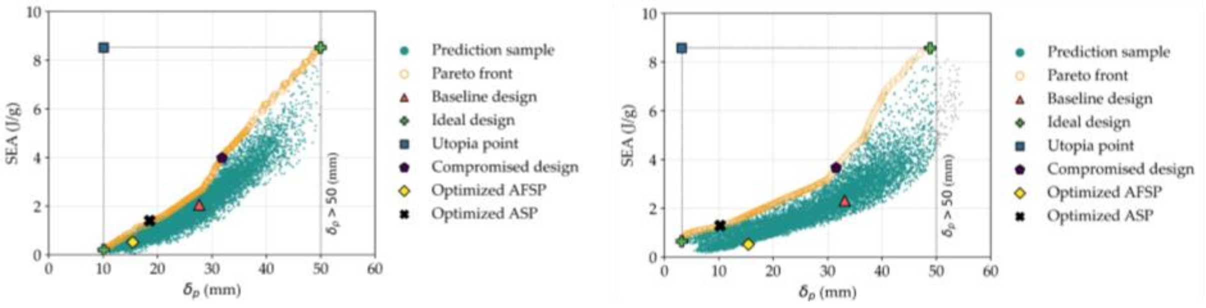
Parametric and multi-objective optimization approaches have also been widely used in this field. For instance, Andika et al. combines FEM with machine learning techniques to program the auxetic sandwich panels (ASPs) for armored fighting vehicles and perfect the procedure to obtain the optimal designs for the highest blast worthiness. Their global sensitivity analysis based on Shapley Additive explanations (SHAP) demonstrated the dominant role played by core cell wall thickness and geometry in energy absorption and in permanent deformation [76]. Another study also utilized ESO with nonlinear finite element analysis to minimize the topology of sandwich panels subjected to impact loads. His results demonstrated up to 50% weight reduction and 30% increase in energy absorption by changing core heights, unit cell number, and a specific layout of stiffeners [77]. In line with these attempts, Pandey et al. performed a multi-objective optimization of cellular core composite panels with aluminum honeycomb through RSM and reported that the optimal face sheet thickness and cell size result in maximum specific energy absorption and minimum peak impact load [78].

While gradient-based methods have certainly optimized sandwich panel structure, additional approaches show promise. Santos and colleagues explored rectangular honeycomb cores using the Method of Moving Asymptotes for out-of-plane bending loads on steel panels. Their solutions incorporated buckling and yielding failures into simplified yet accurate plate models. Remarkably, such reduced analyses provided practical design guidance on par with computationally intensive full simulations. Separately, recent topological techniques empower designers. By encoding panel composition and properties within an algorithm, automation evaluates thousands of configurations for a given loading. Emerging geometries outperform predecessors, holding weight constant or lessening mass considerably. Combined, numerical and generative methods advance lightweight, high-performance construction [79].

Adherence to design codes and standards is paramount in modeling structural systems, as they aim to ensure safety and performance. While few direct contrasts exist between the specifications set forth by organizations like the American Concrete Institute, Precast/Prestressed Concrete Institute, and Eurocode standards, numerous investigations have evaluated the code-prescribed equations against tangible test results. In one such study, Chakravarti and colleagues found that while predicted flexural capacities for reinforced concrete sandwich beams closely aligned with typical code formulations, the specified formulas for shear strength overestimated what could be borne. They consequently proposed modified expressions that demonstrated considerably improved correlation when put up against the experimental findings gathered, highlighting the need for periodic revision of design guidelines as new data becomes available and suggesting the need for tailored shear design provisions in modern sandwich construction [80]. Figure 18. illustrates the outcome of multi-objective optimization (via Non-dominated Sorting Genetic Algorithm (NSGA-II), showing how different auxetic core geometries (e.g., Reinforced Edge Hinge (REH), Double Angle Hinge (DAH), Shear Hinge (SH), Corner Hinge (CH) affect displacement and specific energy absorption. It supports your discussion on parametric optimization and highlights how design choices influence performance. As shown in Fig. 18, the Pareto front demonstrates the trade-off between δp (peak displacement) and SEA (specific energy absorption) for different auxetic models.

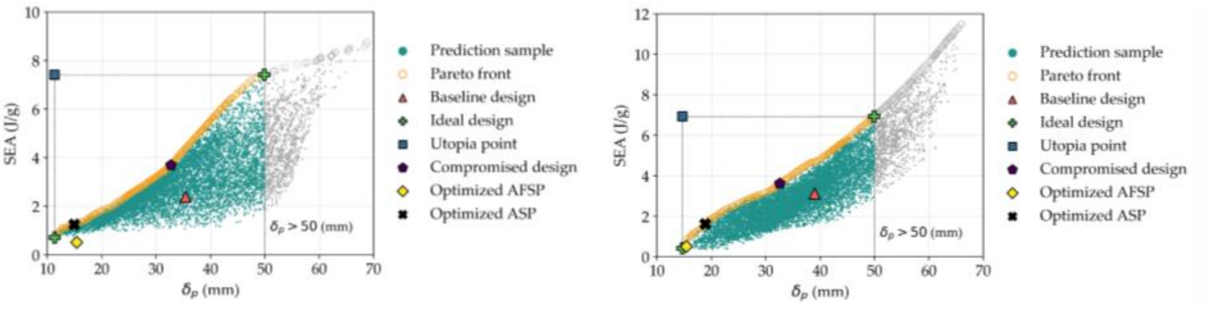
7.1 Design Code Context

Current sandwich-panel practice is guided by ACI 318-19, ACI 551R, PCI 150-24 (2024), and Eurocode 2 (EN 1992-1-1). These standards govern concrete strength, connector spacing, and load-combination limits for insulated precast panels. Comparative studies (Chakravarti et al., 2022; Tawil et al., 2024) reveal that shear-strength predictions in existing codes tend to be conservative or occasionally overestimated, indicating the need for updated, composite-specific provisions.



(a)

(b)



(c)

(d)

Fig. 18. Pareto front for each auxetic model showing trade-off between δp (peak displacement) and SEA (specific energy absorption) [76]

8. Challenges and Limitations

In spite of their ability for transformation, precast, and 3D sandwich wall panels have several major challenges and limitations, which must be tackled to be widely used in practice. One of the factors that makes thermal insulation performance problematic is heat loss by thermal bridging or metal or stiff connectors passing through the thermal insulating layer and reducing the thermal resistance of the panel system. While new shear connectors and hybrid materials have been developed to address this, reliable and proven solutions are still scarce. Another key restriction is that there are no complete and universally recognized codes and standards, particularly for more recent improvements (e.g., fiber reinforced polymer (FRP) connectors, bio-based insulation, 3D-printed panel designs). A lack of regulations also threatens to limit design options as well as challenge engineers and constructors to adopt innovative solutions confidently.

Furthermore, the transportation is also a problem and the settings being traditional precast settings, the formwork must be standardized. Although 3D printing and digital fabrication offer solutions to this challenge, applications in large-scale projects are still affected by the initial setup cost and by the fabrication process speed. Moreover, the long-term performance of UHPC exposed to fires, freeze-thaw cycles, earthquakes and humidity in practice requires further study. The use of shotcrete application processes, although possibly suitable for on-site manufacture, also relies heavily on labor skill and site-based conditions for consistency and final product finish. These issues indicate that more vigorous material testing, design, and codification work should be taken before sandwich panel could be used to its full potential in all types of construction.

9. Conclusion

Precast and 3D sandwich wall panels integrate strength, insulation, and rapid assembly, offering measurable improvements in construction speed and energy efficiency. Future research should prioritize experimentally validated connector designs that comply with ACI 318-19, ACI 551R, and PCI 150-24 specifications, along with the refinement of anchorage and shear-transfer detailing as prescribed in Eurocode 2 (EN 1992-1-1). At the same time, incorporating smart sensors and digital monitoring tools will enable real-time measurement of temperature, strain, and moisture, ensuring reliable performance throughout the service life of the panels. Emerging computational techniques are also reshaping the design philosophy of sandwich systems. Artificial-intelligence-based optimization methods, such as NSGA-II and SHAP analysis, allow multi-objective evaluation of parameters including core geometry, fiber orientation, and connector configuration. These approaches can enhance energy absorption, stiffness, and ductility while reducing life-cycle cost by approximately 15–20 % compared with conventional wall assemblies. Integration of additive manufacturing and digital-twin platforms will enable precise fabrication, continuous feedback, and predictive maintenance. The combination of topology optimization and 3D printing can further minimize material waste and improve consistency between simulated and experimental behavior.

From an environmental standpoint, the transition toward low-carbon and recyclable materials is critical. Substituting traditional cores with polyurethane foam, cellular lightweight concrete, or natural-fiber composites can decrease density by nearly 80% and improve thermal insulation by threefold. Recycling of construction and demolition waste as core fillers also supports circular-economy principles without compromising strength. To validate these innovations, coordinated experimental and numerical studies are needed to establish standardized evaluation methods for long-term durability, fatigue, and fire resistance. Finally, collaboration among researchers, industry professionals, and regulatory bodies is essential to harmonize global design and testing standards. By aligning advanced materials and digital fabrication with codified frameworks such as ACI, PCI, and Eurocode, precast and 3D sandwich panels can evolve into intelligent, regulation-compliant systems that ensure structural safety, superior thermal efficiency, and measurable sustainability for the next generation of building infrastructure.

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