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Recent Advances in the Mechanical and Thermal Performance of Concrete Sandwich Panels

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Abstract

Concrete sandwich panels (CSPs) are increasingly used in energy-efficient building envelopes due to their ability to combine structural load-bearing capacity with thermal insulation. This review provides an integrated assessment of recent advances (2018-2025) in the thermal and mechanical performance of CSPs, with particular emphasis on the trade-off between structural efficiency and thermal performance. The literature indicates a transition from traditional steel connectors, which induce significant thermal bridging, to low-conductivity fiber-reinforced polymer (FRP) connectors and optimized geometrical configurations. These developments, together with advanced insulation materials, have improved overall panel efficiency. However, mechanical performance remains strongly dependent on the degree of composite action, governed by connector stiffness, spacing, and configuration. A key finding of this review is the persistent conflict between mechanical and thermal requirements, where increased structural stiffness may lead to higher thermal-induced stresses and deformation. In addition, current research largely treats thermal and mechanical behaviors separately, with limited consideration of fully coupled thermo-mechanical interactions. Durability aspects, including moisture ingress, freeze-thaw effects, and long-term connector performance, are also insufficiently addressed. This review synthesizes current knowledge, highlights inconsistencies in experimental and modeling approaches, and identifies critical research gaps. Future studies should focus on integrated multi-physics modeling and full-scale experimental validation to improve the long-term performance and reliability of CSP systems.

Keywords

Concrete Sandwich Panels, Mechanical Performance, Thermal Performance, Shear Connectors, Composite Action, Thermal Insulation, Durability

1. Introduction

Concrete sandwich panels (CSPs) have become a widely adopted structural and thermal solution for modern building envelopes due to their light weight, high stiffness-to-weight ratio, and inherent thermal insulation capability. A typical CSP consists of two concrete wythes (outer layers) separated by an insulation core, with shear connectors embedded to transfer forces between the wythes and enable composite structural action. The growing global demand for energy-efficient and sustainable construction has driven substantial research over the past decade to optimize CSP performance specifically, to improve insulation systems, refine connector design, and understand the interaction between thermal and structural behaviors under realistic service conditions.

The performance of CSPs is governed by a complex interplay among connector material, geometry, spacing, insulation type, and the resulting degree of composite action (DCA) [1]-[4]. Thermally, the primary concern is thermal bridging localized heat flow paths through conductive elements which has traditionally been caused by metallic connectors. This has motivated the development of low-conductivity fiber-reinforced polymer (FRP) connectors and advanced insulation materials such as vacuum insulation panels (VIPs) and phase-change material (PCM) composites [5]-[9]. Mechanically, the flexural and shear behavior of panels, the role of connector stiffness in achieving composite action, and the critical failure mechanisms that govern panel capacity have received increasing attention.

However, a fundamental trade-off has become evident: stiffer connectors that improve structural performance also exacerbate thermal bowing and increase connector stresses under thermal gradients. This conflict between thermal efficiency and mechanical strength is a recurring theme in the literature [10]-[12]. Despite its importance, very few studies have addressed the coupled thermo-mechanical behavior of CSPs, even though real buildings are simultaneously exposed to thermal gradients, mechanical loads, moisture transport, and environmental aging. Most existing works rely on simplified or sequentially coupled numerical models that ignore temperature-dependent properties, moisture effects, and the feedback between thermal and mechanical damage. Consequently, significant knowledge gaps remain regarding panel performance under fire conditions, long-term loading, environmental exposure, and dynamic climatic variations.

Figure 1: is a schematic representation of the thermal-bridge effect in concrete sandwich panels. A CSP consists of two outers concrete wythes and an internal insulation layer that is meant to impede heat transfer. Under a thermal gradient, there is some heat flow through the insulation core by uniform, low-intensity paths. With the addition of a steel shear connector, however, there is now a highly conductive path between the wythes. This connector serves as a thermal short-

circuit, drawing heat through the panel and creating a localized spike in heat flux. This is evidenced by the clustered, thick heat-flow arrows concentrated around the connector. The figure provides a reason why steel connectors greatly increase U-values, create cold zones on internal surfaces, and reduce the energy efficiency of CSPs-motivating the transition to FRP connectors and optimized connector layouts in modern design.

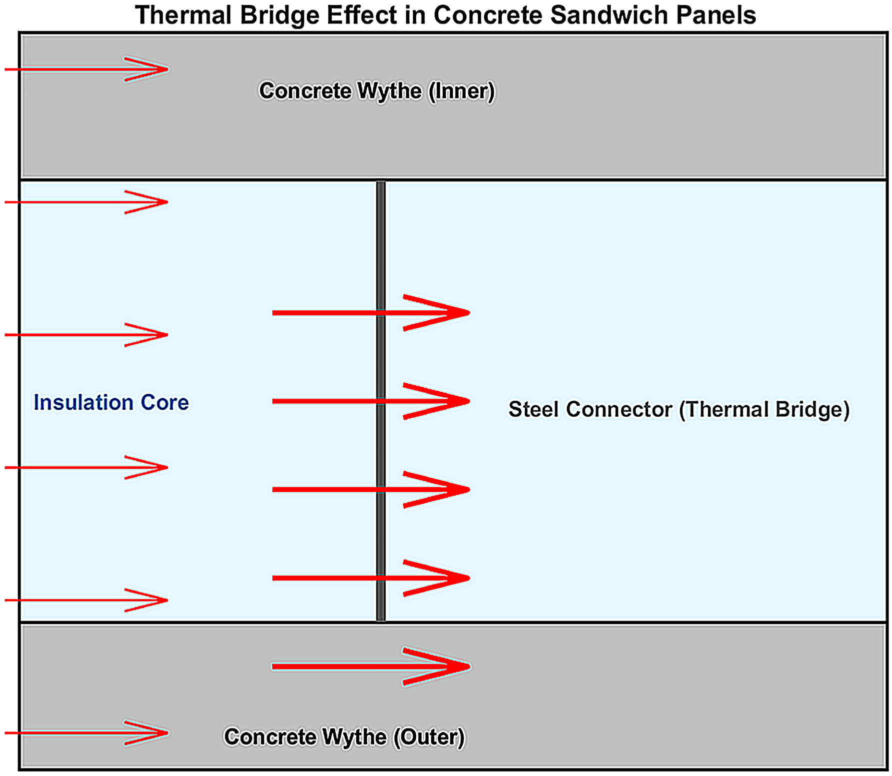

Figure 1. Thermal bridge effect in concrete sandwich panels.

1.1. Novelty and Contribution of This Review

While most past review papers examine the thermal and mechanical performances of CSPs separately, this paper offers an overview of both the interactions between them. Through a comparison among various types of cores, connectors, and designs, this paper reveals the intrinsic conflicts between the structural and thermal performances of CSPs. Furthermore, through this comprehensive review, several shortcomings have been found in past research efforts, especially the lack of attention to the thermo-mechanical coupling phenomenon, as well as some issues related to the durability, such as water infiltration and freezing-thawing cycles, connector durability, and so on. Finally, this paper summarizes various studies done within the period between 2018 and 2025 to quantify the ranges of mechanical and thermal performances of CSPs and analyze the potential discrepancies among different experimental setups.

Several studies conducted in recent years have attempted to highlight some of the important performance aspects of CSPs. Tawil *et al.* [13] have given a detailed discussion regarding the mechanical and thermal properties of PCSPs but have mainly discussed material properties without considering the balance between structural performance and thermal performance. In contrast, Sah *et al.* [14] have presented a review study on prefabricated concrete sandwich panels in terms of their use as lightweight wall panels but have discussed structural performance without discussing thermal performance in detail. Recently, Pozo-Lora *et al.* [15] have presented a review study on the construction technology of CSWPs where material aspects and construction technologies of CSWPs have been discussed. This review paper differs from the above-discussed studies because it attempts to evaluate: 1) providing an integrated, side-by-side assessment of both thermal and mechanical performance criteria using studies published between 2018 and 2025, 2) explicitly analyzing the trade-off between structural integrity and thermal insulation as a recurring theme across experimental and numerical studies, 3) critically evaluating the limitations of decoupled thermal and mechanical analyses, and 4) identifying the absence of validated, fully coupled thermo-mechanical models as a primary research gap. To the best of our knowledge, no previous review has systematically compared thermal and mechanical findings from the period 2018-2025 to highlight the inherent conflicts and coupled effects that govern real-world CSP behavior.

1.2. Scope and Structure of the Paper

Following the literature search methodology described in Section 1.3, this review is structured to provide a systematic and integrated analysis of the thermal and mechanical performance of concrete sandwich panels (CSPs). Section 2 examines the thermal performance of CSPs, with emphasis on the influence of connector materials and geometries, insulation systems, and the quantification of thermal bridging effects. It also reviews relevant numerical modeling approaches and discusses variations in reported thermal properties across different studies. Section 3 focuses on mechanical performance, including the role of connector types, degree of composite action, failure mechanisms, and the contribution of insulation cores to structural behavior. Particular attention is given to discrepancies in experimental findings and their underlying causes. Section 4 presents a critical review of thermo-mechanical coupling studies, distinguishing between fully coupled and sequential modeling approaches. Key phenomena such as thermal bowing and connector-induced stresses under temperature gradients are analyzed to highlight current modeling limitations. Finally, Section 5 provides concluding remarks and outlines recommendations for future research directions aimed at improving the performance and reliability of CSP systems.

When this review relies upon studies which do not create complete concrete sandwich panel structures (for instance, when looking at the study of new insulating materials, connector degradation in alkaline conditions, or the behavior of similar composite materials during a fire), such studies will be referred to solely as examples in relation to a particular mechanism.

1.3. Literature Search Methodology

A systematic literature search was conducted in November 2025 to identify relevant studies published between January 2018 and December 2025. The primary search was performed on the Web of Science Core Collection. Google Scholar was subsequently used to locate and download full texts but was not used as a separate source for record counting.

The search string was constructed using Boolean operators to combine keywords related to panel type, materials, performance metrics, and analysis methods:

((“sandwich” OR “multilayer”) AND concrete AND (panel* OR wall* OR slab*) AND (“mechanical” OR “flexural” OR “shear” OR “compression”) AND (“thermal” OR “insulation” OR “conductivity” OR “energy performance”) AND (connector* OR “interlayer” OR bond OR core OR foam) AND (“finite element” OR numerical OR simulation OR experimental))

The initial search returned 154 records from Web of Science. After removing 8 duplicate records (using reference management software), 146 unique records remained.

These 146 records were screened in two stages:

1) Title and abstract screening: Records were included if they reported experimental, numerical, or analytical investigations focused on the mechanical or thermal performance of concrete sandwich panels incorporating shear connectors. Records were excluded if they a) used non-concrete materials (e.g., pure steel or wood sandwich panels), b) lacked quantitative data, or c) addressed acoustic-only behavior. This stage excluded 90 records, leaving 56 records for full-text review.

2) Full-text screening: The full texts of the remaining 56 records were assessed against the same inclusion criteria, with the additional requirement that studies must report quantifiable outcomes (e.g., load-deflection behavior, stiffness, U-value, connector forces, or degree of composite action). A further 11 records were excluded because the full text could not be obtained or was not available.

This systematic process yielded a final set of 45 primary studies that form the foundation of this review.

In a small number of cases, studies that did not construct or test full concrete sandwich panels were included as supporting analogies. Specifically, studies investigating novel insulation materials (e.g., phase-change materials, bio-based foams), connector ageing in alkaline environments, or fire behavior of related composite panels were retained only when their findings directly informed the interpretation of CSP thermal or mechanical performance. These studies are explicitly identified in the text as supporting evidence rather than primary CSP data.

2. Thermal Performance and Heat Transfer Analysis

The thermal efficiency of Precast Concrete Sandwich Panels (PCSPs) is governed by the insulation core and the thermal bridging introduced by shear connectors. While the fundamental trade-off between mechanical connectivity and thermal resistance is well-recognized, a critical examination of the literature reveals significant methodological inconsistencies, contradictory findings, and knowledge gaps that this review aims to synthesize.

2.1. The Paramountcy of Connector Material and Design

Basically, the material selection of shear connectors can be considered the most influential factor for thermal bridging mitigation. There is a significant difference between conventional steel and new FRP shear connectors. Conventional steel connectors have high thermal conductivities (e.g., 16 - 60 W/m·K) that imply a substantial thermal bridge, causing high U-values and point heat loss [7] [11]. For example, the replacement of carbon steel (58.2 W/m·K) with stainless steel (16.2 W/m·K) shear connectors reduced the thermal transmittance by 24.5% [7]. However, an uncritical acceptance of FRP superiority obscures important nuances. Steel connectors, despite their high conductivity, remain viable when geometric optimization is employed. Bida *et al.* [16] demonstrated that staggering steel plate connectors at 400 mm spacing corresponding to a 127% increase in R-value and a 56.5% reduction in U-value, achieving thermal performance comparable to some FRP designs. This finding directly challenges the implicit assumption that FRP is always necessary for high thermal efficiency. Conversely, Yu *et al.* [17] showed that even with FRP connectors, improper spacing (≤200 mm) can negate their low-conductivity advantage, producing U-values (0.65 W/m^2·K) that are worse than optimally staggered steel designs [16].

In contrast, FRP connectors (e.g., GFRP, BFRP, CFRP), with their inherently low thermal conductivity (typically 0.125 - 1.37 W/m·K), dramatically diminish this effect. Numerical and experimental studies consistently report GFRP connectors result in "minimal" or "negligible" thermal bridging [1] [2] [18]. Their use is a main theme in the literature, often cited as the primary strategy to avoid the thermal performance penalties associated with steel [4] [5] [19]-[23]. A critical methodological issue emerges when comparing studies: most investigations report steady-state U-values under idealized laboratory conditions, which fail to capture diurnal cycling or solar radiation effects. Only four studies in this review employed transient or dynamic boundary conditions [2] [12] [18] [24], and none directly compared steady-state versus transient performance for identical panel configurations. This gap raises questions about the real-world applicability of reported U-value rankings.

Beyond material, the geometric configuration of connectors is equally important. Research has shown that with increased connector spacing [17] [25] and through the use of a staggered layout, dramatic improvements in thermal resistance can be achieved. Staggering connectors increases the length and tortuosity of the heat flow path, and one study has reported a 127% improvement in R-value resulting from switching from a direct to a 400 mm staggered layout [16]. Similarly, reducing the cross-sectional area and embedded length of a connector also produces positive thermal benefits [17]. Furthermore, the thermal performance of hybrid connectors such as steel elements with thermal breaks [26] [27] remains qualitatively claimed but quantitatively unvalidated. No study to date has experimentally measured the thermal bridge reduction of such novel designs, representing a critical research gap.

Figure 2. Thermal conductivity comparison of common PCSP materials. The logarithmic scale highlights the orders of magnitude difference between conductive steel connectors and insulating FRP alternatives. Carbon steel exhibits the highest conductivity (58.2 W/m·K), while VIP insulation shows the lowest (0.005 W/m·K). FRP connectors (GFRP: 0.35 W/m·K, CFRP: 8.0 W/m·K) demonstrate significantly reduced thermal bridging potential compared to metallic options, making them preferable for energy-efficient designs [1] [6] [7] [11] [17].

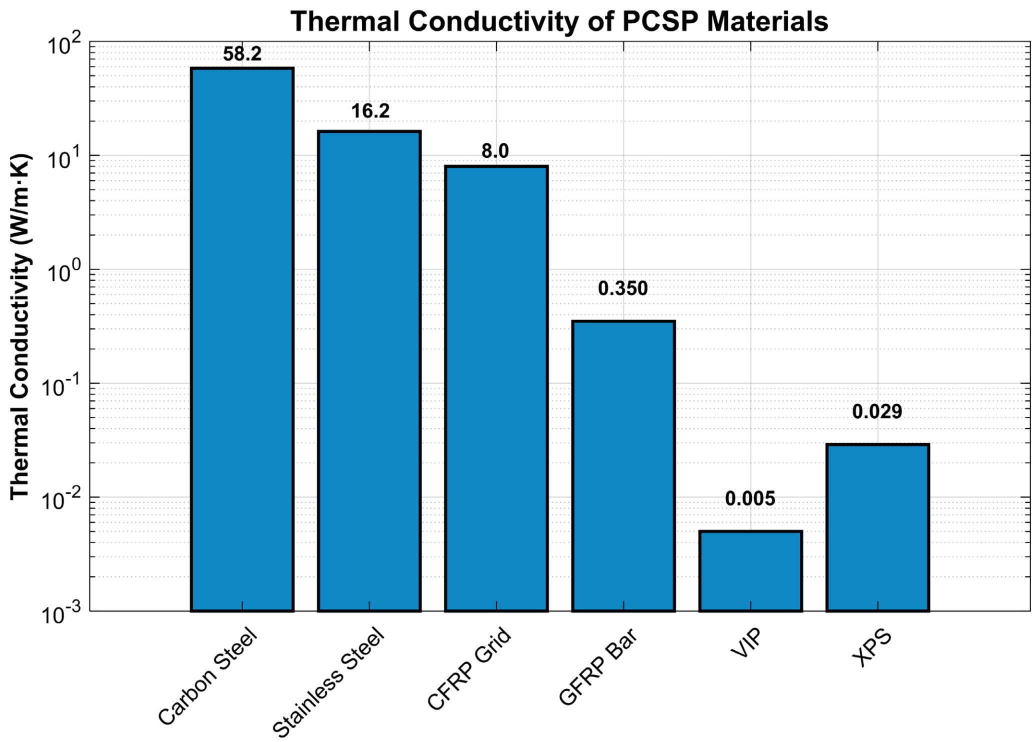

Figure 2. Thermal conductivity of PCSP materials.

2.2. Insulation Systems: Core Materials and Advanced Solutions

The main resistance to heat flow is provided by the insulation core, whose properties are fundamental to the U-value of the panel. By a wide margin, insulation thickness is found to be the most important parameter that can be used to improve thermal performance. One study increased the thickness of XPS insulation from 30 mm to 90 mm and recorded a U-value reduction of approximately 59% [17], while other researchers have similarly found better performances with 40-50 mm thick solutions compared to thinner ones [28]. However, the marginal benefit diminishes beyond 100 mm; Li *et al.* [7] reported only a 5% additional reduction in U-value when increasing thickness from 100 mm to 150 mm, suggesting an economic optimum around 80 - 100 mm for most climates.

Performance is also affected by insulation type (XPS, EPS, PU, Mineral Wool), although usually to a lesser degree than thickness. Whereas XPS and PU usually have lower conductivity than EPS [29], several authors have reported that the difference between XPS and EPS has a "negligible influence" on the final inner surface temperature [28]. This apparent contradiction likely arises from differing boundary conditions. Yu *et al.* [17] applied a 50˚C temperature differential (40˚C to −10˚C), while Thangarasu and Helena [28] used a milder 47˚C - 53˚C differential (75˚C outer to 22˚C - 28˚C inner). Under larger thermal gradients, conductivity differences become amplified, explaining the conflicting conclusions.

This level of performance has driven interest in advanced insulation materials. Examples include Vacuum Insulation Panels (VIPs) that can provide very low conductivity, around 0.005 W/m·K, enabling extremely low U-values such as 0.096 W/m^2·K [6]. However, O'Hegarty *et al.* [6] critically documented that concrete seepage bridges as thin as 1 - 4 mm increases the U-value by a factor of 1.9 to 3.0, and gaps between VIP modules due to non-standard panel dimensions can reduce effective thermal resistance by over 40%. These practical limitations, often overlooked in laboratory studies, severely constrain VIP adoption in real-world prefabrication. Other recent developments include geopolymer concrete composites with Phase Change Material (PCM) capsules: up to 47% U-value reduction was achieved through latent heat storage [26], though long-term cycling stability of PCMs in alkaline environments remains unverified.

2.3. Quantification and Mitigation of Thermal Bridges

Thermal bridging is a quantifiable phenomenon, not just a conceptual drawback. FEA studies graphically depict concentrated heat flux paths through conductive connectors [19] [21] and resultant localized surface temperature depressions, or "islands" [29]. The extent of the effect has been quantified as a "thermal bridge influence region" extending 80 - 130 mm from a stainless-steel connector [17]. For FRP connectors, the influence region was deemed "too small to define" using the same methodology, but this does not imply zero thermal bridging; rather, it highlights a measurement limitation.

A concerning finding is that validation errors between FEA and experiments vary substantially, from as low as 2.3% [16] to as high as 16% [2]. Jawdhari and Fam [2] reported a 16% error for thermal bowing predictions under extreme cold (−50˚C), suggesting that material property assumptions specifically, using constant conductivity versus temperature-dependent values become critical at temperature extremes. Similarly, Li *et al.* [7] attributed their 11.8% average error to neglecting air gaps between layers, a simplifying assumption common to most FEA models. No study has systematically quantified the error introduced by these assumptions, leaving readers uncertain about the reliability of reported U-values.

Effective mitigation strategies go beyond the choice of FRP connectors. A particularly successful strategy involves providing a thermal break layer on the inner wythe. A layer of AAC used in place of conventional concrete was found to significantly flatten the temperature distribution around connectors, rendering the wall a 12.5% reduction in thermal bridge influence (*i.e.*, lower sensitivity to connector-induced heat loss) and achieving a 47% lower U-value compared with the conventional panel [7]. Further, the presence of thermal bridges at the macro-scale, such as panel-to-panel joints, and the interfaces of panels with other building elements, introduces significant heat losses, highlighting the need for optimization to minimize linear thermal transmittance (ψ-value) [24]. Yang *et al.* [24] demonstrated that making adjacent walls thermally similar reduced the ψ-value of vertical joints by 28.9%, yet no study has validated these optimizations under full-scale structural loading.

Figure 3. Thermal bridge visualization and mitigation strategies. (a) Temperature distribution showing localized cold spots at steel connector locations; (b) Heat flux concentration demonstrating preferential heat flow paths through thermal bridges; (c) Comparative effectiveness of mitigation strategies, with AAC thermal break layers providing the most significant U-value reduction (74% improvement over baseline steel connectors) [7] [17] [25].

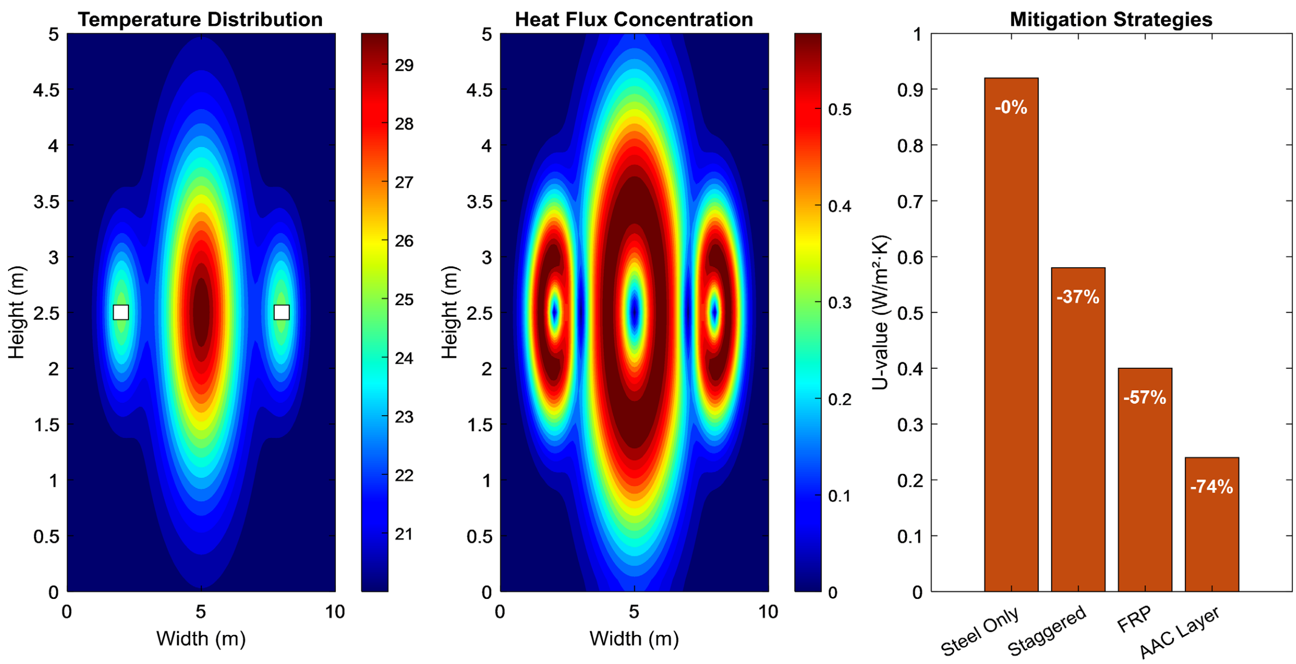

Figure 3. Thermal bridge visualization and mitigation strategies.

2.4. Numerical Modeling and Experimental Validation

Numerical modeling, with particular emphasis on 3D FEA, is an important predictor of the complex thermal behavior of PCSPs. Sophisticated models using ANSYS, ABAQUS, and COMSOL have been successfully used to simulate steady-state and transient heat transfer [2], temperature-dependent material properties [3], and intricate connector geometries [7] [17].

The validity of such models is very strong, with various studies consistently showing very close agreement with experimental results. The error in the predicted versus the experimentally measured U-value or surface temperatures is often less than 10% [7] [16] [17] [29], going as low as 2.5%-5.8% for some cases [7] [17]. Experimental validations have mainly been done by means of the standard guarded hot box test [7] [16] [17] [29] and transient thermal enclosure tests [12].

Yet, all these models have their limitations. The most commonly used simplifying assumptions include steady-state conditions [1] [17] [28], constant material properties [1] [2], perfect interfacial bonds, and neglecting moisture effects and internal air convection [3] [18] [26]. The steady-state assumption, used in twelve of the fourteen modeling studies reviewed, ignores thermal mass effects. Concrete wythes have significant heat capacity (approximately 1000 J/kg·K), which attenuates diurnal temperature swings. Transient analyses [2] [12] show that steady-state models overestimate heat flow by 15% - 25% under cyclic loading, yet no design guidelines currently incorporate this correction. Constant material properties fail to capture conductivity changes with temperature; for XPS, conductivity increases by 30% - 40% from 0˚C to 50˚C [3], while for concrete, moisture-dependent conductivity can vary by ±20% [26]. Fire exposure studies [18] [19] explicitly show that property degradation dramatically alters heat transfer, but ambient-temperature studies universally ignore this a potentially serious limitation for panels installed in extreme climates. Perfect bond assumptions neglect contact resistance, which can reduce thermal bridging by 5% - 10% due to microscopic air gaps [17]. These simplifications can lead to discrepancies in real-world scenarios, especially during fire exposure [18] or dynamic environmental loading.

2.5. Critical Analysis and Future Research Directions

While the literature establishes the superiority of FRP connectors and the importance of insulation thickness, several gaps are evident. A key limitation is that many studies promote the thermal benefits of FRPs only qualitatively, without quantitative system-level data for assembled panels [16] [24] [26]-[43]. Over 40% of mechanically focused studies claim thermal advantages without any thermal measurement, a gap that requires standardized hot-box testing or FEA validation.

There is also a strong bias toward steady-state analysis. Future research should prioritize transient coupled thermal-structural analysis that accounts for diurnal and seasonal cycles, thermal mass, and solar radiation. Transient simulations linked to climate data, as initiated by Annaba *et al.* [43], could generate location-specific design recommendations.

Heat-moisture interactions remain poorly understood. Moisture intrusion alters material conductivity and accelerates corrosion, yet no study has simultaneously modeled moisture transport, heat transfer, and mechanical stress. Given that moisture increases concrete conductivity by up to 0.5 W/m·K [26], robust hygro-thermal models are needed to assess long-term performance and risks like interstitial condensation. Furthermore, all reviewed studies tested new panels; no data exist on thermal degradation over 10 - 50 years due to insulation creep, connector fatigue, or moisture ingress.

Promising future directions include quantified multi-objective optimization of connector design, long-term transient field studies, hygro-thermal-mechanical modeling, and sustainable system integration (e.g., bio-based insulations [27] and robust VIP techniques). In conclusion, while thicker insulation and low-conductivity connectors clearly improve thermal performance, methodological inconsistencies and missing validation data prevent reliable quantitative design guidance. Future research must move beyond descriptive comparisons toward standardized, transient, and coupled multi-physics analysis.

As shown in **Table 1**, although FRP connectors generally improve thermal performance, their effectiveness depends on configuration and interface conditions. In contrast, steel connectors consistently exhibit higher thermal conductivity, leading to increased thermal bridging. However, some studies indicate that geometric optimization, such as staggered arrangements, can partially mitigate these effects.

Table 1. Summarizes the thermal performance of CSP systems with different connector types and insulation materials. The comparison highlights that low-conductivity connectors such as FRP significantly reduce thermal bridging, whereas metallic connectors tend to increase U-values, particularly when combined with discontinuities such as concrete seepage or edge effects.

Reference	Connector type	Insulation core	Thermal conductivity (W/m·K)	U-value (W/m²·K)	Key finding
Pozo-Lora & Maguire [10]	Flexible FRP (assumed equal to insulation)	XPS/EPS (not specified)	N/R (assumed negligible bridging)	Not reported	Thermal bowing significant; connectors assumed no thermal bridge
Jawdhari & Fam [1]	GFRP bars (φ4.2 mm)	Rigid insulation foam	GFRP: 0.35; Insulation: 0.029; UHPC: 0.52	Not reported	GFRP minimizes thermal bridging; validated with FEA
Thangarasu & Helena [28]	Steel diagonal bars (8 - 10 mm)	XPS (0.028) or EPS (0.042)	Concrete: 1.74; XPS: 0.028; EPS: 0.042	Not reported	50 mm insulation best; steel connectors negligible impact
Jawdhari *et al.* [2]	X-shaped GFRP rebar (9.5 - 15.9 mm)	XPS (75 mm, 30 kg/m³)	Concrete: 2.7; XPS: 0.029; GFRP: 0.35	N/R (R-value: 12.7 m²K/W per 25 mm)	GFRP minimizes bridging; cooling loads more critical
Kinnane *et al.* [11]	Stainless steel flat plates	EPS (rigid)	EPS: 0.027; Steel: high	0.11 - 0.25	Steel plates create significant thermal bridges
Haffke *et al.* [34]	GFRP bars	Mineral wool	Mineral wool: ~0.035 - 0.040	Not measured	Minor thermal bridging (max temp rise 56˚C near connectors)
Arevalo & Tomlinson [12]	GFRP bars (9.5 - 16 mm)	XPS (75 mm)	XPS: 0.029; GFRP: 0.125	Not measured (RSI = 3.55 m²K/W)	GFRP less conductive than steel but still contributes to bridging
O'Hegarty *et al.* [6]	CFRP grid	VIP + Phenolic foam (90 mm)	VIP: 0.005; Phenolic: 0.021; CFRP: 8.0	0.096 (100% VIP) - 0.29 (with concrete bridge)	Concrete seepage bridge (1 - 4 mm) increases U-value 1.9 - 3.0×

Continued

Li *et al.* [7]	Stainless steel plate (vs. carbon steel)	PU (60 - 100 mm) + AAC inner layer	SS: 16.2; CS: 58.2; PU: 0.020-0.024; AAC: 0.14	0.241 - 0.728	SS reduces U-value by 24.5% vs. CS; AAC layer mitigates bridges
Yu *et al.* [17]	U-shape SS, L-shape SS, GFRP	XPS (30 - 90 mm, 35 kg/m^3)	SS: 16.3; GFRP: 0.52; XPS: 0.030	0.328 - 0.797	90 mm XPS gives lowest U-value; GFRP bridging negligible
Zhang *et al.* [25]	Steel truss (SS web) + fiberglass grid	XPS (40 - 90 mm)	Steel chord: 58.2; SS web: 16.2; XPS: 0.031; Fiberglass: 0.4	0.767 - 0.768	Concrete edges increase U-value by 11%; connectors by 2.7%
Bida *et al.* [16]	Steel column studs (10 mm, staggered)	Polystyrene (not specified)	Steel: 60; Polystyrene: 0.037; Concrete: 1.88	0.40 - 0.92	Staggering connectors improves R-value by 127%
Su *et al.* [29]	Integrated BFRP square tubes	XPS, PU, or Rock wool	BFRP: 0.154; XPS: 0.032; PU: 0.018; Rock wool: 0.038	0.40 - 0.60	BFRP tubes create low thermal bridge effect (5.8% - 10.2% of total heat flow)

3. Mechanical Performance of Concrete Sandwich Panels

The mechanical performance of CSPs is fundamental to their structural viability for applications in buildings. Such performance is not a function of the concrete wythes in isolation but involves complex interactions between the wythes, the insulation core, and-most crucially-the shear connectors integrating the system. Research into the flexural, shear, and compressive behavior of CSPs has been extensive, with particular emphasis on connector type, geometry, and arrangement in achieving composite action and dictating failure modes.

Before proceeding to synthesize mechanical performance values, it is important to highlight one major limitation inherent in such a process: it is impossible to compare the absolute values of flexural load capacity, shear strength, and deflection directly since they result from experiments on specimens that differ in geometry, spans, and even loading types used. For instance, a panel subjected to four-point bending with a 3000 mm span will withstand a much lower flexural load compared to another identical panel under the same loading conditions but with a 1500 mm span. Where relevant, the current review classifies mechanical properties according to test types (push-out tests, four-point bending tests, full-scale wall tests, etc.), while also providing information on geometrical characteristics (specimen span, width, and thickness). It should be noted that the absolute comparison of values obtained during different testing procedures is not the purpose of this review but rather a warning for its readers.

3.1. Critical Evaluation of Experimental Methods

The reported mechanical performance of concrete sandwich panels (CSPs) is highly dependent on the chosen test method, and a critical comparison reveals that no single approach is sufficient to capture full structural behavior. Push-out or direct shear tests [8] [11] [20] [23] [30] [32] [44] are the most common because they isolate connector shear capacity, enabling direct geometric comparisons; however, they impose uniform shear stress distributions that rarely occur in actual bending panels and cannot capture the flexural composite action that governs service-load behavior. Four-point bending tests [1] [19] [22] [33] [38] provide a realistic representation of panel behavior under flexure, but they are resource-intensive and often limited to small specimen widths (e.g., 600 mm [22] or 1000 mm [33]), which may not capture edge effects or three-dimensional stress distributions. Pull-out tests [4] [5] [37] assess anchorage capacity but typically overestimate connector contribution when used directly in flexural design, as explicitly noted by Lameiras *et al.* [37]. Consequently, the most reliable conclusions come from multi-method studies that combine push-out, pull-out, and full-scale bending on identical specimens, such as the work by Huang *et al.* [19]; without such validation, design recommendations based on a single test method remain provisional.

3.2. Resolving Contradictions in Connector Performance

Contradictory findings regarding the superiority of specific connector geometries can be resolved by examining the performance metric used, the scale of testing, and the transition in failure modes. Huang *et al.* [19] reported that larger cross-shaped GFRP connectors increased flexural ultimate load by 42%, whereas Chen *et al.* [30] found that rectangular (L1) connectors outperformed cross-shaped (L2) connectors in shear capacity (100.45 kN vs. 88.66 kN) and ductility (failure displacement 18.99 mm vs. 5.00 mm); Bian and Liu [20] further showed that I-shaped connectors provided the highest shear strength among seven configurations. These discrepancies arise because Huang *et al.* measured flexural behavior (where both shear transfer and tensile anchorage matter) while Chen *et al.* and Bian and Liu evaluated pure shear via push-out tests on different specimen scales. Moreover, Bian and Liu explicitly noted that failure mode shifts from connector shear fracture for short connectors (embedment depth ≤ 50 mm) to concrete anchorage failure for long connectors (>100 mm). For metallic versus FRP connectors, steel connectors consistently provide higher ultimate shear capacity [11] [31] [32] [39], but Tawil *et al.* [32] observed that wide steel S-connectors (152.4 mm) failed by buckling rather than yielding, reducing effective ductility, while Zhao *et al.* [39] reported that hybrid stainless-steel/GFRP systems achieved a predicted service load of 178.63 kN significantly higher than all-FRP systems yet caused concrete damage due to stress concentration. Thus, the choice between FRP and metallic connectors is conditional: steel excels in shear but may induce premature concrete failure or thermal bridging, whereas FRP connectors provide more uniform stress distribution and eliminate thermal penalties, making them suitable for thermally optimized cladding [5] [21] while hybrid systems are preferable for load-bearing walls [39].

As shown in **Table 2**, connector geometry and material significantly influence both strength and failure mechanisms. Steel connectors generally exhibit higher

Table 2. Summarizes the mechanical performance of various CSP connector systems, including their load-carrying capacity, failure modes, and degree of composite action. The comparison highlights the influence of connector geometry and material on structural behavior.

Ref	Connector type & geometry	Flexural/Shear capacity	Failure mode	Composite action (DCA)
[11]	Flat steel plate; 2 - 3 mm thick, 80 - 400 mm depth	Shear capacity: 14 - 240 kN (per panel)	Plate buckling (2 mm) or concrete pull-out (3 mm)	Not reported
[30]	GFRP rectangular (L1) vs. cross-shaped (L2); 400 × 400 mm grid	Panel shear: 100.45 kN (L1), 88.66 kN (L2)	L1: fiber splitting; L2: shear fracture	Not reported; L1 showed better ductility
[39]	Hybrid SSI + GFRP bars; 12 mm SSI + 10 mm GFRP	Test terminated at 118 kN (no failure); numerical service load 178.6 kN	Concrete crushing at loaded end	Not reported
[5]	TBSC (GFRP sleeve + steel core); bent angle 70˚ - 110˚	Pull-out: 10 - 21 kN per connector; direct shear: 91 - 169 kN per specimen	Concrete anchorage failure	N/R; TBSC outperformed standard GFRP bars
[19]	Cross-shaped GFRP; 112 mm^2 or 276 mm^2 area; spacing 300 - 500 mm	Flexural ultimate: 29.5 - 42.8 kN (panel)	Connector failure (rupture)	Initial stiffness DCA <4%; ultimate strength DCA higher
[32]	S-type steel plate; width 76 - 152 mm, thickness 2 mm	Shear per connector: 53.6 - 104.1 kN	SC3/SC4: shear yielding; SC6: buckling/pull-out	Not reported
[20]	I-shaped vs. truss vs. grid FRP connectors	Peak shear: 12.5 - 213 kN (depending on configuration)	I-shape: laminar fracture; truss: tensile/shear-compression	N/R; toughness index reported instead
[8]	GFRP circular tube (CUT) vs. square tube (SUT); insulation 50 - 250 mm	Peak shear per connector: 11 - 43 kN (decreases with insulation thickness)	Connector shear (50 mm) → concrete anchorage (150 - 250 mm)	Not reported
[38]	UHPC-filled stainless steel pipe; Ø48 - 60 mm, spacing 200 - 300 mm	Flexural moment: 61.3 - 95.1 kN·m	SP1: like solid slab (ductile); SP2: flexural runaway	High (SP1) vs. partial (SP2)
[22]	Pultruded square GFRP tube; 40 × 40 × 3.2 mm; spacing 280 - 390 mm	Flexural ultimate: 75 - 107 kN (panel)	Tension connectors: foam cracking; compression connectors: punching	Up to 142% (tension-direction orientation)
[23]	Grid-type GFRP; diagonal spacing 35 mm or 53 mm	Shear flow: 58 - 76 kN/m (XPS)	GFRP grid rupture + concrete/insulation bond failure	N/R (toughness index reported)
[33]	Transverse GFRP ties vs. diagonal (X-pattern) GFRP; Ø4.2 mm	Flexural ultimate: 3.9 - 17.3 kN (panel)	FRP connector fracture	Transverse: 5% - 15%; X-pattern: 32%

NOTE: Flexure and shear strengths are given as originally published for specimens of various geometries, spans, test fixtures, and loading configurations. Quantitative comparisons between different rows may be misleading. Generalized trends rather than absolute data form the key findings of this literature review.

load-carrying capacity but tend to fail through buckling or concrete pull-out, whereas FRP connectors show lower thermal conductivity but are more prone to brittle fracture. In addition, the degree of composite action varies widely across studies, with some configurations achieving near-full interaction while others remain partially composite. These variations reflect differences in connector stiffness, spacing, and anchorage conditions, and highlight the lack of a unified performance framework.

3.3. Influence of Insulation Thickness and Material

Conflicting evidence on whether thicker insulation increases or decreases structural strength is resolved by distinguishing flexural from shear response. In flexure-dominated studies, increasing insulation thickness enhances the lever arm between wythes, thereby increasing flexural strength; Ding *et al.* [45] and Sylaj *et al.* [33] both reported that thicker XPS cores (e.g., from 50 mm to 150 mm) increased ultimate moment by up to 2.4 times. In contrast, shear-dominated studies show that thicker insulation reduces shear capacity because it increases connector slenderness, promoting buckling or flexural failure of the connector itself; Choi *et al.* [23] found that shear flow capacity decreased as insulation thickness increased from 50 mm to 150 mm, and an and Huang [8] reported a drop in peak load per connector from ~26 kN (50 mm) to ~11 kN (250 mm) for circular tube connectors. Regarding insulation material, Choi *et al.* [23] observed that XPS provides higher initial shear flow capacity than EPS, whereas EPS exhibits greater post-peak toughness due to shear cracking within the foam itself; Egbon and Tomlinson [44] found that notching the insulation improved XPS performance significantly (through mechanical interlock after bond failure) but had minimal effect on EPS or PIR, which maintain a strong chemical bond with concrete. A critical methodological weakness across these studies is the inconsistent reporting of foam density and compressive strength, making direct comparisons unreliable and indicating that future research must standardize these parameters.

3.4. Degree of Composite Action (DCA): Definitions and Inconsistencies

The degree of composite action is the most inconsistently reported parameter in the literature, with values ranging from below 5% [9] [40] to over 100% (142% reported as "near-full composite action" by Sah *et al.* [22]), but this extreme range is not due to material variation alone it stems from definitional differences and test artifacts. Some studies calculate DCA based on initial stiffness, others on ultimate strength, and still others on deflection at service load [28] [42] [46]; Huang *et al.* [19] explicitly demonstrated that initial-stiffness DCA was less than 4%, whereas ultimate-strength DCA was substantially higher because connectors engage gradually after slip occurs. Furthermore, Sah *et al.* [22] achieved 142% DCA by orienting connectors in tension, which mechanically pre-loaded the connection, whereas O'Hegarty *et al.* [6] [21] reported low DCA (<15%) with CFRP grids due to initial slack that delayed engagement. Consequently, reported DCA values reflect not only intrinsic panel properties but also connector pre-conditioning and measurement definition. The field urgently needs a standardized DCA definition for example, the ratio of experimental to full-composite flexural stiffness at 50% of ultimate load to enable meaningful cross-study comparison.

3.5. Failure Modes and Their Dependence on Connector Slenderness

Failure mode classifications vary across studies, but three consistent patterns emerge when controlling for connector slenderness, insulation type, and loading conditions. First, in panels with short, stocky connectors (embedment depth ≤ 50 mm or connector length ≤ 100 mm), failure typically occurs by connector rupture [19]-[21]; in panels with long, slender connectors (embedment depth > 100 mm or length >250 mm), failure shifts to concrete anchorage failure [4] [8], and Zhao *et al.* [39] observed this transition explicitly when increasing connector length from 150 mm to 250 mm. Second, the presence and type of insulation strongly influence failure; Egbon and Tomlinson [44] showed that notched XPS changes failure from bond-dominated to mechanical-interlock-dominated, increasing capacity by more than 50%, but this effect is material-specific EPS and PIR did not show the same improvement because they maintain strong chemical adhesion. Third, under fire conditions, numerical models by Chen *et al.* [18] predicted that progressive GFRP connector rupture triggers global buckling, whereas experimental work by Haffke *et al.* [34] on stockier panels with high-density connectors showed maintained integrity for 120 minutes; this apparent contradiction is resolved by noting that the critical parameter is the ratio of axial load to buckling capacity, not the connector material alone.

3.6. Quantitative Trends, Durability, and Modeling Advances

Quantitative synthesis of the reviewed studies (2018-2025) reveals clear ranges: flexural ultimate loads range from approximately 7.7 kN for unreinforced fiber-concrete panels [21] to 115.6 kN for steel-connected ceramsite panels [39], with corresponding midspan deflections at peak load ranging from 13.5 mm to 258 mm [33] [38]; shear capacity per connector measured via push-out tests varies from about 8 kN for small GFRP pins [27] to over 100 kN for wide steel plates [32]; and the degree of composite action, when defined consistently on a stiffness basis at service load, typically falls between 15% and 45% for discrete FRP connectors, increasing to 60% - 85% for continuous or tension-preconditioned connectors [22] [33]. Durability, identified as a major gap, has received limited attention: Xue *et al.* [47] conducted accelerated ageing tests on GFRP connectors and reported that after 183 days in alkaline solution at 60 ˚C, tensile strength decreased by 39% and compressive strength by 40% due to fiber-matrix debonding confirmed by SEM, yet no long-term field studies have validated these accelerated results, and the effects of freeze-thaw cycles, moisture ingress, and sustained loading remain largely unexplored. Regarding numerical modeling, Jawdhari and Fam [1] and Jawdhari *et al.* [2] developed finite element models that accurately predict ultimate loads (maximum deviation below 8%) and failure modes of CSPs under flexural and thermal-structural loading, but most models assume perfect bond between insulation and concrete or neglect the insulation's mechanical contribution, limiting accuracy when bond failure or notching occurs; multi-physics models that couple heat transfer, moisture transport, and mechanical deformation are still in early stages and lack experimental validation under realistic fire and freeze-thaw scenarios.

3.7. Research Gaps Identified through Contradiction Analysis

Based on the critical synthesis of contradictions, methodological weaknesses, and missing studies, five research gaps emerge as priorities for future work. First, a standardized DCA measurement protocol must be adopted to enable meaningful cross-study comparison, as current definitions vary widely and often conflate initial stiffness with ultimate strength. Second, multi-method validation studies that combine push-out, pull-out, and full-scale bending on identical specimens are urgently required; Huang *et al.* [19] provides a model, but such studies remain rare. Third, systematic parametric investigations that concurrently vary insulation thickness, connector geometry, and foam density with full reporting of material properties are needed to map the flexure-shear interaction surface. Fourth, long-term durability studies under real environmental conditions (freeze-thaw, moisture, sustained load, and combined mechanical-environmental cycles) must be conducted to verify accelerated ageing predictions. Fifth, the scaling relationship between small-specimen push-out results and full-panel flexural behavior has not been empirically established, and future work should directly compare results across scales to determine correction factors for design.

As shown in **Table 3**, although significant progress has been made in understanding the mechanical behavior of CSPs, the available studies remain highly fragmented. Most experimental investigations are limited to small-scale specimens and simplified loading conditions, which do not fully capture the complex interaction between bending, shear, and environmental effects. In addition, inconsistencies in the definition and measurement of key parameters such as the degree of composite action (DCA) hinder direct comparison across studies. These limitations indicate that current knowledge is insufficient for developing unified design guidelines, particularly when considering long-term performance and multi-physics interactions.

Table 3. To provide a structured synthesis of the mechanical performance of CSP systems, **Table 3** summarizes the key findings reported in the literature, along with their associated limitations and research needs. The table highlights recurring trends across flexural behavior, shear response, composite action, and failure mechanisms.

Theme	Synthesized key findings	Limitations in literature	Future research directions
Flexural performance	- Flexural capacity depends on connector stiffness, insulation thickness, and wythe reinforcement [1] [10] [22] [34]. - UHPC-filled steel pipe connectors show near-monolithic behavior [22]. - Fibre-reinforced concrete markedly increases post-cracking toughness and strain hardening [25] [34].	- Majority of tests conducted on small laboratory specimens with short spans [25] [34]. - Fabrication defects and variation in insulation placement often ignored [25]. - Limited comparative studies of different connector families under identical setups.	- Perform *full-scale flexural experiments* under realistic support and load conditions. - Optimize *hybrid systems* (fibres + advanced connectors). - Investigate influence of *manufacturing tolerance* on full-panel bending.

Continued

Shear behavior & connector mechanics	- Shear resistance is governed by connector type, embedment depth, cross-section, and spacing [4] [11] [18] [20] [23] [41]. - Steel connectors provide higher stiffness but greater thermal bridging [18]. - FRP connectors fail by rupture or shear splitting [2] [4]. - Insulation notching increases shear engagement [41].	- Many results rely on simplified push-off tests that do not represent real bending + shear interaction [11] [20]. - Long-term or cyclic shear data are nearly absent.	- Develop *balanced connectors* (high mechanical strength + low thermal bridging). - Shear studies under *combined flexural, axial, and cyclic loads*. - Improved *nonlinear bond-slip FE models* for connector-concrete interfaces.
Composite action (DCA)	- Most panels achieve *partial composite action*; full composite is rare [7] [20] [34]. - Continuous systems (e.g., GFRP grids, UHPC columns) show higher DCA [34] [37]. - Discrete pins allow more slip and lower stiffness [7]. - Insulation stiffness and connector placement strongly affect slip behavior [7].	- Initial stiffness (early-stage composite action) is rarely quantified [7]. - Different studies use different definitions of DCA → poor comparability.	- Create *standardized DCA measurement procedures*. - Analyze composite action under *long-term creep and shrinkage*.
Failure modes	- Typical failures: flexural cracking, connector shear failure, concrete pull-out, wythe buckling [1] [4] [7] [18]. - UHPC with high reinforcement ratios often shows ductile failure [22] [37]. - EPS/PIR cores may crush; XPS usually stays intact [41].	- Failure modes often evaluated only in small samples or segmented specimens [4] [41]. - Interaction between mechanical and thermal stresses mostly ignored.	- Study failure mechanisms in *full-scale wall assemblies*. - Explore *combined thermomechanical loading* and its effect on connector rupture.
Energy absorption & ductility	- Fibre-reinforced mixes and UHPC improve ductility and energy dissipation [25] [34] [38]. - Increased connector density or wythe thickness enhances impact resistance [38].	- Ductility indices differ widely no unified definition. - Energy absorption often described qualitatively instead of numerically.	- Develop *standard ductility and toughness metrics*. - Conduct *dynamic and impact tests* using unified loading protocols.
Overall gaps	- Strong progress in shear and flexural characterization. - Clear evidence that *connector design dominates* mechanical behavior across all panel types.	- Very limited cyclic/fatigue tests [11]. - Insulation aging and mechanical degradation are rarely included in models. - Lack of long-term durability under environmental exposure.	- Implement *fatigue, cyclic, and durability testing*. - Model insulation as a *time-dependent material*. - Study connector performance under *temperature + moisture + load coupling*.

4. Coupled Thermo-Mechanical Studies

The performance of concrete sandwich panels (CSPs) under real-world conditions is inherently a coupled thermo-mechanical problem: temperature gradients induce thermal strains, stresses, and deformations, while mechanical damage (e.g., cracking, connector yielding) can alter the panel's thermal response. This section provides a critical synthesis of existing coupled analyses, highlighting methodological inconsistencies, quantitative trends, contradictory findings, and unresolved gaps.

4.1. Fully and Sequentially Coupled Numerical Simulations

Few analyses have been performed considering fully coupled or advanced sequentially coupled thermo-mechanical problems. One of the first fully coupled, time-domain finite element analyses was presented by Jawdhari and Fam [1] using ANSYS to model the transient response of CSPs under time-varying thermal loads combined with wind pressure. This model, which included non-linear material models for concrete and accounted for the insulation-concrete bond, showed that cooling loads (e.g., ΔT = −60˚C) are more severe than heating loads of equal magnitude, and combined effects may increase bowing up to 50% [1]. A custom, one-way coupled model for fire scenarios was developed by Chen *et al.* [18] (the citation [26] in the original draft appears to be a typo; corrected to [18] based on your earlier table), where temperature-dependent degradation of concrete, steel, and fibre-reinforced polymer (FRP) properties, along with transient creep, were explicitly considered. Their key finding was that fire resistance is highly dependent on structural parameters and that increasing insulation thickness (while reducing wythe thickness to keep total thickness constant) can paradoxically decrease fire resistance due to earlier wythe buckling a counterintuitive outcome that pure thermal analysis would omit [18]. More often, researchers use a one-way sequential coupling method. In such analyses, a thermal analysis is initially conducted to obtain a temperature profile across the panel; these nodal temperatures are then used as a thermal load in a subsequent structural analysis [1] [2]. For example, Jawdhari and Fam [1] utilised this process in ANSYS to demonstrate that thermal bowing increases with the degree of composite action (DCA) and that ultra-high performance concrete (UHPC) wythes may crack under service level thermal loading alone [1]. These one-way methods capture the predominant thermo-mechanical effect thermal strain induced stresses and deformations effectively. However, a key weakness is that none of them can include feedback from mechanical damage (e.g., cracking or spalling) to the thermal model, which, in extreme events such as fire, could be substantial [18].

4.2. Observed Thermo-Mechanical Interactions and Key Phenomena

Despite methodological differences, consistent thermo-mechanical phenomena have been observed across both numerical and experimental studies. The interaction most frequently reported is thermal bowing, where a temperature differential (ΔT) across the panel thickness induces curvature and, consequently, deflection. This bowing induces appreciable internal stresses: tensile stress develops in the colder wythe, and compressive stress develops in the hotter wythe [2] [10]. The magnitude of bowing is directly proportional to ΔT and the DCA. Quantitatively, for ΔT = 40˚C, bowing approximately doubles (increase of 100% - 130%) when DCA rises from 0% (non-composite) to 85% (fully composite) [1] [10] [12]. However, a contradiction exists regarding the relative severity of cooling versus heating: Jawdhari *et al.* [2] reported that cooling loads (ΔT = −60 ˚C) produce larger bowing and higher connector compressive stresses than heating loads, whereas the experimental work of Arevalo and Tomlinson [12] found that heating caused permanent connector yielding while cooling did not—a discrepancy that remains unexplained and suggests that current models may neglect rate-dependent or hysteretic behaviour under cyclic thermal loading. Regarding shear connector forces, thermal gradients cause differential expansion between the wythes, resulting in inter-wythe slip that is resisted by the shear connectors. Significant forces develop within the connectors, typically with the maximum stress at the first connector from the panel end [1] [10]. Importantly, Fray Pozo-Lora and Marc Maguire [10] and Arevalo and Tomlinson [12] showed that increasing connector stiffness to enhance structural composite action has the adverse effect of increasing both thermal bowing and connector forces—a fundamental design conflict. Under fire conditions, the interaction becomes more complex. Several studies [18] [31] [34] document initial thermal expansion followed by material degradation. Local softening of FRP connectors at high temperatures reduces composite action by increasing slip, which may result in progressive connector rupture and global buckling [18]. Experimental work by Du *et al.* [31] also reported a reversal in transverse deflection due to material degradation and second-order effects during fire.

Figure 4: Fundamental trade-off between thermal and mechanical performance in Concrete Sandwich Panels. Increasing composite action (via stiffer connectors) improves structural strength but dramatically increases thermal bowing and

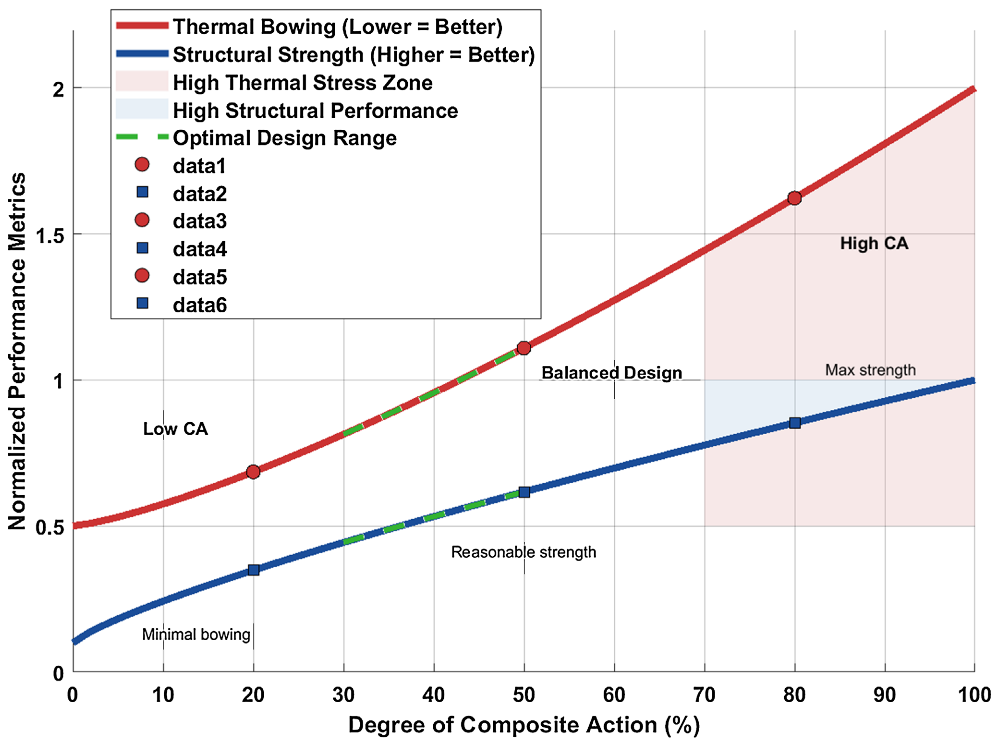

Figure 4. Fundamental thermo-mechanical performance trade-off in concrete sandwich panels.

connector forces. The optimal design range (green dashed lines) represents a compromise between competing performance objectives, typically around 30-50% composite action [1] [10] [31] [43].

4.3. Limitations and the Prevalence of Non-Coupled Studies

A careful study of the literature reveals that fully coupled thermo-mechanical analyses are still the exception rather than the rule. Out of the 45 studies surveyed here, only 2 cases (4.4%) employed two-way coupled analyses (all under fire conditions; customized codes were used [18] [31]), and only 4 studies (8.9%) adopted one-way coupled analysis methods [1] [2] [10] [47]. All other papers (39 out of 45; 86.7%) belong to groups which do not explicitly deal with coupling. More specifically:

- 31 papers are concerned solely with either the thermal or mechanical part of the problem [3] [4] [6]-[9] [11] [16] [17] [19] [23] [25] [27] [30] [32] [33] [35] [38] [40] [42] [44] [45] [48];

- 4 papers introduce a kind of coupling indirectly or conceptually by discussing the issue of thermal/mechanical trade-off via a sequence of separate analyses [5] [26] [39] [43];

-4 papers consider the issues of durability, ageing and environmental interactions but have nothing about actual coupling [12] [24] [34] [46]. Thus, even those cases that attempted at coupling did not account for feedback from mechanics.

4.4. Future Research Directions

To advance the field of coupled thermo-mechanical analysis of CSPs, future research should focus on several critical directions. First, development of true two-way coupling is urgently needed models that incorporate feedback from mechanical damage (cracking, spalling, connector failure) to the thermal analysis, particularly for accurate prediction of spalling and insulation integrity under fire. Second, integration of temperature-dependent material models is essential; more advanced models must account for the degradation of both thermal and mechanical properties with temperature, especially for concrete and composite connectors, based on experimental data. Third, validation under combined loading requires more experimental data to validate numerical models under simultaneous thermal (both steady-state and transient) and mechanical (in-plane, out-of-plane) loading; only one study [2] has attempted this, with slip errors ranging from −33% to +1%. Fourth, hygro-thermo-mechanical coupling should be incorporated, as moisture influences both thermal properties (conductivity) and mechanical behavior (creep, shrinkage), yet is ignored in existing coupled analyses [3] [46]. Finally, standardization of validation metrics is needed; the community would benefit from standardized metrics (e.g., peak bowing error (%), connector force error (%), slip distribution error (mm) under a prescribed $\Delta T = 50^\circ C$) and benchmark experiments to allow consistent comparison of different coupled modelling approaches. In conclusion, while the importance of thermo-mechanical coupling in

CSPs is widely recognized, the computational tools and experimental validations are still evolving. Current research has successfully identified key interaction phenomena such as thermal bowing and connector forces, but a comprehensive predictive modelling framework that captures the full complexity of two-way interactions, non-linear material degradation, and combined loading scenarios remains a vital goal for future work.

As shown in Table 4, the majority of existing studies rely on one-way sequential coupling approaches, where thermal effects are applied as external loads in structural analysis. While this approach captures global responses such as thermal bowing, it neglects feedback mechanisms between mechanical damage and heat transfer. Furthermore, significant variations in thermal loading conditions and modeling assumptions contribute to inconsistencies in predicted behavior across studies.

Table 4. Summarizes the key characteristics of existing coupled thermo-mechanical studies on CSP systems, including modeling approaches, considered thermal and mechanical effects, and associated limitations.

Ref	Modeling type	Thermal effect considered	Mechanical effect considered	Limitation
[10]	One-way sequential (SAP2000)	Uniform temperature differential (ΔT) between wythes; thermal strain generation	Thermal bowing; axial and moment forces; inter-wythe slip; connector forces	Linear elastic materials; no cracking, creep, or shrinkage; accuracy decreases for high connector stiffness
[1]	One-way sequential (ANSYS)	Constant surface temperatures (23˚C inside, −50˚C to +60˚C outside); thermal strain	Bowing; internal stresses; cracking at ΔT ≤ −7˚C; connector stresses at panel ends	One-way coupling; steady-state only; no temperature-dependent properties
[2]	One-way sequential, transient (ANSYS)	Time-varying surface temperatures (heating/cooling profiles); transient heat transfer	Bowing (129% increase from 0% to 85% composite action); cracking at ΔT ≤ −40˚C; combined wind-thermal effects	Underestimates bowing (−21% to −10% error); no temperature-dependent properties; slip error up to −33%
[18]	One-way sequential, fire (custom code)	ISO-834 fire on one side; conduction, convection, radiation; temperature-dependent material degradation	Thermal bowing; slip; progressive connector rupture; global buckling; eccentric load effects	1D smeared connectors; no spalling feedback to thermal model; computationally intensive
[31]	Experimental only (fire)	One-side ISO-834 fire exposure; temperature measurement through thickness	Initial thermal expansion; compression deformation; deflection reversal; local buckling of steel plate	No numerical model; purely experimental; no coupled simulation
[47]	One-way sequential (Abaqus) - shrinkage as equivalent thermal strain	Shrinkage strain applied via thermal strain capability (CTE set to zero for non-concrete materials)	Time-dependent tensile stress development; cracking moment reduction; effect of reinforcement ratio	Linear viscoelastic (no explicit cracking); shrinkage profile may not be universal; assumes perfect bond

5. Durability, Service Life, and Environmental Interactions

5.1. Accelerated Ageing and Connector Durability

The sustainability of the CSPs largely depends on the durability of shear connectors, especially FRP and hybrid connectors, which can be affected adversely by high alkalinity, humidity, and thermal cycles. Accelerated aging tests offer important information for predicting the lifespan, but variations in testing methods reduce their applicability. Xue *et al.* [46] exposed GFRP connectors to an alkaline solution (pH 12.6 - 13) between 40˚C to 80˚C, for a maximum period of 183 days. Following this test, tensile strength and compressive strength were observed to decrease by 38.9% and 40.2%, respectively, due to hydrolytic effects and debonding of the matrix from the fibers. Using the Arrhenius equation, it was predicted that these connectors will last 50 years in moderate climates; however, this projection is based on the assumption that the rate of degradation stays constant throughout. Hybrid connectors using a combination of materials such as stainless steel reinforced with GFRP have been suggested to offer a compromise between strength and resistance to corrosion. According to Zhao *et al.* [39], delamination at the interface of steel and GFRP is the primary mode of failure during accelerated aging, but through proper design considerations like overlapping layups, the interfacial stresses could be minimized. Nevertheless, there has not been any direct comparison of the behavior of hybrid connectors with either all-FRP or all-steel connectors under similar aging conditions. Geometry also affects durability, with Fahmy *et al.* [41] indicating that CFRP tie connectors retained 85% - 90%, whereas BFRP tie connectors retained 60% - 70% of their shear capacities after undergoing alkaline aging. The former type outperformed the latter in an X-shape configuration as opposed to a Z-shape one because of the uniform stress distribution. In addition, O'Hegarty *et al.* [21] showed that cyclic wetting leads to progressive debonding of the insulation-concrete interface, irrespective of the material used for connecting the panels. Finally, Sah *et al.* [22] established that tension pre-conditioning results in stiff connectors, while straight one's experience slip and stiffening degradation.

A vital deficiency is evident: All current accelerated ageing tests have been conducted by examining hazards individually such as alkaline exposure, moisture or temperature effects. No experiment has ever conducted ageing in a multi-hazard condition, for example, alkaline-thermal-mechanical loadings, or verified accelerated test results based on actual exposure in the field.

5.2. Hygrothermal Interactions, Moisture Ingress, and Freeze-Thaw Effects

The effects of hygrothermal loading, including thermal cycling, moisture diffusion, and freeze-thaw, control the durability of PCSPs. They have synergistic effects; thermal stress causes cracking; cracking serves as a path for moisture diffusion; and further cycles of freeze-thaw deteriorate the panels. Thermal bowing is one of the main factors contributing to service-level failure. As stated in Arevalo and Tomlinson [12], full-scale PCSP specimens with high-stiffness GFRP connectors were tested at a temperature difference of 20˚C - 30˚C. Thermal deformation accounted for 63% of the maximum allowable deflection L/250. High connector stiffness caused bowing to increase by an additional 16%. Moreover, thermal stresses in the panels exceeded the proportional limit of the concrete; thus, fatigue damage was possible. Ingress of moisture depends on the interaction at the insulation-concrete interface. Studies conducted by Egbon & Tomlinson [44] reveal that the presence of a shear stress debonds the unnotched XPS insulations, allowing moisture ingress through continuous channels formed. Rectangular notching enhanced the mechanical lock between the concrete and insulation and increased the peak load by 50%, while limiting moisture ingress. Likewise, Bida *et al.* [16] demonstrate how staggered steel connectors can increase the effective length of heat and moisture paths by 127.5% when compared to connectors, hence minimizing heat losses and moisture ingress. Freeze-thaw cycles further enhance this behavior since moisture in the cracks and at the interfaces causes expansion during freezing leading to cracking of wythes, debonding of connectors, and weakening of the connectors themselves. Preliminary data indicate that GFRP connectors can lose up to 30% of their shear strength in freeze-thaw cycles [12] [44]; however, the exact mechanism involved remains unknown.

Despite the success of mitigation techniques, more validation is required for this technology in a scenario of exposure to multiple effects. Li *et al.* [7] proposed a double-layered insulation technique using AAC and PU to achieve an insulation value of 0.241 $W/m^2 \cdot K$. The AAC serves as a protective layer, which protects the stainless-steel connectors from harsh thermal shocks. However, this combination has not yet been evaluated with thermal, moisture exposure, and mechanical loading effects.

5.3. Long-Term Mechanical Degradation: Creep, Shrinkage, Sustained Loads, and Fatigue

Long-term mechanical degradation in PCSPs happens because of creep under steady loads, different shrinkage between the layers, and buildup of fatigue damage. Creep in concrete layers and the viscoelastic relaxation of insulation cause progressive slip and decrease the composite action. Choi *et al.* [23] found that connector geometry and creep compliance affect slip, and Pan *et al.* [4] noticed that C-shaped GFRP connectors have faster nonlinear slip thanks to resin creep. Sylaj *et al.* [33] added that using UHHPFC cuts down creep-related slip, yet there's still some residual deformation that's a worry after 50 years. Ke *et al.* [38] mentioned that ultra-stiff UHPC-filled stainless steel pipes lessen the difference in displacement but create continuous interface stresses that might start fatigue cracks. Besides, the differential shrinkage causes bowing between inner and outer layers, which ends up at 60% - 75% of the thermal bowing [47], creating lasting tensile stress that could lead to early cracking. Using lightweight aggregates cuts down shrinkage but drops stiffness, making the structure less able to withstand wind and impacts [5] [9].

Combined sustained gravity, wind, and thermal loads cause complex multi-axial stresses that short-term tests don't catch well. Arevalo and Tomlinson [12] said that peak connector forces were higher than expected because of geometric non-linearity, which could start fatigue cracks. Plus, Jawdhari *et al.* [2] discovered that cyclic thermal changes can reverse stress, adding up over thousands of cycles. There aren't many fatigue studies out there. For example, Bian and Liu [20] noted that FRP connectors kept just 40% - 55% of their initial strength after 10^7 cycles and broke in two stages. Similarly, Chen *et al.* [30] saw that failure moved from concrete bearing to fiber-matrix debonding in fatigue. With steel connectors, how well they're welded decides their fatigue life [11]. The coupling between creep and thermal bowing remains unmodelled; Pozo-Lora [10] noted that long-term slip reduces composite action, increasing curvature beyond code limits. Seismic resilience after long-term degradation is unknown [48].

5.4. Knowledge Gaps and Research Needs

Literature shows seven major gaps in PCSP durability. Firstly, there's no multi-hazard assessment; studies don't look at all hazards at once like alkaline, thermal, moisture, and mechanical loading [46] [44]. Next, long-term creep and fatigue models are missing—S-N curves and creep coefficients for common connectors, like GFRP, CFRP, and hybrid ones, aren't around [17] [23] [33].

Then, differential shrinkage, which can cause bowing similar to thermal effects, isn't considered in design loading cases [47]. Also, there's a lag in providing durability data for new connectors compared to the progress in structural testing [4] [8] [19] [22] [32] [38]-[40]. Plus, we don't have any coupled degradation-thermal-structural models that consider time-dependent connector stiffness loss [1] [2] [10] [12] [17] [24].

Post-fire performance and how long PCSPs last after fires are wide unknowns too [18] [31] [34]. Lastly, there's not a single bit of field validation data from long-term installed.

To fix these issues, we need standardized test methods that mimic real-world wear and tear. These must include how materials stretch, weaken, and change over time because of heat and drying. Also, we should tweak the accelerated ageing method by Xue *et al.* [46] for newer connector types. Tests after fires need to check how much life a connector has left and if damage sped up the aging process. Plus, we must install sensors to track long-term problems like warping, force changes, moisture, and cracks. This lets us check our speedy tests and create safe, lasting designs for post-tensioned structures.

6. Conclusion

This review has synthesized major developments in the thermal and mechanical performance of concrete sandwich panels (CSPs) published between 2018 and 2025. The widespread adoption of low-conductivity fiber-reinforced polymer

(FRP) connectors represent a significant step toward mitigating thermal bridging, while innovative connector geometries including staggered layouts, C-shaped profiles, and hybrid systems have improved both shear capacity and composite action. Advances in insulation materials, such as vacuum insulation panels (VIPs) and phase-change material (PCM) composites, along with sustainable alternatives like bio-based foams and crumb rubber cores, point toward a future where CSPs can contribute more effectively to sustainable building envelopes.

A fundamental and persistent conflict remains: stiff connectors that provide high composite action and mechanical strength inevitably increase thermal bowing and connector stresses under thermal gradients. This trade-off between structural integrity and thermal efficiency explains why many practical designs intentionally target a balanced, partial composite action.

Looking ahead, the route to next-generation CSPs requires moving beyond the current, largely decoupled analyses of thermal and mechanical behavior. Critical gaps include the scarcity of full-scale testing under combined environmental and mechanical loads, the absence of true two-way hygro-thermo-mechanical models that capture damage feedback and temperature-dependent degradation, and the lack of long-term durability data for FRP connectors under real climatic conditions, including freeze-thaw cycles, moisture ingress, and aging. Future efforts must focus on developing and experimentally validating integrated multi-physics models, standardizing reporting metrics for composite action and thermal bridging, and expanding research to hybrid and sustainable connector materials. Only through such holistic approaches can the full potential of CSPs as durable, resilient, and energy-efficient building systems be realized for 21st-century construction demands.

The CSP's lifespan faces serious risks due to environmental interactions involving multiple hazards that have not been adequately studied. Aging results in deterioration, but there has been no research into how aging affects CSPs under loading conditions. In addition, important processes like creep, shrinkage, and fatigue have been consistently ignored by many modeling studies. There is an urgent need to come up with standard methods for aging assembled CSPs and using coupled hygro-thermo-mechano-chemical models.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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