

# Review of Bending (Static & Dynamic) Behavior of Multilayer/Sandwich Concrete Slabs with Interlayer Connections

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## Abstract

Slab bending behavior is researched through investigation of the effects of various parameters such as longitudinal ribs volume ratios of concrete, number of support edges, and end connections. The connection between interlayers is very important to render bending performance due to the fact that material-based bonds (e.g., roughened interfaces, adhesive) and mechanical connectors (e.g., dowels, steel bars, shear keys) significantly influence the amount of composite action between interlayers. Complete composite action yields greater stiffness and strength, while partial or non-composite action may lead to premature slip, shear failure, or loss of capacity. The current review summarizes experimental results, analytical solutions, and numerical models in the literature, summarizes current research gaps, and charts future research directions for designing more efficient and ductile slab systems.

## Keywords

Review Report, Bending, Multilayer, Concrete, Connections

## 1. Introduction

Multilayer or sandwich concrete slabs have emerged as an important structural solution in modern construction, particularly in high-strength and long-lasting slender lightweight member applications. They typically consist of two or more layers of concrete (wythes or layers) with a core material or interface between the two and a mechanically joined or material-based interlayer connection. These configurations are intended to realize minimum self-weight with high bending resistance, thermal performance, and structural efficiency.

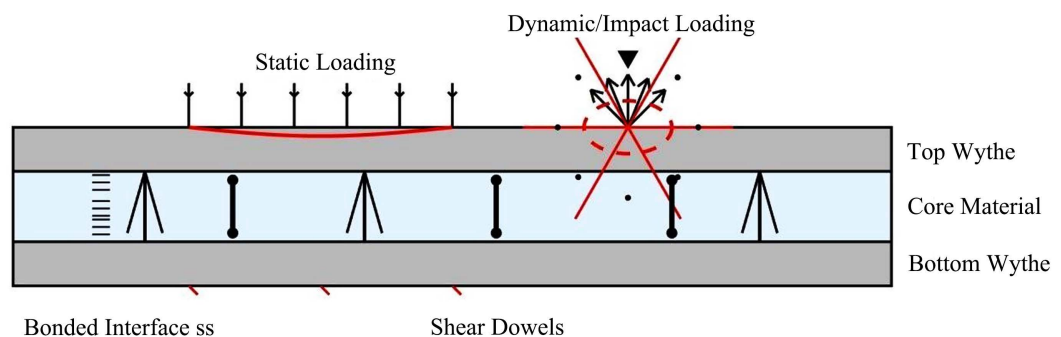
It should be considered that the functional characteristics in modern architec-

ture extend beyond strength alone; designers aim to provide enhanced thermal insulation and sound insulation as well. This doubled aim reflects the increased emphasis placed on structural systems that not only meet safety and durability but also help to promote enhanced energy efficiency and occupants' building comfort, particularly in the area of applications requiring high-strength and durable lightweight members. These slabs typically consist of two or more concrete layers (layers or wythes) separated by a core material or interface and connected by a mechanical or material-based interlayer connection. These configurations are designed to combine minimum self-weight with high bending resistance, thermal performance, and structural efficiency [1]-[4].

Multilayer concrete slab bending behavior is a fundamental problem in ensuring structural safety and serviceability. Static loading must be sustained by slabs under long-term service and gravity loads without excessive deformation or cracking. At the same time, under dynamic loading conditions such as impact, vibration, or seismic, the ability to resist stiffness, energy absorption, and crack control by the slab assumes high priority. Understanding both static and dynamic bending responses is therefore fundamental to good design. The flexural behavior of slabs is investigated by varying parameters such as the volume ratios of longitudinal concrete ribs, the number of support edges, and the types of end connections [5] [6].

One of the key factors that governs bending performance is the type and efficiency of interlayer connections [5]-[10]. Material-based bonds (e.g., adhesive or roughened interfaces) and mechanical connectors (e.g., steel bars, dowels, shear keys, and fiber-reinforced polymer ties) govern the degree of composite action between layers [7] [11] [12]. A composite action that is full allows the slab to behave monolithically, with maximum stiffness and strength, whereas partial or non-composite action can lead to early slip, shear failure, or reduced capacity. Therefore, developing the types of connections, spacing, and material properties to the optimum is a major focus in recent years [6] [8].

Core Material in Multilayer Concrete Slab (**Figure 1**): The core consists generally of lightweight or insulation material such as rock wool, foam, or felt. It reduces weight and improves acoustic/thermal performance but reduces bending stiffness and thus requires interlayer connections to maintain composite action.



**Figure 1.** Schematic illustration of multilayer concrete slab under static and dynamic bending loads.

Therefore, this review aims to collate and critically assess the literature on the bending behavior of multilayer/sandwich concrete slabs subjected to static and dynamic load conditions with a specific emphasis on the role of interlayer connections. The review collates experimental data, analytical solutions, and numerical models, summarizes the current gaps in research, and suggests future avenues of research towards the evolution of more efficient and resilient slab systems.

### **Literature Search Methodology**

A systematic literature search was conducted to identify relevant studies published predominantly between the years 2018 and 2025. The search employed a range of academic databases, including Scopus, Web of Science, and Google Scholar. The search terms used were (multilayer “sandwich” composite slab concrete (slab OR panel), “bending (flexural, three-point, or four-point)”, “interlayer”, “interface”, “connection”, “connector”, “key”, “dowel”, “shear”, “dynamic”, “impact”, “drop-weight”, “rate”, “strain-rate”, “finite element”, “numerical model”, “simulation”, “damage”, “plasticity”, “cohesive”, “embedded truss”. The preliminary search results were filtered by titles and abstracts using inclusion criteria focusing on experimental, numerical, or analytical studies specifically regarding the flexural behavior of concrete sandwich panels with given shear connectors. Those addressing only in-plane behavior or non-concrete materials were excluded. This exercise resulted in a final list of over 39 primary studies which form the foundation for this review.

## **2. Interlayer Connections**

The structural behavior of multilayer or sandwich concrete slabs is intrinsically governed by the efficiency of the interlayer connection system. The connectors are critical to achieve composite action, which governs the structural stiffness, strength, ductility, and failure mode of the entire assembly. Connector selection is a challenging trade-off between structural performance, thermal efficiency, manufacturability, and durability. This section attempts a synthesis of the different types of connectors, materials, geometric shapes, and their resultant effect on structural behavior, compiling evidence from existing literature.

A wide variety of types of connectors have been researched and manufactured, with their pros and cons. They can broadly be categorized as discrete mechanical connectors, continuous systems, and bonded interfaces.

### **2.1. Types and Materials of Connectors**

The most common ones are Discrete Mechanical Connectors. Headed steel studs are an old favorite, which have high shear strength and stiffness [13]. Bolted connections, widely utilized in steel-concrete-steel (SCS) structures, provide high-strength demountable connections, high-strength bolts demonstrating excellent performance [8] [14]. Truss-type connectors, either steel [15]-[17] or Glass Fiber-Reinforced Polymer (GFRP) [4] [11], are continuous shear grids with mesh reinforcement as a favorable combination. New proprietary systems include I-shaped [18] or dumbbell-shaped [1] GFRP connectors specifically designed to optimize

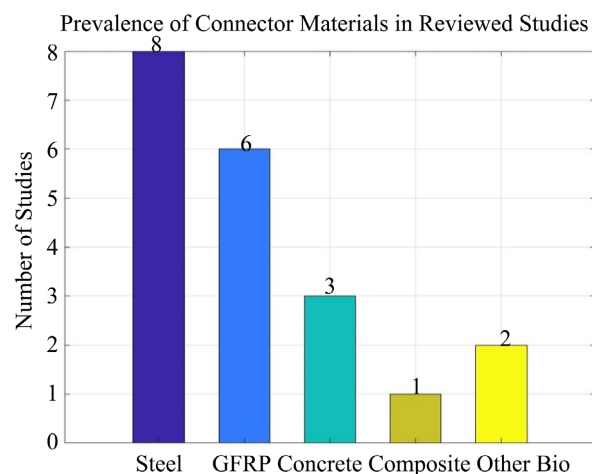
anchorage at the expense of thermal bridging. Pin-type GFRP connectors also exist in the market, though they provide very limited composite action, effectively resulting in non-composite design [19]. Other new discrete connectors are stainless steel pipes packed with UHPC [12] and even biobased materials like hemp hooks injected with epoxy [5] [20].

“In addition to structural efficiency, long-term durability of the connectors is a serious concern. Steel connectors may corrode in aggressive environments, and GFRP may degrade under exposure to ultraviolet radiation or alkaline exposure. Adhesive bonds may also degrade under exposure to alternating moisture and temperature cycles. All these points highlight the necessity to take environmental exposure into account in designing the connectors for reliable service behavior.”

Continuous Connector Systems are put in place to provide more uniform shear transfer. These include steel lacing systems with cross rods, which create a very effective and ductile shear transfer mechanism that resists brittle weld failures [21]. Concrete ribs, made of cast-in-place concrete over the insulation layer, is another type of continuous solution. These can be intended structural details [2] [3] [22] or unintended “concrete bridges” from construction seepage, which, despite significantly adding stiffness and strength, are severe thermal shorts and a manufacturing defect [6].

Bonded and Non-Mechanical Connections rely on adhesion, friction, or mechanical interlock with no separate components. Such examples are adhesive bonding of GFRP profiles to concrete [23], alkali activation cementitious bonds to grooved insulation [24], and the composite action inherent in the overlap arrangement of modular cellular slabs [25]. The primary advantage is elimination of thermal bridges, but performance is heavily dependent on surface preparation and mechanical quality of the insulation material itself, which often leads to delamination failure if not properly engineered [24] [26].

This bar chart illustrates the frequency of different connector materials (e.g., Steel, GFRP, Concrete) investigated in the 40 studies reviewed, highlighting steel and GFRP as the most prevalent (**Figure 2**).



**Figure 2.** Prevalence of connector materials in reviewed studies.

## 2.2. Influence of Connector Geometry and Spacing

The geometry and spatial layout of connectors are of the most significant importance in the establishment of Degree of Composite Action (DCA).

Spacing is also a most significant design parameter. Investigations always reveal that reduction in spacing significantly enhances composite action. For headed studs, reducing spacing from 400 mm to 200 mm increased panel stiffness by 54.7%, the maximum load by 114.9%, and ductility by 26.4% [13]. Similarly, for the GFRP truss connectors, reducing spacing from 900 mm to 225 mm increased peak load by 15% - 32% and largely improved ductility [11]. Below a certain point, however, diminishing returns are achieved; once composite action is finished or nearly finished, reducing spacing has little impact on strength or ductility [2]. Spacing has an influence on failure modes as well; greater spacings could lead to connector pull-out or composite action loss, while closer spacings keep failure consistent with material crushing and yielding [13].

The geometry greatly influences connector anchorage, strength, and stiffness. Cross-sectional area increase (e.g., jacket thickness or dumbbell end diameter) in new GFRP connectors led to improvement in ultimate load capacity (46% - 49%) and flexural stiffness (9% - 16%) [1]. The geometry also has a significant role to play in the distribution of stress; I-shaped GFRP connectors with punctured flanges for the anchorage of rebar successfully prevented brittle failure of the connector and allowed the panel to fail in the ductile flexural mode [18]. Orientation of the truss connector also plays a role; 45° inclination was found optimal, which had greater ultimate load and much better ductility compared to a 60° orientation [16].

This trendline scatter plot is analyzing the trend between connector spacing (mm) and its qualitative effect on structural strength (as a multiplier), based on synthesized data from experiments where spacing was the main variable (Figure 3). The trend is a general increase in strength as spacing is reduced.

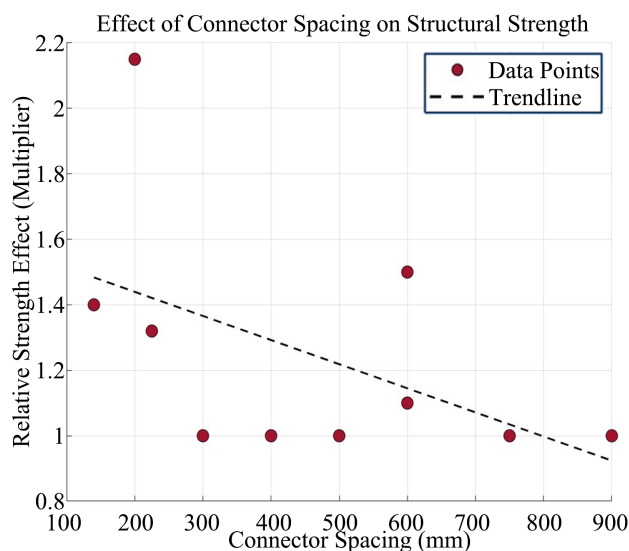


Figure 3. Effect of connector spacing on relative structural strength.

Quantitative outcomes from [11] [13] and qualitative trends reported in [1] [2] [8] were combined to yield data points. An overall inverse relationship is depicted by the trendline of these combined data.

### 2.3. Effect on Structural Performance

**Stiffness:** The connectors' shear stiffness is the dominant influence for the panel's initial flexural stiffness [10]. More stiff and denser connectors increase the DCA, and hence the panel acts as a solid section. It can be seen in concrete ribbed structures [2] [22], densely spaced closely located studs [13], and rigid continuous lacing [21]. Conversely, connectors which are flexible or spaced (e.g., pin-type GFRP [19]) allow non-composite action, and panel stiffness is merely the sum of single wythes.

**Strength:** Max strength of the section is achieved by good shear connection. Composite action is initiated by connectors, shifting the neutral axis and allowing the two wythes to resist the moment effectively. This causes extremely greater cracking, yield, and ultimate loads than non-composite panels [3] [4]. Strengthening can have dramatic effect; e.g., concrete ribs increased ultimate load by 28% [3], whereas post-tensioned steel bar connectors increased it by 252% compared to an unconnected panel [27].

**Ductility and Failure Modes:** Connectors have significant influence on the ductility and failure sequence of a sandwich panel. Ductile connector systems, e.g., steel lacing [21] or bolts in the core of an Engineered Cementitious Composite (ECC) [14], can achieve high deformation and energy absorption by plastic deformation and yielding, to progressive, non-catastrophic failure. Brittle connectors like certain GFRP pins can catastrophically fail, though usually only upon steel reinforcement yield, which is what preserves system ductility in general [19]. The preferred mode of failure is a flexural ductile mode of tensile reinforcement yielding and concrete crushing, and connectors still in undamaged state [18] [28]. The most common connector-related modes of failure are pull-out from the concrete [13], buckling and delamination of the GFRP members [29], debonding between the concrete and the connector [18], and shear failure at the core [5].

## 3. Modeling Strategies

Accurate prediction of structural behavior for multilayer concrete slabs is essential to their design and application. With complexity arising from composite action, material nonlinearity, and connector interaction, numerical and analytical modeling comes into prominence. In this section, the prevailing modeling strategies, software, material constitutive relations, and most importantly, the essential strategies for modeling interlayer connections are discussed with emphasis on strengths and limitations of available methods.

### 3.1. Modeling Software and Element Types

Finite Element Method (FEM) is the most widely used numerical approach to

simulate multilayer slabs. ABAQUS/CAE is the most widely used commercial software, found in a vast majority of research based on its powerful library of material models and element formulation capabilities [1] [3] [11]-[15] [18] [22] [26] [28] [30] [31]. For high-strain-rate and impact applications, e.g., drop-weight testing, ANSYS/LS-DYNA and LS-DYNA are employed since they contain explicit solvers and advanced material models with the capability to simulate dynamic effects [7] [8]. ATENA 3D for fracture-plastic analysis [16] and Open Sees for section analysis by fibers [21] are the other computer tools utilized.

The preferred element types are the same in all research work. Solid elements (usually 8-node reduced integration linear bricks, C3D8R in ABAQUS) are used to model concrete wythes, insulation cores, and explicit connector geometries [1] [18] [22]. Truss elements (T3D2) are all usually used to simulate steel reinforcement and discrete shear connectors like bars or trusses, which are then “embedded” into solid concrete elements [22] [28] [30]. Shell elements are typically reserved for thin steel faceplates in the steel-concrete-steel system [7] [8]. This is to allow for a proper and accurate depiction of the composite system’s geometry.

### 3.2. Material Constitutive Models

The accurate modelling of material nonlinearity is the most significant. For concrete, the Concrete Damaged Plasticity (CDP) model of ABAQUS is de facto standard [1] [11]-[13] [18] [22] [28] [30] It is so popular since it is capable of capturing the various behaviors of concrete under compression (hardening leading to crushing) and tension (cracking with softening). Model parameters like dilation angle ( $\sim 30^\circ$ ), eccentricity ( $\sim 0.1$ ), and viscosity ( $\sim 0.0005 - 0.005$ ) usually are calibrated with reference to national codes like the Chinese GB 50010 [22] [28]. More sophisticated models like the Continuous Surface Cap Model (CSCM) in LS-DYNA are used for detailed high-fidelity impact calculations to consider strain-rate responses and high-pressure behavior [7] [8].

Steel reinforcements and steel plates are almost always modeled with the ideal elastic-perfectly plastic constitutive model derived from experimental ultimate and yield strengths [1] [22]. Strain hardening bilinear material is sometimes inserted for connectors and other steels [16]. The new materials ECC and UHPC are modeled with CDP but require special input of their unique strain-hardening tensile response [11] [12] [14]. GFRP and composites are typically idealized as linear elastic orthotropic material up to failure, with failure criteria like Hashin’s damage model used to simulate complex failure mode such as fiber breakage and matrix cracking [1] [11]. Insulation materials like EPS and XPS are commonly simplified to linear elastic material because the structural contribution of the insulation materials is usually considered negligible [18] [22] [28].

### 3.3. Strategies for Modeling Interlayer Connections

The modeling approach for shear connectors is the most critical aspect and varies significantly with respect to the research question and desired degree of detail.

1) **Explicit Modeling:** The most sophisticated method is to model the precise geometry of connectors (e.g., studs, bolts, GFRP profiles) by solid or shell elements and subsequently determine the interaction with concrete by surface-to-surface contact algorithms with Coulomb friction (e.g., 0.22 - 0.3 coefficients) [1] [11]. The most realistic behavior simulation of connectors can be done with this method, with the ability to record local effects like bearing, slip, and separation. This is computationally demanding and requires accurate definition of contact interactions.

2) **Discrete Element Simplification:** Connectors are often simplified as beam or truss elements connected to the wythes. The bond may be simulated by consolidating nodes in the interface [8] or “tie” constraints [12], which assume an ideal bond and are computationally efficient but do not account for slip. More sophisticated is to simulate the shear stiffness of the connector using nonlinear spring elements [9] [10]. The Generalized Beam-Spring Model (BSM) is a good example of this, where any physical connector is generalized to a one-value shear stiffness ( $K_s$ ) from experimental tests, and thus it is a general and material-independent approach to prediction of elastic behavior [10].

3) **Implicit Modeling through Constraints:** Composite action by connectors is implied in the majority of studies and not modeled explicitly. The use of “tie” constraints or “embedded” regions between wythes and insulation is an assumption of full interaction with no slip [2] [5] [30]. While this is a gross simplification that can overestimate stiffness and neglect debonding failure, it is justified in assemblies where connectors are abundant and full composite action can be expected, or where the research interest lies elsewhere.

4) **Analytical Modeling:** Closed-form analytical models are applied for rapid design and analysis for rapid design and analysis. These will typically employ an effective width approach or a section analysis to calculate flexural capacity, effectively simplifying for connectors by defining the level of composite action [4] [32] [33]. These are computationally trivial but lack the ability to make predictions on complicated failure modes, progressive failure, or detailed load-deformation response.

### 3.4. Model Validation and Performance

Experimental data validation ranks at the top of the list. Representative validation goals are:

**Global Response:** Load-deflection curves (initial stiffness, yield point, peak load, post-peak behavior) [1] [18] [22].

**Failure Modes:** Concrete crushing, crack patterns, reinforcement yielding, and connector failure [2] [13] [18].

**Local Phenomena:** Strain distribution in reinforcement, interlayer slip [12], and, in impact tests, force-time and displacement-time histories [7] [8].

Well-validated models show excellent agreement, often with prediction errors in ultimate load less than 5% - 10% [1] [18]. There are, however, discrepancies

and these consist of overestimation of initial stiffness due to omitted microcracking and imperfections [22] [30], and delayed cracking initiation because of idealized boundary conditions and material representations [31] (Table 1).

**Table 1.** Summary of key findings from reviewed literature on sandwich slab connectors.

Paper (Author, Year)	Connector Type	Connector Material	Spacing (mm)	Loading Regime (Static/ Dynamic)	Failure Mode	Effect on Stiffness	Effect on Strength	FEM Software	Connector Modeling Strategy (FEM)
Wenjie (2025) [13]	Dowel Rebars	Steel (HRB400)	Inferred	Dynamic (Impact)	Shear/ Flexural at connection	Higher concrete strength increased global stiffness	Higher concrete strength increased peak impact force	ANSYS/ LS-DYNA	Tied contact, Merge nodes
Yonghui Wang (2022) [30]	Bolts + Stiffeners	Steel (Q235)	140	Dynamic (Impact)	Faceplate Yielding & Buckling	Stiffeners significantly increased stiffness	41.56% higher peak force with stiffeners	LS-DYNA	Tied nodes, Merged nodes
Luis Mercedes (2022) [6]	Hemp/ Sisal/ hooks, Bolt	Hemp, Sisal, Steel	N/A	Static	Fabric Break/Matrix Cracking	Connectors increased panel stiffness	Slightly increased bending strength	Abaqus	Not explicitly modeled ("Tie" constraint)
Feng Xiong (2025) [22]	Bolted Plates/ Angles	Steel (Q235B)	420 - 1400	Static	Flexural (Reinforcement Yielding)	Enabled composite action, increasing floor stiffness	Increased serviceability load by 50% - 111%	ABAQUS	Represented by spring elements
Yan Meng (2023) [31]	Headed Studs	Steel	200 - 400	Static	Stud Shear/Concrete Crushing	54.7% increase by reducing spacing	114.9% increase by reducing spacing	ABAQUS/C AE	"Tied" contact, Surface-to- surface contact
Chaoyang Zheng (2023) [22]	Concrete Ribs	Concrete (C30)	N/A	Static	Flexural (Reinforcement Yielding)	High DCA (up to 98.9%) led to high stiffness	Governed by reinforcement yielding	ABAQUS	Explicitly modeled with solid elements
Yi Wang (2022) [7]	SFCB (Dumbbell)	Steel-GFRP Composite	600	Static	Flexural (Ductile)	Increased with jacket/end thickness	Increased with jacket/end thickness (46% - 49%)	ABAQUS/E xplicit	Explicit solid elements with friction contact
Qi Ge (2025) [8]	Concrete Ribs	Concrete	300 - 750	Static	Flexural (Reinforcement Yielding)	Highly dependent on spacing	Peak load largely unaffected by spacing	ABAQUS	Explicitly modeled as part of concrete

## Continued

Zhaochengyuan Liu (2025) [18]	I-shaped GFRP	GFRP	N/A	Static	Flexural (No Connector Failure)	High stiffness, DCA > 90%	High strength, no connector failure	ABAQUS	Explicit solid elements, embedded rebar
Feng Xiong (2024) [2]	GFRP Truss	GFRP	89 - 1000	Static	Flexural/Web Buckling	Closer spacing significantly increased stiffness	Closer spacing dramatically increased peak load (15% - 32%)	ABAQUS	Explicit shell elements, Hashin damage model
Mahmoud Anwar Gad (2023) [11]	Bolts	Steel (Grade 8.8)	100 × 200	Static	Core Shear (ECC)/Bolt Bending	Enhanced by ECC core	Significantly increased, failure mode shifted	ABAQUS	Explicitly modeled as 1D truss elements
Jun-Qi Huang (2021) [19]	Pin-type GFRP	GFRP	600	Static	Non-Composite (Wythe Separation)	Very low composite action (DCA < 3.1%)	Very low composite action (DCA < 10.5%)	ABAQUS	Not modeled (analysis for benchmark only)
Tiancai Zheng (2023) [9]	GFRP Truss, Steel Truss	GFRP, Steel	500	Static	Flexural	Ranking: CR > SP > ST > GT > GP	Ranking: CR > ST > GT > GP	N/A (Analytical)	N/A

## 4. Loading Regimes

Mechanical loading response of composite sandwich panels is among the most important aspects of their structural functionality and use. The next section summarizes the available literature on loading protocols, structural behavior for various load types (static, dynamic), boundary condition impact, and resulting ultimate strength, stiffness, and ductility.

### 4.1. Testing Approaches and Loading Protocols

Numerous test techniques have been used to characterize the shear and flexural behavior of sandwich panels, which primarily fall into two categories: dynamic and static.

The majority are static tests, with the four-point bending test being the most utilized method of determining the flexural capability [1] [2] [4] [5] [11] [13] [14] [20] [25] [26] [31]-[34]. This configuration produces a region of equal moment between the loading points, ideally suited to study flexural yielding and cracking. The remaining configurations include three-point bending [15], two-point loading [21] [30], and six-point bending [13] [35] to simulate a uniform load. Quasi-static displacement-controlled loading is most commonly used protocol with rates typically between 0.5 and 5 mm/min [11] [22] [27] [31]. The majority of tests em-

ploy a staged loading procedure with the retention of increments (e.g., 5 - 10 minutes) of loads to follow crack advancement and creep behaviors [3] [9] [22] [28] [30].

Dynamic testing is less common but is a necessity for determining impact resistance. These are generally conducted with drop-weight impact testers using instrumented hammer tips to deliver low-velocity impacts. The loading rate is defined by the impact velocity, which can be quite dissimilar; for instance, Wenjie (2025) utilized velocities of  $\sim 7.7 - 8.1$  m/s [7], while Yonghui Wang (2022) used velocities of 5 - 7 m/s [8]. These tests are essential to establishing the panel performance when tested using impulsive loads, such as wind-borne debris or unintended impacts, that produce high strain-rate effects not found in static tests.

**Critical Discussion:** The ubiquity of generic static bend tests provides a convenient reference standard between different panel configurations. Still, there exists a vastly disproportionate gap between such idealized laboratory testing and the hard, often dynamic loading regimes of real structures (e.g., seismic, blast, or creep due to long-term loading). There also exists a strong lack of standardized testing for cyclic or fatigue loading. Though static and impact testing is covered, in-service performance of such slabs in seismic areas or under repeating loading (e.g., in industrial floors or bridge decks) remains inadequate. Developing such protocols is necessary to achieve a full understanding of energy dissipation, stiffness degradation, and low-cycle fatigue failure of connectors under reversing or repeating loading.

## 4.2. Influence of Loading Rate

There have been several test procedures used to characterize the shear and bending behavior of sandwich panels that essentially fall under two groups: dynamic and static.

The majority of them are static tests, and the four-point bending test is the most widely used technique for measuring flexural capability [1] [2] [4] [5] [11] [13] [14] [20] [25] [26] [31]-[34]. This setup produces a region of constant moment between the points of load, which is optimum to study flexural cracking and yielding. Other setups are three-point bending [15], two-point loading [21] [30] [36], and six-point bending [13] [35] in an attempt to simulate uniform load. The protocol most commonly employed with quasi-static displacement-control loading is the one where rates are most commonly varied between 0.5 and 5 mm/min [11] [22] [27] [31]. All the tests adopt a staged loading technique with the retention of load steps (e.g., 5 - 10 minutes) to monitor crack extension and creep response [3] [9] [22] [28] [30].

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These are usually carried out using drop-weight impact testers with instrumented hammer tips to deliver low-velocity impacts. The loading rate is determined by the impact speed, which can be quite variable; e.g., Wenjie (2025) uti-

lized speeds of ~7.7 - 8.1 m/s [7], while Yonghui Wang (2022) utilized speeds of 5 - 7 m/s [8]. These tests are required for determining the panel performance when subjected to impulsive loads, such as accidental impacts or wind-borne debris, which induce high strain-rate effects that cannot be achieved in static tests. Critical Discussion: The widespread occurrence of uniform static bending tests provides a convenient benchmarking standard for different panel configurations.

But there is a huge difference between such idealized lab tests and actual structures' stressful, often dynamic loading conditions (e.g., seismic, blast, or creep under extended loading). Furthermore, static test load rate choice, while often standardized, is rarely justified on the basis of its likely influence on measured material properties such as strength and ductility.

### 4.3. The Role of Boundary Conditions

Boundary conditions used in tests are a crucial parameter that could potentially alter the structural behavior with a significant difference.

Most tests use a simply supported condition with roller as well as pin support [1] [2] [5] [11] [13] [15] [18] [21] [23] [32]. This is because such an arrangement in an analysis situation is simple and provides a conservative estimate for bending capacity by allowing free rotation and longitudinal translational motion. Although, more and more research stresses the need for more realistic "actual" or static boundary conditions.

It is found by research that restraint against rotation by restraint to immovable structural frames (such as through steel angles and bolts) also results in enhanced performance.

Cheng *et al.* (2023) found bolted corner (BA) connections experienced the greatest increase in stiffness in polygonal precast slabs over bolted tread (TB) or simple support (SS) conditions [22]. In the same vein, Yan *et al.* (2023) concluded that the top and bottom steel-restrained wall panels exhibited a higher cracking load and ultimate capacity in negative bending because of the restraining effect [28]. This restraint is sure to alter failure mechanisms and trigger more composite effect. Critical Analysis: Although simple supported tests are required in rigorous comparative studies, their predominance is an oversimplification. Test results for studies with practical boundary conditions [22] [28] [36] show that connection details are not trivial issues but a natural part of the structural response of the system. Future test standards must encourage supplementary testing under constrained boundary conditions to enhance design practices.

### 4.4. Ultimate Load and Failure Modes

The ultimate flexural capacity is controlled by the combined effects of the following:

Material Strength: Stronger designed concrete [7] [36] and the use of high-performance materials like UHPC [12] or ECC [14] have a direct effect of higher ultimate loads.

Connector Density and Type: More closely spaced connectors [13] and more ductile and stronger connectors (e.g., headed studs, hybrid connectors) encourage composite action, leading to higher capacity [8] [32].

Wythe thickness: Thicker wythes of concrete significantly increase the moment capacity, as attested by the diverse capacities obtained [13] [21].

Failure modes are also varied. Most common failure modes are:

Yielding of the reinforcement and subsequent crushing of the concrete in the compression zone, which indicates a ductile flexural failure [3] [30] [33].

Brittle shear failure of the core or debonding of the core-wythe interface, frequently encountered in low-strength core panels or poor shear connection [20] [24] [29].

Pull-out or shear fracture of connectors, either brittle (GFRP pin failure [6] [19]) or ductile (steel stud yielding) [13].

Buckling of thin steel facings of SCS panels [8] [32].

#### 4.5. Stiffness and Serviceability

Stiffness, which is a significant parameter of the serviceability limit state, is generally recorded as the initial slope of the load-deflection response or as flexural rigidity (EI). The information further reveals that stiffness is highly sensitive to:

Degree of Composite Action: Stiffness values in composite panels that are fully composite are orders of magnitude higher than in non-composite panels [10] [18] [19]. Features that promote composite action, such as concrete ribs [2] [3] and effective shear connectors, maximize stiffness.

Material Properties: Panels constructed of high-strength material [7] [14] and with larger wythes [13] are stiffer by nature.

Boundary Conditions: As discussed, restrained boundaries provide greater effective stiffness [22] [28].

Serviceability testing such as that of Xiong (2025) [9] and Zheng (2023) [22] terminated tests at deflections like  $L/200$ . They indicated that slabs built on the ground were capable of supporting service loads far in excess of regular design live loads ( $2 \text{ kN/m}^2$ ), generally  $8 - 12 \text{ kN/m}^2$ , but less than a monolithic slab's strength [9].

#### 4.6. Ductility and Energy Dissipation

Ductility, defined as a standard for the capability to deform considerably without a severe loss in strength, is a fundamental property for structural toughness. It can be assessed through ductility coefficients ( $\mu = \Delta_u/\Delta_y$ ) or qualitatively defined from load-deflection curves.

There exists an enormous range of ductile performance in literature:

High Ductility: Yielding steel reinforcement in panels [2]-[4] [30], ductile connectors [32], and strain-hardening material like ECC [14] or UHPFRC [34] possess high ductility ( $\mu$  generally  $> 4 - 6$ ). Some systems, like laced steel-concrete composites, showed ultimate deformation capacity with deflections more than 150 mm [21].

Low/Brittle Failure: Panels failing by connector fracture (e.g., GFRP pins [6]), core shear [20] [29], or fabric break [20] have brittle behavior with sudden load drops and low ductility measures.

Energy absorption upon impact is another method for measuring ductility. Tests show that panels can absorb large amounts of energy through inelastic deformation [8], for which recovery rates (Deflection Recovery Rate, Q) after impact are used as an indicator [7].

Critical Analysis & Future Direction: Ductility is commonly reported, but occasionally the tests used (e.g., displacement ductility, energy-based ductility indices) are not standard across studies. A standardized approach for the measurement and reporting of sandwich panel system ductility is needed. Besides, the balance between high stiffness (usually desirable for serviceability) and high ductility (most desirable for ultimate limit states) is a significant design problem that needs more investigation. Optimized connector and material designs should be achieved in future research to achieve an optimal combination of strength, stiffness, and ductility.

## 5. Gaps Remain

The most important and first-order research challenge is to fundamentally eliminate the interlayer connector's structural-thermal performance trade off. This entails next-generation connector systems through next-generation composite materials, geometry design optimization, and integral thermal breaks that have high shear strength and stiffness but low thermal bridging. Parallel to this, there needs to be the development of standardized test procedures for the definition of connector behavior and generation of stable, multi-physics design models in an effort to translate these innovations from research into code acceptable, reliable engineering practice and eventually permit extensive application of high-performance, sustainable sandwich slabs.

Even though significant progress in experimental testing and numerical simulation of multilayer or sandwich concrete slabs, a fundamental gap remains in the general understanding of the interlayer transmission of forces and bending mechanisms, especially in three or more-layer systems. The bending simulations that are carried out to date still remain overly idealized. There is a common neglect of essential phenomena such as bond slip interactions, progressive cracking, and degradation of connectors of basic significance in realistic structural behavior. This yields a shortage of experimentally validated simulation models that account for realistic interlayer behavior, nonlinear material response, and coupled static-dynamic bending interactions. Bridging this gap is essential to the development of design-driven predictive models that more accurately reflect real-world performance.

## 6. Conclusions

This review demonstrates that the flexural behavior of sandwich slabs depends

primarily on the efficiency of the interconnecting joints, the nature of the materials used, and the loading and limit conditions. Studies have shown that achieving full composite action between the layers enhances stiffness, strength, and energy absorption, while ineffective joints or joints too closely spaced result in poor performance and brittle failure modes. Research has also shown that numerical modeling methods such as the finite element model (FEM) represent a powerful tool for predicting behavior, but they still suffer from simplifications that overlook some realistic phenomena such as gradual cracking, sliding, and joint deterioration under dynamic loads.

To develop new connection systems that balance structural performance and thermal efficiency, as well as to establish standardized testing protocols that take into account realistic loading conditions and limit constraints. Furthermore, integrating advanced numerical models with comprehensive experimental data will provide a more accurate simulation environment capable of representing the actual behavior of slabs under static and dynamic loads. This represents a promising approach toward designing practical predictive models that support the expanded use of these systems in sustainable engineering applications.

Outside structural performance, the evolution of multilayer sandwich slabs has broader connotations for sustainable construction, resource efficiency, and improved resilience of the constructed environment to extreme loading events.

## Conflicts of Interest

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

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