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Advances in Multilayer Concrete Slab Technology: Structural Performance, Vibration Mitigation, and Acoustic Insulation

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Abstract

This state-of-the-art review provides a critical overview of advances in multilayer concrete slab technology by systematically exploring three interconnected performance pillars: structural integrity, vibration serviceability, and acoustic insulation. The development of these composite systems is inherently complex due to the conflicting performance requirements and hence inevitable trade-offs; most notably, the role of stiff shear connectors as acoustic and vibration bridges. The basis for the analysis is a systematic survey of the literature for studies published between 2014 and 2025. Experimental evidence shows that composite action, and in particular connector behavior, significantly enhances bending stiffness and load-carrying capacity against monolithic construction; substantial gaps remain regarding stress redistribution, combined states of stress, and impact-related behavior. Vibration serviceability, which controls occupant comfort, is governed by natural frequency but also acceleration response, damping, mode shapes, and boundary conditions; simplified frequency limits such as those in Eurocode 5 shall hence be interpreted with regard to human perceptual response. Acoustic performance, in particular impact sound insulation, is often neglected within structurally oriented studies, despite bare slabs frequently failing to meet regulatory limits; hence, separation strategies, such as floating floors, are required, although these may conflict with rigid structural connections. The review points out a need for system-level multidisciplinary research, innovative connector solutions, validated multiphysics models, and holistic design frameworks in order to achieve an optimum balance between strength, comfort, and sustainability in high-performance building systems.

Keywords

Sandwich Panels, Composite Systems, Vibration Serviceability, Acoustic

Bridge, Shear Connectors, Acoustic Insulation

1. Introduction

The search for efficient, sustainable, and high-performance materials and systems is at the heart of the development of modern construction. Among these solutions, composite structural systems, specifically multilayer concrete slabs, have emerged as a persuasive solution that promises the synergistic integration of strength, serviceability, and environmental control. These systems combine materials such as timber, concrete, and advanced composites in layered arrangements in an attempt to benefit from the unique advantages of each component, represented by the tensile strength and lightness of timber, the compressive strength and thermal mass of concrete, and the engineered performance of shear connectors and insulating cores. In turn, this class of structures demonstrates great versatility in application, be it floors, walls, or roofs, while being capable of responding to the complex demands of today's buildings.

Even though their growing adoption, the development and optimization of multilayer slabs represent a complex, interdisciplinary challenge. Performance is not monolithic but rather segmented across three critical and often competing domains: structural integrity under various loading regimes; dynamic response and vibration control for occupant comfort; and acoustic insulation for auditory privacy. Traditional research often focuses separately on these aspects. On the one hand, structural investigations carefully consider the load-carrying capacity and failure modes; dynamic analyses target vibration serviceability criteria; and acoustic studies measure sound transmission loss. However, this compartmentalized approach may very well fail to appreciate intrinsic interactions and trade-offs native to composite design. For example, an optimal shear connector for maximum structural stiffness may act as an acoustic bridge, enabling undesirable sound transmission, while the addition of mass to improve sound insulation can have negative effects on vibrational frequency responses.

Therefore, a gap exists in the overall understanding of how the design decisions made in one domain propagate into others. A clear and present need exists to synthesize current knowledge, clarify interdependencies, and finally determine integrative design pathways that balance structural safety with human comfort and acoustic performance. This review paper seeks to address this by providing an overall critical overview of the current state of knowledge on multilayer concrete slab technology. We will systematically explore the three pillars of performance: first by discussing the structural behavior under static, dynamic, and impact loading; second by discussing vibration characteristics and mitigation strategies vital to serviceability; and third by discussing acoustic and impact sound insulation capabilities. The proposed integrated analysis intends to consolidate key findings through highlighting persistent research limitations, while coherently identifying directions for future investigation aimed at better performance, higher balance, and more reliable engineering of composite building systems. The rest of this paper is organized as follows: Section 2 discusses the structural performance related to mechanical loading, including flexural behavior, shear mechanics, and response to non-static loads. Section 3 deals with vibration and dynamic response, including experimental modal analysis, predictive modeling, and human comfort criteria. Section 4 summarizes the acoustic and impact sound insulation performance, including testing standards, treatment efficacy, and predictive approaches. Each section terminates with a critical discussion of the current limitations and future research directions being put forward, leading to general conclusions that draw together the interdisciplinary strands relating to the performance of multilayer slabs.

Figure 1: Cross-sectional diagram of a multilayer concrete sandwich panel showing structural wythes, insulation core, and shear connectors with typical dimensions (wythes: 40 mm, core: 120 mm, total: 200 mm).

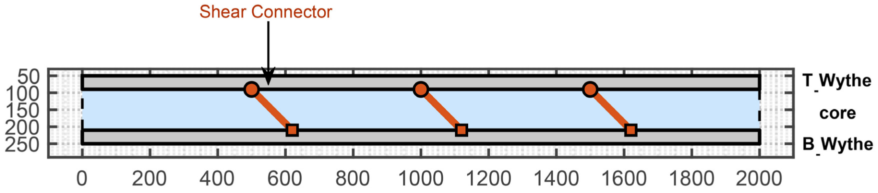

Figure 1. Cross-sectional view of a multilayer concrete sandwich panel showing key components and dimensions.

Literature Search Methodology

A systematic literature search was carried out to identify relevant studies published between 2014 and 2025. Major academic databases, such as Scopus, Web of Science, and Google Scholar, were utilized for this purpose. The Boolean string used in searching was: (“multilayer” OR “sandwich” OR “composite”) AND concrete AND (slab OR panel) AND (bending OR flexural OR shear OR structural) AND (vibration OR dynamic OR footfall OR impact OR “natural frequency”) AND (“sound insulation” OR “impact sound” OR “sound transmission” OR acoustics OR “airborne sound” OR STL OR L’n,w). Inclusion criteria were applied to the preliminary findings by title and abstract, whereby experimental, numerical, or analytical investigations targeting structural performance, vibration response, or acoustic and impact sound insulation were considered. The final set included more than 25 primary studies that form the backbone of the present review.

2. Structural Performance under Mechanical Loading

For this purpose, the structural performance of multilayer slabs subjected to mechanical loads involves, among others, flexural and shear actions. The main parameters are those related to bending stiffness (EI), ultimate load-carrying capacity, failure modes, and ductility.

2.1. Flexural and Bending Behavior

Under static bending loads, composite slabs show significantly improved performance compared to their monolithic counterparts. For example, NLTCC floors had a 78.3% increase in bending stiffness and a 79.5% increase in moment-resisting capacity compared to pure NLT panels [1]. The degree of composite action, which is controlled by the shear connection, is the important parameter. Provided there is full composite action, the system is able to approach the stiffness of a monolithic section of the same overall depth. Most systems tend to exhibit partial composite action. Research into TCC beams with crossed inclined coach screws has confirmed that such beams are able to satisfy floor vibration serviceability requirements (fundamental frequency > 8 Hz) while providing high ultimate loads in the range of 242 - 317 kN [2].

The failure mode in bending is usually layered-material-specific. For TCC systems, failure tends to initiate with tensile cracking or rupture of the bottom timber laminations [1] [3], provided the shear connection remains intact. In concrete sandwich panels, the failure mode can involve yielding of reinforcement, crushing of concrete in the compression wythe, or, importantly, failure of the shear connectors [4]-[6]. For instance, in UHPC sandwich panels, failure was controlled by the progressive fracture of GFRP shear connectors [5]. The application of fiber-reinforced concrete in cores or wythes can modify failure modes by enhancing toughness and ductility, as experienced in SCS beams with polypropylene fiber-reinforced concrete cores [7].

A synthesis of key experimental studies investigating the structural response of multilayer slabs under various mechanical loads is presented in **Table 1**. The findings, categorized by load type, highlight the central role of shear connection, material choice, and system geometry in determining performance.

Table 1. Summary of experimental studies on structural performance under mechanical loading.

Ref.	Slab System Type	Primary Load Type	Key Experimental Findings	Failure Mode/Critical Observation
Static Flexure /Bending				
[3]	Timber-Concrete Composite (TCC) Panel	Four-point bending	Panel capacity 26% - 132% higher than isolated beams; dowel connections offered best performance-cost compromise.	Tension failure at bottom of timber logs.
[1]	Nail-Laminated Timber-Concrete Composite (NLTCC) Floor	Four-point bending (ASTM D198)	Stiffness (EI) increased by 78.3%, moment capacity by 79.5% compared to NLT alone.	Successive tensile cracking of NLT laminations; concrete cracking preceded lamination failure.
[2]	TCC Beam with Crossed Inclined Screws	Static bending & dynamic test	Met vibration comfort requirement ($f_1 > 8$ Hz); stiffness increased with concrete slab width/height.	Ultimate loads of 242 - 317 kN reported.
[4]	Precast Lightweight Sandwich Panel	Three-point bending	45˚ connectors gave best composite action; CFR strips improved thermal insulation.	Cracking at mid-span; shear connector failure.

Continued

[5]	UHPC Sandwich Panel (GFRP Connectors)	Combined axial & four-point bending	Achieved 25% - 78% composite action; serviceability met wind requirements.	Progressive fracture of GFRP shear connectors.
[6]	Precast Insulated Sandwich Wall Panel	Four-point bending	GFRP connectors showed better ductility; 45˚ connectors outperformed 30˚ connectors.	Shear-compression failure in bending-shear zone.
[7]	Steel-Concrete-Steel (SCS) Composite Beam	Four-point bending	PP fibers increased toughness & ductility; micro-silica increased strength but not deflection.	Shear failure (diagonal cracks) in lightweight cores; buckling of top plate.
Shear & Connector Behavior				
[8]	Mass Timber Panel-Concrete (MTPC)	Lateral shear (connection test)	Insulation gap of 5 - 15 mm reduced connection stiffness by 35% - 60%.	Focus on stiffness and slip; friction significant without gap.
[9]	Precast Concrete Sandwich Panel (SSI/GFRP)	In-plane push-out (shear)	Shear capacity increased with SSI/GFRP ratio & connector diameter; concrete strength had minimal effect.	Concrete cracking/crushing at anchorage; connector bending/slip.

2.2. Shear Performance and Connector Behavior

The shear performance of the interface is often studied via push-out tests or analyzed in beams with high shear spans. The connector type dictates shear behavior. Inclined screw connectors in TCC systems provide both shear and axial resistance, enhancing stiffness [2] [8]. Research on precast concrete sandwich panels with hybrid stainless-steel and GFRP (SSI/GFRP) connectors showed that stainless steel components bear higher shear stress, and that shear capacity increases with the SSI/GFRP ratio and connector diameter [9]. A very important finding is that concrete strength has a minimal effect on the shear capacity of such connector systems, which is instead dominated by connector properties and anchorage [9].

Shear failures in infill walls can take the form of diagonal cracking through the concrete wythes, especially in those with lightweight cores [7], or debonding between the insulation core and concrete faces [10]. Connector angle is important; 45˚ inclined connectors normally produce better composite action and performance than 30˚ connectors do [4] [6].

2.3. Performance under Non-Static Loads

Impact and Perforation: A niche but important area investigates high-velocity impact resistance. Hierarchical sandwich panels with Autoclaved Aerated Concrete (AAC) cores and glass/epoxy skins showed that multi-core configurations outperform single-core ones in Specific Energy Absorption (SEA) [11]. Similarly, Steel Fiber Reinforced Cementitious Composite (SFRCC) layered panels demonstrated improved impact resistance with higher fiber volumes, failing through cracking and spalling without perforation [12]. Beyond impact resistance, although fatigue performance under cyclic loading has a direct relevance to the long-term serviceability, it has received rather limited attention in the literature. Liu *et al.* [13] reported that the prior tension-compression fatigue loading can reduce the subsequent bending-shear capacity of the sandwich wall panels with GFRP connectors by up to 37.1%, while the number of cycles shows a more profound influence than the load amplitude. This represents an important knowledge gap: most fatigue tests focus on residual strength while ignoring the progressive changes of stiffness, damping, vibration characteristics, and acoustic transmission properties after repeated loading. Given that service-induced vibrations and structure-borne noise are all cumulative in nature, future fatigue tests should explicitly track dynamic response and impact sound insulation changes over the entire loading history to enable durability-based serviceability design. In parallel, concerning Dynamic/Vibration Serviceability: For floor systems, human-induced vibration is a primary serviceability limit state. Studies of mass timber floors with floating concrete toppings have determined that the added mass and stiffness of the topping can shift vibration performance from "unacceptable" to "acceptable", even with very low composite action [14]. The response of the fundamental frequency to added concrete mass is non-deterministic, based on the tradeoff between added stiffness and added mass [2] [14].

2.4. Critical Analysis of Mechanical Performance Studies

The literature characterizes short-term static flexural behavior quite robustly for different systems; however, a number of limitations are apparent Regarding Scale and Sample Size, Most of the studies have small-scale specimens, for example, [4] [7], or a limited sample size per configuration, for example, [1], questioning their statistical validity and scale effect. Simplified Loading: Most tests are performed under pure flexure or shear. Real structures are subjected to complex combined loading axial-flexural-shear, as in walls, which is underrepresented [5] being an exception. Material Variability: The natural variability in the properties of timber and concrete has often been recognized as one of the limitations to result consistency [1]. Failure Mode Focus: Although ultimate failure is documented, detailed analysis of crack propagation, damage accumulation, and post-peak behavior in composite systems is less common. Future research directions should be focused on the following issues: standardized test methods for composite systems in combined stress states; large-scale and full-system tests to capture realistic boundary conditions and system effects; and detailed investigation of fatigue and long-term cyclic performance to provide input on durability design.

3. Vibration and Dynamic Response Characteristics

Vibration and dynamic response are important properties for assessments of serviceability and occupant comfort related to building floors and walls in vibration-sensitive environments such as residences and offices. The research on the dynamic performance of composite structures, essentially timber-concrete composites and concrete sandwich panels, is reviewed through the description of experimental methods, numerical modeling, influencing factors, and comfort criteria.

3.1. Experimental Modal Analysis and Dynamic Testing

Experimental modal analysis is the chief method for acquiring dynamic parameters, such as natural frequencies, damping ratios, and mode shapes. The method has been adopted in a number of studies dealing with timber-concrete composite floors. For example, Martins *et al.* [3] tested a timber-concrete composite panel through free vibration using hammer impact excitation and obtained a fundamental frequency of 17.1 Hz, which, being higher than the threshold of 8 Hz recommended by Eurocode 5 (EC5), indicates a good dynamic performance without special analysis. Wen *et al.* [2] performed modal analysis on TCC beams connected with crossed inclined screws using hammer excitation. They obtained a fundamental frequency in the range of 18 - 26 Hz and damping ratio between 2.1% and 2.9%. These authors found that the fundamental frequency decreases with increased concrete slab mass, while damping increases with a decrease in the diameter of screws.

In contrast, various studies reported frequencies below the comfort threshold. Binder *et al.* [15] mentioned that both their CLT and TCC floors had fundamental frequencies below 8 Hz, which, according to them, would require more detailed dynamic analysis according to the provision of EC5, although no frequency values were provided. This indicates that dynamic performance varies with regard to particular design aspects and composite action.

More comprehensively, detailed experimental studies were carried out on the mass timber floors with floating concrete toppings by Guo *et al.* [14]. Testing different boundary conditions through instrumented hammer testing, they indicated not only several frequencies (f_1, f_2, f_3) but also quantified the significant increase in damping ratios from 1% - 4% for the bare timber to 5% - 7% after adding the concrete topping. Their work also documented the evolution of mode shapes from localized bending in bare DLT panels to more homogeneous global bending with the topping present, visually illustrating the impact of composite action on dynamic behavior. Separately, for non-traditional floor systems, dynamic testing has also been applied in impact scenarios. Yari *et al.* [11] and Prakash *et al.* [12] investigated the high-velocity impact (HVI) response of composite sandwich panels, focusing on transient dynamic penetration resistance rather than serviceability vibration. While not providing modal properties, these studies represent an important branch of dynamic response under extreme loading conditions, relevant for safety and blast-resistant design.

Figure 2: Experimental damping characteristics reveal clear trends across timber composite systems: bare timber exhibits 1% - 4% damping, timber-concrete composites (TCC) with mechanical connectors show moderate improvement (2.1% - 2.9%), while systems with concrete toppings achieve substantially higher damping (5% - 7%). This enhancement, surpassing the approximate 5% threshold associated with satisfactory vibration serviceability, contributes directly to improved occupant comfort, often compensating for potential reductions in natural frequency.

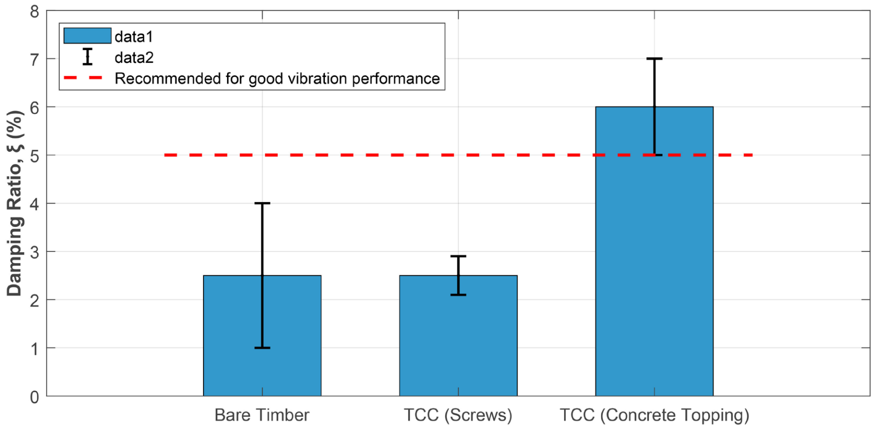

Figure 2. Damping ratio comparison across different timber composite systems.

3.2. Numerical Modeling and Predictive Approaches

Numerical modeling provides a complementary route to dynamic response prediction and extrapolation of experimental results. Different approaches can be followed, from simplified analytical methodologies to detailed FE and explicit dynamic models.

Several works focused on modal validation using FE models. Guo *et al.* [14] compared RFEM models that simulated the dynamic behavior of timber-concrete floors and concluded that a composite plate model outperforms an equivalent plate model in case of higher modes and simply-supported boundary conditions. Likewise, Palermo *et al.* [16] presented a 3D FE model developed in SAP2000 for a full-scale sandwich wall building tested on shake-table, and the comparison between the predicted and experimental frequencies was carried out in order to investigate the stiffness degradation after seismic events. Alternatively, Explicit FE codes such as LS-DYNA were used for impact dynamics. Yari *et al.* [11] verified their HVI simulation against experimental results on residual velocity and damage patterns, which confirmed the capability of the model to capture the complex transient response. Similarly, Manawadu & Qiao [5] simulated low-velocity impacts on concrete panels using ABAQUS Explicit for impact identification studies, with good correlation observed on the experimental force-time histories. Concurrently, simplified predictive methods also find their place in design-oriented studies. Corti & Muciaccia [17] made use of a closed-form vibration criterion, borrowed from literature, within a MATLAB optimization script to check vibration serviceability of TCC slabs, pointing out that vibration often controls the design for this type of element more often than deflection. The adopted approach was efficient but did not account for damping and full modal analysis. Churchill & Hopkins [18] resorted to SEA to predict the airborne sound transmission across a composite floor, being primarily interested in vibro-acoustic performance rather than in human-induced vibration.

Figure 3: Three-dimensional relationship between fundamental frequency, bending stiffness (EI), and span length for timber-concrete composite floors. The red plane represents the EC5 8 Hz threshold, illustrating the parameter space requir-

ing special analysis.

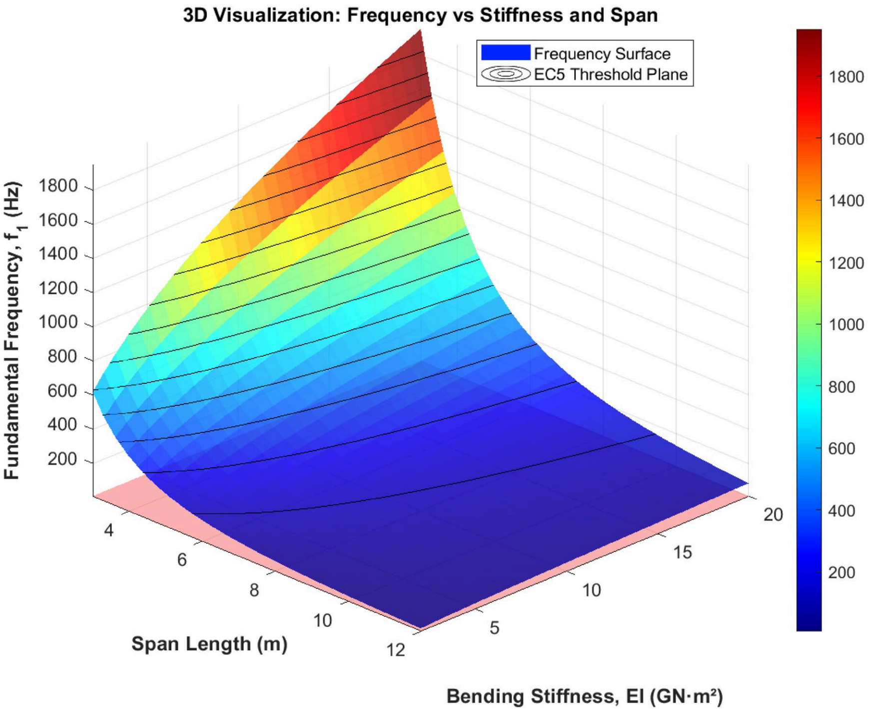

Figure 3. 3D surface plot showing frequency dependence on both stiffness and span.

3.3. Key Factors Influencing Dynamic Performance

The reviewed literature identifies several key factors that significantly influence the dynamic response of composite systems. Primarily, Composite Action and Connection Detail: Depending on connector type and stiffness, the degree of interaction between layers is critical. Mirdad & Chui [8] identified that connection stiffness will have a direct impact on the vibration performance; however, they did not perform any direct dynamic tests. Wen *et al.* [2], through experimental investigation, demonstrated that screw configuration has an impact on both frequency and damping. Additionally, Mass and Stiffness Distribution: Adding mass, for example, in the form of concrete topping, does not always enhance dynamic performance. Corti & Muciaccia [17] demonstrated that an increase in the thickness of the concrete may actually have a negative impact on vibration serviceability, as the process would be countered by increased mass even though effective stiffness was higher. Guo *et al.* [14] found that adding concrete topping had various system-dependent frequency responses: one DLT system saw a decrease in f_1 by ~30%, while another experienced an increase in it by 15% - 30%. Moreover, Boundary Conditions: Support conditions greatly influence dynamic characteristics. In the work by Guo *et al.* [14], it was determined that flexible beam supports reduced the fundamental frequency by roughly 10% compared to rigid supports. This follows basic principles of structural dynamics and thus must be considered with great care in testing and modeling. Ultimately, Damping is a key parameter for the vibration serviceability of a structure and is hardly ever reported. In those studies that measured it, like for example Guo *et al.* [14] and Wen *et al.* [2], composite systems (in particular with concrete) can provide damping ratios around 5% - 7%, which are very helpful to avoid resonant vibrations.

Overall, the studies reviewed indicate that dynamic performance is linked to a balance between mass and stiffness in multilayer slabs. Adding concrete topping does not provide an inherent assurance of improved vibration serviceability, as added stiffness can be counterbalanced sometimes even surpassed by the increase in mass. Vibration control cannot be attained through mass enhancement only but calls for system-level dynamic analysis taking into view composite action, damping, support conditions, and higher vibration modes.

3.4. Human Comfort and Vibration Serviceability Criteria

One of the primary motivations for studying floor dynamics is to ensure occupant comfort. Several standards and criteria are cited in the literature.

The most-often referenced is the Eurocode 5 (EC5) 8 Hz limit for residential floors [2] [3] [15]. Although this is a good indicator, its general applicability is questionable since frequency is only part of the indicator of comfort. Guo *et al.* [14] took a more comprehensive approach by performing subjective evaluations according to ISO/TR 21136 in which human evaluators gave a rating of floor acceptability. The authors noted that concrete toppings significantly enhanced subjective ratings and were well correlated with increased damping and altered mode shapes, meanwhile other studies focus on acoustic comfort. Bao *et al.* [19] investigated the impact sound insulation of CLT-concrete floors in accordance with Chinese GB/T standards by measuring impact sound pressure levels. Their contribution, though important regarding acoustic performance, did not tackle the issue of human-induced vibration comfort. It thus illustrates the difference between acoustic and vibration serviceability criteria.

3.5. Limitations and Future Research Directions

The existing body of literature has certain limitations, including inconsistent reporting, as important dynamic parameters such as damping ratios and mode shapes are seldom reported, thus limiting comparative analysis or holistic understanding. Furthermore, most works implement simplified analytical models that neglect damping, higher modes, and nonlinear connector behavior [8] [17] [18]. Additionally, many composite panel studies are narrowly focused on static, fire, or acoustic performance while explicitly excluding vibration serviceability [4] [7] [10] [20] [21] [22]. resulting in knowledge gaps for these systems in vibration-sensitive applications. Finally, many tests are conducted on small-scale specimens or idealized boundaries that may not fully represent in-situ conditions [11] [12] [23].

Therefore, future research should focus on dynamic Testing Protocols Standardized: To encourage the full reporting of frequency, damping, and mode shapes for all dynamic studies. Integrated Comfort Assessment: By combining objective measures (frequency, acceleration) with human subjective assessment of various occupant activities such as walking and running. Advanced Multiphysics Modeling: Development of validated FE models accounting for frequency-dependent damping, nonlinear connector behavior, and soil-structure interaction for improved prediction. Systematic Parametric Studies: Determination of the influence of a wider range of design variables such as connector type, core material and topping variability on dynamic performance, by means of coordinated experimental and numerical campaigns. Long-Term and Fatigue Effects: A discussion on the evolution of dynamic properties under both long-term service loading and exposure to the environment is rarely touched upon in the literature.

4. Acoustic and Impact Sound Insulation Performance

In sandwich and composite panel systems, acoustic performance contributes to both airborne sound insulation Sound Transmission Loss, STL and impact sound insulation Impact Sound Level, L'n,w. The literature reviewed showed a wide range of engagement from the topic at hand: some pieces had detailed experimental and numerical studies, whereas other documents only generally stated acoustic performance as a secondary benefit. This section synthesizes the findings on test methodologies, measured performance, the efficacy of acoustic treatments, predictive modeling approaches, and identifies prevalent research gaps.

4.1. Standards of Testing and Methodological Approaches

Comparisons of acoustic performance across studies require a standardized approach. For the papers that did perform acoustic tests, the most common methodology was laboratory measurements to the ISO 10140 series and related national standards such as China's GB/T 19889.6 [3] [18] [19]. These standards provide testing in coupled reverberation rooms for the weighted sound reduction index, R_w, for airborne sound, and the weighted normalized impact sound pressure level, L'n,w. For specialized materials such as sound-absorbing foamed concrete, impedance tube tests to ISO 10534-2 provided the absorption coefficient, α [20]. However, a significant portion, approximately 60% of the papers in **Table 1** of the reviewed structural literature did not perform any acoustic testing [1] [2] [4]-[16] [21]-[24]. Where acoustic testing was not performed, the acoustic performance was either inferred from mass law principles [15] [17], or qualitatively mentioned as a known benefit [1] [2] [16] [21] [22], or considered out of scope. This reflects a disconnect between structural/thermal research and acoustic validation that may limit holistic application of these panels.

4.2. Measured Acoustic Performance of Panel Systems

Where measured, the data illustrates the intrinsic performance of various systems and the transformative effect of added treatments. Bare TCC panels had an airborne sound insulation of R_w = 63 dB but delivered poor impact sound insulation at L_nw = 67 dB [1]. Bare CLT and concrete floors similarly produced high impact sound levels of 88 dB and 80 dB, respectively, confirming that monolithic structural slabs are often inadequate to satisfy stringent acoustic requirements [10]. Mass is a dominant principle, as analytically demonstrated by Corti & Muciaccia [17], where the addition of a concrete topping over timber slabs considerably increased the predicted STC. However, regarding impact noise, mass alone does not suffice, and isolation becomes paramount.

These dramatic improvements were realized through the use of floating floor systems. For instance, a suspended ceiling over the TCC panel reduced L_nw from 67 dB to below 50 dB, allowing for code compliance [3]. In CLT-concrete composite floors, dedicated floating floor assemblies including elastic layers, air cavities, and decoupled masses reduced the impact sound levels from ~85 dB down to between 53 - 59 dB, earning high acoustic class ratings [19]. These treatments decouple the impact source from the structural slab, reducing the transmission of structure-born vibration.

Figure 4: To illustrate this performance gap and the effectiveness of acoustic treatments, **Figure 4** presents a comparison of the impact sound levels (L'n,w) of different bare and treated composite floor systems based on data gathered from the literature reviewed [3] [19]. The dashed line at 50 dB corresponds to a typical building code requirement for impact sound insulation in residential buildings, as given, for example, by the Portuguese regulations [3]. From **Figure 4** it can be seen that the bare structural floors-both timber-based, such as CLT, and concrete-exhibit impact sound levels that consistently exceed this limit, within the range of 67 - 88 dB. In striking contrast, systems that incorporate floating floors or suspended ceilings achieve dramatic reductions, bringing the (L'n,w) values below 50 dB, thus making them compliant. This visual comparison underlines an important limitation of bare structural assemblies and quantifies the transformative effect of proper acoustic detailing by decoupling strategies.

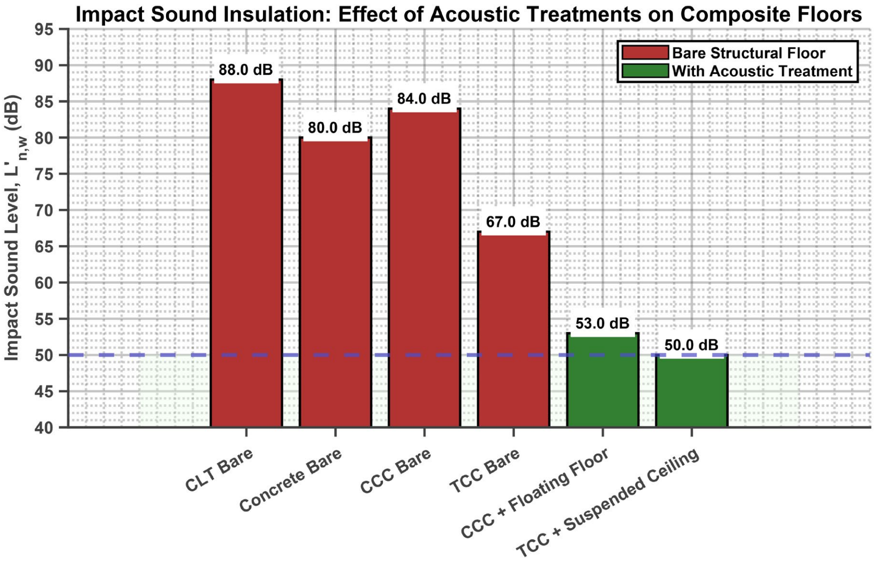

Figure 4. Impact sound insulation performance comparison of composite floor systems with and without acoustic treatments.

4.3. Role of Acoustic Treatments and Connector Effects

These reviewed studies emphasize that integrated acoustic detailing is required. Successful treatments have included resilient underlayments, such as polyurethane rubber pads [19], suspended ceilings [3], and specialized acoustic mats incorporated into floating toppings [14]. Additionally, gravel layers or heavy screeds are used as a mass-based solution for impact sound improvement in those same life-cycle comparisons [15]. The most significant acoustic consideration peculiar to composite systems is that involving the shear connectors. Bao *et al.* [19] further designated screw connectors as "acoustic bridges" in that the inclusion of these limited the potential improvement from added interlayers to $\Delta Lw \leq 3.8$ dB, illustrating a basic conflict between structural efficiency (which requires stiff, rigid connections) and acoustic performance (which requires disconnection or highly resilient connections). This latter trade-off is seldom confronted by structurally focused papers and forms a principal area for innovative connector design. 4.4 Simulation and Predictive Modeling In predictive analysis, SEA has been successfully used to model both airborne [18] and impact [19] sound transmission in complex floor systems. Churchill and Hopkins [18] were able to use SEA to predict R_w within 2 dB of the measured values and also identified dominant paths for sound transmission. In a similar manner, Bao *et al.* [19] used a SEA simplified model for floating floors and attained less than 6 dB prediction error for impact sound. These works validate SEA as a reliable tool in acoustic design for composite panels. Other modeling approaches have used empirical mass-law formulas for initial estimates [17], as well as advanced Boundary Element Methods that model structure-borne noise due to large barrier systems [25]. 4.5 Critical Analysis and Future Research Directions The literature reveals several limitations and opportunities for future work. A pronounced imbalance exists, in that many structural investigations acknowledge but do not quantify acoustic performance. Future studies of composite systems should include basic acoustic testing as a standard validation step. Another significant issue is the acoustic bridge effect of connectors. Research is needed to develop and characterize "acoustically broken" or highly resilient connectors that provide adequate structural shear capacity with minimum sound transmission. Thirdly, most acoustic tests are performed on idealized lab specimens, while field studies are needed to understand the real performance in actual buildings with flanking transmission, complex boundaries, and workmanship variability. Finally, there is a need for multi-physics optimization models that simultaneously consider structural, thermal, acoustic, and environmental performance-like the so-called "Stiffness Warming Potential" [17], to drive the sustainable design of next-generation sandwich panels.

4.4. Simulation & Predictive Modeling

In the context of predictive analysis, Statistical Energy Analysis (SEA) has been employed effectively with varying degrees of accuracy to simulate airborne [18] and impact sound transmission through complex floor structures. In these studies, predictions of R_w with a difference of no more than 2 dB from actual results were obtained, while also tracing the dominant modes of sound transmission. In a similar fashion, a simplified SEA approach was also adopted by Bao *et al.* [19] using a floating floor and obtained errors of no more than 6 dB when simulating impact sound transmission. These studies confirm that SEA is a useful tool for performing acoustic designs of composite panels. In other studies, predictions were carried out using mass laws [17], while more sophisticated methods such as the Boundary Element Method (BEM) have been adopted when dealing with large barrier structures and structure-borne noise transmission [25].

4.5. Critical Analysis and Future Research Directions

The literature identifies several deficiencies and key areas for future research, starting with a striking imbalance between the quantified and identified acoustic performances of studied structural systems, which points to a need for future studies on composite systems to include basic acoustic testing validation. Another critical challenge is the acoustic bridging caused by rigid shear connectors, which stresses the need for focused research in designing "acoustically broken" connectors, connection systems that will provide sufficient shear resistance for composite action but will incorporate elastic or resilient materials, such as elastic inserts, slotted interfaces, or steel-polymer composites with acoustically resistive interfaces to interrupt the direct transmission path of structure-borne sound. In addition, acoustic testing is usually performed on idealized laboratory specimens, and much more field testing needs to be done to assess performance in real buildings by accounting for flanking transmission and workmanship issues. Finally, there is a dire need for the development of multi-physical optimization models that include structural, thermal, acoustic, and environmental performances, such as the "Stiffness Warming Potential", to design sandwich panels sustainably.

5. Critical Gaps in the Literature

Even considering the growing volume of research, a number of critical gaps remain. Few experiments investigate the multilayer concrete slabs for combined seismic, fire, and mechanical loading; most material-specific findings cannot be generalized. Experimental work is typically limited to small-scale specimens that are unable to capture the full-system behavior, while the simplified models developed are seldom validated through comprehensive experiments or monitoring on real structures. Many ignore the vibration analysis totally and focus on static, fire, or acoustic performances. Again, those that cover dynamics normally make use of an over-simplification while neglecting the effects of damping and higher modes of vibration. Composite action variability also complicates the prediction, while the few acoustic studies rarely address human-induced vibration comfort. Besides, even though the acoustic bridge effect resulting from structural connectors has been widely recognized, practical measures for mitigation remain undeveloped. Most investigations are laboratory-based with minimum field validation, and trade-offs between structural, thermal, and acoustic performances are seldom quantified. Finally, standardized acoustic testing is missing from most structural studies, creating a persistent disconnect between acoustic and structural research efforts.

6. Conclusions

In this review, there has been a critical synthesis of multilayer concrete slab technology in relation to three clearly interlinked areas of performance: structural integrity, vibration serviceability, and acoustic insulation. It has been more than evident from various studies in the literature that multilayer slabs prove more advantageous compared to traditional ones since they provide improved stiffness, load-carrying characteristics, and functional behavior. At the same time, it has also become obvious that there exist trade-offs among these areas of performance for these structures since they inherently belong to an interdisciplinary field of science.

Structurally speaking, the performance is dominantly influenced by the level of composite action, where the dominant factors again are the design and behavior of the shear connector. Even though the static load behavior in terms of bending and shear is understood relatively well, major uncertainties remain in the area of long-term fatigue performance, multi-axial load conditions, and impacts or extreme dynamic loads.

Vibration serviceability, an important criterion for comfort, is revealed to be a complex system-level problem influenced by the parameters of mass, stiffness, damping, connector behavior, and boundary conditions. While the Eurocode 5 frequency criterion can serve as a rough guideline, the literature review underscored that a comprehensive approach that takes into account acceleration response, damping ratios, mode shapes, and human perception criteria must necessarily follow for the realistic assessment and design.

Acoustic performance, especially impact sound insulation, is not sufficiently represented in structurally focused research, whereas it plays a decisive role in dwelling and office buildings. The results uniformly demonstrate that for structural floors made of wood or concrete, a strict acoustic demand is not always satisfied, where a high level of performance can be reached only with a decoupling technique such as floating floors or suspended ceilings. An inherent conflict is found between the demand for structurally efficient stiff shear connectors and the demand to restrict structure-borne sound transmission, thus underlining challenges in creating new, acoustically resilient or "acoustically broken" connectors.

Practically speaking, the results of this review confirm the need for interdisciplinary coordination at an early stage of designing multilayer concrete slab systems. Structural engineers are encouraged to include vibration and acoustic researchers at the conceptual design stage to prevent the implementation of last-resort modifications that might negatively affect the efficiency and sustainability of the structure at the late design stage. Connector design, topping arrangement, and acoustic design should no longer be considered independently within the complex system but instead from the system point of view and are critical for the effective application of advancements in technology for high-performance building solutions. In summary, this review highlights specific and high-priority research needs, which include comprehensive experimental verification, consistent reporting of dynamic and acoustic values, fatigue life tests incorporating vibrations and acoustic transmission, and developing appropriate multiphysics models for systematic simulations and analyses. In this way, multiple layer concrete slab systems can be made to interplay stronger on physical mergers-of-strength/durability/comfort/sustainability and hence further solidify their foundation as a fundamental component for future high-performance construction systems.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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