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Sound Bridge Effects of Mechanical Connectors in Concrete Sandwich Panels: Numerical Modeling Approaches and Design Parameters

—A Review

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Abstract

The use of concrete sandwich panels consisting of two concrete wythes separated by an insulating core and connected by mechanical connectors has become a popular choice for modern building envelopes due to their high structural and thermal efficiency. The mechanical connectors that are required for the composite action of concrete sandwich panels inadvertently create a "sound bridge" that allows for a bypassing of the insulating core and causes a reduction in the sound insulation. The present paper provides a detailed state-of-the-art review of the overall sound bridge phenomena due to mechanical connectors used in concrete sandwich structures, with a focus on numerical modeling techniques and essential design parameters that affect the vibro-acoustic response. A detailed synthesis of the underlying mechanisms for the transmission of sound in sandwich structures is provided, which includes the fundamental principles of mass-spring-mass resonance, coincidence effects, and wave propagation mechanisms over a range of frequency-dependent mechanisms. Various mechanical connectors used in sandwich structures, including steel trusses, shear pins, Fiber Reinforced Polymer connectors, and hybrid connectors, are discussed in detail from the point of view of their dual functionality in ensuring structural integrity while resulting in acoustic compromise. The effects of essential design parameters on the transmission loss characteristics are discussed. The review additionally assesses the range of numerical modeling techniques used in the literature, from complex 3D finite element methods and coupled fluid-structure interaction techniques to more simplified forms of analysis, such as the Transfer Matrix Method and homogenization techniques. Critical analysis of the literature reveals that, despite the significant advances in the ability to numerically predict the behavior, the literature is characterized by a notable lack of experimental verification, the use of ideal boundary conditions, simplified forms of acoustic loading, and the lack of consideration of manufacturing defects and material damping. Notable research areas are identified, including the lack of experimental characterization of the acoustics of the FRP connector, the lack of consideration of low-frequency behavior, and the lack of integrated design consideration for the structural, thermal, and acoustic requirements. The review concludes by discussing the future research directions, which focus on the necessity for experimentally validated high-fidelity models, standardized testing methods that include diffuse fields, and the development of multifunctional connectors that are optimized for both composite action and acoustic insulation. This is necessary for advancing the rational design of concrete sandwich structures that are capable of satisfying the increasingly demanding acoustic requirements for modern building envelopes and transportation structures.

Keywords

Concrete Sandwich Panels, Sound Bridge Effects, Mechanical Connectors, Numerical Modeling, Design Parameters

1. Introduction

In fact, sandwich panels formed by the integration of two thin, stiff face sheets bonded by a lightweight core material have evolved into the fundamental building blocks for modern engineering structures in aerospace, marine, automobile, and civil engineering fields [1] [2]. The high strength-to-weight ratio, along with high stiffness-to-weight ratio, design flexibility, and multifunctional capabilities, have made these structures particularly appealing for weight-critical structures where efficiency is a major concern in the design of modern engineering structures [1] [3]. In fact, over the years, the major focus has been on improving the structural efficiency along with thermal efficiency of these sandwich structures by investigating the load-carrying capacity, fire resistance, connector efficiency, and energy absorption mechanisms of these structures [4]-[7]. Nevertheless, as the requirements for modern engineering structures are becoming increasingly challenging, the acoustic efficiency of these sandwich structures has transformed from a minor concern into a major concern in designing these structures for building envelopes, high-speed trains, aircraft cabins, naval structures, etc. [2] [8] [9].

The inherent acoustic problem with sandwich panel constructions is based on their lightweight design and high specific stiffness. This is a desirable characteristic from a structural integrity standpoint. However, it is a less desirable characteristic from the standpoint of sound insulation. This type of panel is particularly susceptible to low-frequency sound transmission. This is due to coincidence effects that occur when the phase of the structural bending waves is matched with the acoustic waves propagating in the surrounding media. This phenomenon causes significant dips to occur in the sound transmission loss curve. The periodicity of the core topologies can also result in pass-bands for the propagation of sound. This allows for the efficient transmission of sound through the panel. The mass-spring-mass resonance is another significant acoustic problem with the double-wall panel. This resonance is typically found in the frequency range for which the core acts as a spring coupling the two masses of the face sheets. Overcoming these acoustic weaknesses while not impairing the structural efficiency, lightweight design attributes, or manufacturability of sandwich panel constructions has emerged as a key research domain to address, thereby fueling substantial advances in the design of sandwich panel cores and the implementation of smart damping technologies [10]-[13]. The following review aims to summarize the existing literature on sandwich panel acoustics, including the underlying mechanisms for sound transmission, various approaches to improve noise reduction performance, and the interrelation between acoustic performance and structural performance.

Thusly, the current review aims to provide a comprehensive overview of the existing body of literature on the sound bridge effects of mechanical connectors on the vibro-acoustic performance of concrete sandwich panel systems, with a focus on the numerical modeling approaches adopted to explain the underlying mechanisms of the phenomenon. The current state of knowledge on the effects of the type of connector, material properties, geometry, and configuration on the vibro-acoustic performance of the panel system is synthesized to identify the research gaps existing in the current body of literature on the subject. Specifically, the absence of experimental validation of the numerical models developed to explain the sound bridge effects of the mechanical connectors on the vibro-acoustic performance of the panel system is identified as a significant gap.

Figure 1 is a schematic diagram of a typical sandwich panel structure, showing the top and bottom face sheets and the truss-like core, representing common lightweight core topologies used in structural and acoustic applications.

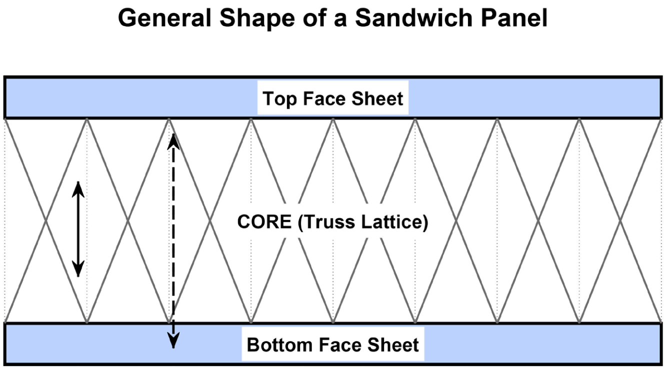

Figure 1. Schematic of a sandwich panel cross-section.

Literature Search Methodology

A systematic literature search was conducted to identify relevant studies published predominantly between the years 2007 and 2026, focusing on the sound bridge effects of mechanical connectors in concrete sandwich panels. The search employed a range of academic databases, including Web of Science and Google Scholar. The search terms used were: (concrete "sandwich panel" OR "sandwich wall" OR "double-leaf wall"), "sound transmission", "sound insulation", "acoustic performance", "sound bridge" OR "acoustic bridge" OR "flanking transmission" OR "structure-borne sound", "mechanical connector" OR "shear connector" OR "tie" OR "truss" OR "FRP connector", "vibration", "impact sound", "finite element", "numerical model", "simulation", and "vibro-acoustic". The initial set of results was then narrowed down based on the title and abstracts, whereby the inclusion criteria concentrated on experimental, numerical, and analytical papers dealing with the acoustic properties, sound transmission, and vibro-acoustic characteristics of multi-layered and sandwich panel assemblies with mechanical joints. Papers whose emphasis was on thermal properties only, structural aspects not associated with acoustic characteristics, or unrelated to the topic, such as aerospace and purely metallic sandwich panels, were excluded. From this set of articles, a total of 25 research papers were finally selected for further analysis in the current literature review.

2. Fundamentals of Sound Transmission in Sandwich Panels

Knowledge of the basic mechanisms of sound transmission in sandwich panels is considered crucial for the rational design of structural elements with optimal acoustic performance. Unlike homogeneous panels, which are mainly subjected to the mass laws of sound transmission, the sound transmission in sandwich panels is associated with complex vibro-acoustic phenomena, which are the result of the interaction between the face sheets, the core, and the enclosed fluid cavity. The examples presented herein are mostly analogies, based on the generalized sandwich concept and studies involving mostly lightweight metals, polymers, or composite sandwich panel systems; whereas the science of resonance and wave propagation is universal, the high mass and inherent damping of concrete wythes may significantly shift these frequency boundaries compared to the lightweight models cited.

2.1. Transmission Pathways and Theoretical Frameworks

Sound transmission in sandwich panels takes place via airborne sound and structure-borne sound. Airborne sound transmission takes place when sound waves impinge upon the faces, inducing vibrations, and these are transmitted via the core and then radiated to the other side. On the other hand, structure-borne sound transmission takes place via vibrations generated within the structure, transmitted via elastic waves, and then radiated to the surrounding fluid. Analysis of sound transmission in sandwich panels has been extended beyond classical theories of mass law, coincidence effect, and mass-spring-mass resonance to include the complexities of the core, including periodicity. Advanced theories, such as Bloch waves, the transfer matrix method, and homogenization, have been employed to accurately predict sound transmission loss, and it has been found that sandwich panels do not behave according to mass law due to their flexible and periodic core.

2.2. Frequency-Dependent Acoustic Behavior

The acoustic performance of sandwich panels is highly dependent on frequency and hence requires special design considerations for various frequency ranges. For low-frequency ranges (0 - 1000 Hz), where the "mass law" is not effective and resonance plays a crucial role in sound transmission through sandwich panels, scientists have attempted to address MSM dip control through optimization of the geometry of sandwich cores [14] [15] and design auxetic/hybrid cores for STL enhancement [11] [15]. For high-frequency ranges above 1000 Hz, coincidence phenomena and band gap phenomena dominate sound transmission through sandwich panels, and truss lattice cores have shown potential for STL enhancement through partial band gaps. For mid-frequency ranges (1 - 10 kHz), where sound transmission through sandwich panels is difficult to model, scientists have come up with innovative ideas such as compliant mechanism cores for designing attenuation zones [16] and analysis of wave propagation through periodic profiles.

2.3. Research Limitations and Future Directions

Critical analysis of existing research indicates that there is a need to overcome several limitations. Firstly, there is a gap between the structural and acoustic research communities. For example, many research works on the mechanics of sandwich panel structures often ignore acoustic aspects altogether [4]-[6]. Secondly, various modeling methods are available to solve panel problems, from efficient methods like TMM to accurate methods like FEM. However, there is a lack of systematic validation of the applicability of various modeling methods to various core materials and frequency ranges [17]. Thirdly, material damping and its frequency dependency have not been well developed, although it is critical to controlling resonance peaks [9]. Lastly, scaling laws showing that band gap frequencies vary inversely with length scales have critical implications for scaling laboratory results to full-scale applications. For example, the effects of manufacturing imperfections on scaling laws have not been well understood.

3. Mechanical Connectors in Concrete Sandwich Panels

This section synthesizes concrete-specific evidence regarding GFRP shear pins and PERFOFRP plates, which rely on unique mechanics like concrete dowel action with analogies drawn from lightweight steel trusses and 3D-woven fabrics; it should be noted that the superior mass and damping of concrete wythes likely reduce the severity of the "sound bridge" penalty compared to the lightweight aerospace or marine models often cited in the literature.

3.1. Types of Mechanical Connectors

Steel Trusses

Steel truss connectors have traditionally been heavily utilized in the construction of sandwich panels, usually made up of welded wire fabric and steel members. Various steel connector configurations have been reported by Sah *et al.* [1], including steel truss, I-section, and C-section connectors. Although steel offers high strength and ductility, it has major thermal bridging issues. The research work of Fu *et al.* [9] [18] has shown pyramidal and tetrahedral steel truss core materials in steel sandwich panels, indicating that strut length, radius, and inclination angle have a significant impact on transverse shear stiffness and structure-borne sound transmission paths. The major advantage of steel trusses is their known mechanical properties and design methodologies; however, steel has high thermal conductivity, and hence thermal issues are of major concern in energy-efficient building envelopes.

Shear Pins

Discrete shear pin connectors are a minimalist design concept in connecting wythes and usually consist of short and high-strength members located in the insulation layer. Haffke *et al.* in reference [4] utilized GFRP bar-type shear connectors that act as shear pins with diameters of 12 mm and a ribbed surface to facilitate mechanical interlocking. The shear pin connectors had their ends cut at 30 degrees and free lengths equal to the core thickness to ensure maximum shear resistance and minimum bending action. De Sousa *et al.* in reference [6] also utilized functional and structural GFRP connectors in micro-concrete sandwich structures, and in this case, structural GFRP bars of 8- and 12-mm diameters act as a primary mechanism of shear transfer between the outer layers of RSFRC and the inner insulation layer. Discrete shear pin connectors allow for strategic placement to ensure maximum composite action.

FRP Connectors

Fiber Reinforced Polymer (FRP) connectors have emerged as universally accepted alternatives to steel connectors, which provide similar levels of strength while maintaining significantly lower thermal conductivity. The Glass Fiber Reinforced Polymer (GFRP) is identified as the most commonly utilized FRP material, which is generally produced using E-CR glass fibers and vinyl-ester/polyester resin systems [4] [5]. Silva and Lameiras [5] have designed PERFOFRP connectors, which are made from perforated GFRP plates of 2.32 mm thickness with strategically placed holes to provide interaction with concrete dowel action through multiple mechanisms, including concrete front bearing, dowel effect via perforations, and frictional resistance. This has emerged as an advanced version of traditional bar connectors, which can potentially provide better load distribution and failure characteristics. Sah *et al.* [1] have reported the entire range of materials utilized in FRP connectors, which includes GFRP, CFRP, and BFRP materials; it is evident that material selection is critical and significantly influences structural as well as economic viability. The ribbed surface textures and end-conditioning processes, such as 30˚ cuts, generally adopted in FRP connectors [4] [6] reflect the construction industry's adaptation of reinforced concrete principles.

Hybrid and Composite Connectors

Recent emerging research has been carried out to investigate hybrid connector systems, in which several materials or geometries are employed to attain synergistic performance benefits. Sah *et al.* [1] found that hybrid steel-FRP connectors are an emerging trend, which may help to attain ductility and thermal efficiency simultaneously. Wan *et al.* [7] and Yan *et al.* [8] studied GFRP lattice truss structures, in which the connector system is not an individual component but rather an integral three-dimensional woven fabric, where the epoxy resin is infused. Gradient layer structures, such as T1, T2, and T3, were designed, consisting of "8"-shaped piles in the warp direction and "1"-shaped piles in the weft direction, thereby developing orthogonal anisotropy that can be tailored to meet specific requirements. This method of weaving is quite different from the conventional method of inserting discrete connectors, in which delamination may be completely eliminated. Xu *et al.* [2] reviewed advanced composite connectors such as FMLs and hybrid materials, indicating that future connectors may be developed to utilize the benefits of hybrid materials rather than individual materials.

3.2. Structural Role vs Acoustic Penalty

The main structural function of mechanical connectors is to facilitate the transfer of shear forces from one wythe of concrete to another to obtain composite or partial composite action against gravity and lateral loads. Haffke *et al.* [4] proved that shear forces are effectively transferred by GFRP bar connectors under combined fire exposure and mechanical loads, though temperature has a major impact on the stiffness of connectors. Silva and Lameiras [5] found that there are three distinct shear force transfer methods from one wythe of concrete to another: concrete bearing at the front of the connector, dowel action through perforations, and frictional resistance at the interface of the connector with concrete. For composite action of panel structures, connectors must be able to withstand not only vertical shear forces but also tension and compression forces from lateral loads such as wind and seismic events [1]. De Sousa *et al.* [6] proved that the structural performance of FRP connectors is comparable to that of steel connectors when properly designed to obtain composite action in building strengthening. However, whereas mechanical connectors are critical for structural integrity, they inevitably introduce structure-borne sound transmission degradation. Atalla [17] found mechanical links to be the primary source of degradation in double-wall sound transmission, whereby a single connector acts as a preferred transmission path for vibrational energy to bypass the insulating air gap. Franco *et al.* [19] and Yang *et al.* [10] found that the geometry of connectors plays a critical role in sound transmission, particularly in terms of angles, cross-sections, and configurations. Moosavimehr and Phani [20] found that core geometries are critical in altering sound transmission loss, regardless of material quantity. Gazzola *et al.* [14] found that ligament flexural characteristics tune mechanical stiffness, which in turn affects the mass-spring-mass system resonance frequency. Li and Yang [11] found that locally varying stiffness can create stopbands to inhibit vibrational energy transmission.

This tension between the structural and acoustic properties is what poses optimization problems. Kohrs and Petersson [21] proved that periodic truss-like cores can be used to achieve pass and stop bands for waves propagating through the material, and that the configuration of the core fundamentally influences the paths that waves propagate. Dede and Hulbert proposed that the connector's geometrical properties can be optimized for the reduction of vibrations without affecting load transfer. Wang *et al.* proved that the material used for the filler has properties that reduce the amplitudes of resonant waves without affecting the material's stiffness. Quinteros *et al.* proposed using phononic crystals and optimized the geometrical properties of the unit cell to achieve band gaps for certain frequencies. Yet despite all of these advances, very little research has focused on the explicit optimization of connectors for sandwich structures made of concrete with regard to structural and acoustic performance. While most research on structural-acoustic design has utilized idealized geometries of connectors that vary significantly from actual connectors used in concrete panel structures, the large mass and damping of the concrete wythes compared to the face sheets of most sandwich structures may significantly impact the acoustic penalty of such a design. It is suggested that research be conducted to determine the impact of various connector geometries on sound transmission through a structure, whether it is possible to design a connector layout that has an acoustic stopband with shear transfer capability, and what the quantitative relationship is between composite action and sound loss.

4. Sound Bridge Effects Induced by Mechanical Connectors

Although the thermal bridging phenomenon of connectors in sandwich panels is widely known and is considered a major reason for the development of innovative materials [1] [5], the role of connectors as a medium for structure-borne sound, *i.e.*, a "sound bridge," is equally significant for a comprehensive assessment of the performance of sandwich panels. The mechanical connectors, irrespective of their thermal conductivity, provide a medium for the direct coupling of the two panels, circumventing the air gap/core, which acts as an isolating medium. This section highlights the findings regarding wave propagation and resonance dips. The findings presented are primarily analogies drawn from lightweight woven composites and 3D printed polymers.

4.1. Theoretical and Numerical Basis for Sound Bridge Effects

The fundamental concept of a mechanical link forming a "bridge" in a sound transmission problem is well-established in the field of acoustics. Atalla explicitly treats this in his work, using a Transfer Matrix Method (TMM) approach to show the degradation of Transmission Loss (TL) in a DW with the addition of mechanical links. The "bridge" concept provides a direct path of transmission for vibrational energy, effectively "short-circuiting" the spring-like isolation of the air gap. This is especially true in a turbulent boundary layer (TBL) excitation condition, which is conducive to resonance in the transmission through the structure.

The core is essentially the bridge in a sandwich panel. Previous research has shown that various core configurations result in different wave propagation modes. These modes are critical in defining the acoustic behavior of a structure. For instance, Franco *et al.* [19] showed that regularly spaced truss cores are responsible for directivity in wave propagation. By introducing randomness in the stiffness of these cores, the directivity was disrupted, resulting in reduced vibration levels and acoustic power. This shows that the periodicity of the connector arrangement is critical in defining efficient sound bridges. Additionally, Moosavimehr and Phani [20] showed that various truss lattice cores result in unique wave propagation modes characterized by partial band gaps. These are ranges of frequencies where wave propagation is impeded. This shows that the sound bridge generated by the connectors is not simply on or off but is a function of its geometry.

4.2. Connector Stiffness and Density Effects

The mechanical properties of the material used in the connector, especially in terms of its stiffness and density, are of primary importance in establishing the strength of the sound bridge. It should be noted that the connector acts as a dynamic element with impedance matching the facings.

Theoretical and numerical studies have clearly proven these facts. Yang *et al.*, in their research on a DW system with interconnected acoustic cavities, have shown that the stiffness of the connecting element, *i.e.*, the value of Young's Modulus (E), plays an important role in the calculation of the stiffness ratio (κ) of the structural component and acoustic cavities. It should be noted here that the value of κ plays a crucial role in the calculation of Sound Transmission Loss (STL). It has been found in the research of Yang *et al.* that a stiffer connecting element would always lead to a lower value of STL compared to a softer one. These findings are in accordance with the research of Atalla *et al.* [17], in which it was clearly shown that the value of stiffness of the connecting element (k) plays a crucial role in the degradation of TL. Kabiripoor *et al.* in their research have shown that an increase in static bending stiffness would always lead to a lower value of STL in the stiffness-controlled frequency range.

The role of material density and its distribution is also significant. In their modeling of periodic sandwich structures, Marczak and Jedrysiak [22] proved that an increase in the stiffness ratio of the core (ξ = E2/E1) increases the lower-order synchronous vibration frequencies, whereas an increase in the density ratio of the core ($\zeta = \rho 2/\rho 1$) reduces all the frequencies. This proves that the connector materials have a significant effect on the modal behavior of the panel, which in turn governs the acoustic radiation and transmission. The difference in the materials of the connector and the facings/core filler is a significant factor. For example, replacing a dense and stiff steel connector with a less dense and less stiff Glass Fiber-Reinforced Polymer (GFRP) connector not only removes the thermal bridging effect [4] [5], as discussed earlier, but may also affect the structural dynamics of the sound bridge and hence reduce the efficiency of the sound bridge in transmitting the sound.

4.3. Connector Spacing, Orientation, and Layout

Apart from the inherent material properties, the spatial arrangement and the details of the geometry of the connectors play an important role in the vibro-acoustic response. The arrangement of the connectors essentially describes the periodic structure.

The research on randomization of stiffness conducted by Franco *et al.* [19] may be seen as a tacit recognition of the role of spatial regularity. A regular and periodic arrangement of structures provides a coherent waveguide with high transmission efficiency, whereas the addition of irregularity or "perturbations" can disrupt the coherence of the vibrations and localize them, reducing the effect of the sound bridge. This idea underlies the concept of phononic crystals, as studied in the research conducted by Quinteros *et al.* [23]. It was shown that the band gap frequency in phononic crystals depends inversely on the length scale (L). If all the parameters of a sandwich panel are uniformly scaled in size, the band gap width remains unchanged. However, if only certain parameters, e.g., the diameter of struts, are changed in a "distorted scaling," the band gap may be entirely eliminated, changing the transmission characteristics of the sound bridge.

Other geometric parameters are also significant. For example, Yang *et al.* [10] have shown that an increase in the inclined angle θ of the connecting beam results in improved sound insulation. This result can be interpreted in terms of an impact on the transmission of out-of-plane motion, either facilitating or hindering it. Fu *et al.* [9] [18] have shown that an increase in core height (h_c) and radius (r) shifts the positions of the natural frequencies and affects the amplitude of STL. For example, an increase in height results in an increase in natural frequency, shifting the dips in STL to higher values. Fu *et al.* have also shown that an increase in core radius results in a decrease in natural frequency but can increase STL. Li and Yang have shown that an inhomogeneous core, achieved by varying the cell angle θ, can be used to shift dips in STL, thus optimizing sound transmission. Finally, the number of unit cells [15] and the ligament dimensions of the core [14] are also significant, with changes leading to performance fluctuations and shifts in key resonances.

4.4. Frequency-Dependent Sound Transmission

The sound bridge effect is naturally frequency-dependent and is seen most prominently in certain resonant frequencies. The literature has consistently pointed out certain critical frequency regimes where the effect is seen to be particularly acute.

The most fundamental is the mass-spring-mass (MSM) resonance, in which the two facings vibrate out-of-phase on the stiffness of the core/connectors. Gazzola *et al.* [14] explicitly related the geometry of an elastic ligament to this phenomenon, showing that a decrease in ligament thickness causes the MSM resonance dip to occur at lower frequencies (e.g., 187 Hz for their configuration). This is a dip in frequency for drastically reduced insulation, where the sound bridge is most effective. Wan *et al.* [7] found a similar resonance dip at 160 Hz for all tested woven lattice truss panels, irrespective of thickness, highlighting its fundamental origin from the interaction between the two facings on the stiffness of the connectors.

Aside from this basic resonance effect, the connector geometry defines the entire modal response of a panel, which is a series of transmission paths that vary as a function of frequency. Most studies have measured natural frequencies for different cores [9] [11] [13] [18] [22] [24], which directly relate to maxima in vibration response [12] [24] and minima in STL [8] [10] [11]. For example, different topologies of truss cores, such as pyramidal, kagome, or tetrahedral topologies, result in different first resonance frequencies [9], which are also evident from corresponding minima in the STL curves [15]. Higher-order resonances, like that of the frame flexural mode at 630 Hz reported by Gazzola *et al.* [14], provide additional transmission paths for sound. Periodic structures also have band gaps, which are ranges of frequencies where wave propagation is inherently forbidden. Dede and Hulbert [16] designed a compliant mechanism core that had a broadband attenuation zone starting from 2320 Hz, where the top layer vibration is significantly reduced. Moosavimehr and Phani [20] reported coincidence frequencies and double-wall resonances that vary depending upon the topology of cores, which results in the enhancement of STL by up to two orders of magnitude at band gap frequencies.

Table 1 summarizes the key literature research results on the acoustic bridging effect of mechanical connectors, including connector parameters, observed effects on sound transmission, and relevant frequency ranges.

Table 1. Summary of key literature findings on the sound bridge effects of mechanical connectors.

Ref.	Connector Parameter	Key Finding on Sound Bridge Effect	Most Relevant Frequency
[19]	Stiffness Periodicity	Regular stiffness creates waveguides; Randomizing stiffness disrupts this, reducing vibration.	Broadband
[10]	Inclined Angle (θ)	A larger inclined angle generally improves STL.	System modes
[20]	Core Topology	Different topologies create distinct wave propagation and partial band gaps.	Core-dependent (e.g., ~100 Hz - 4 kHz)

Continued

[9]	Core Height/ Radius	Increasing height shifts resonances higher; larger radius lowers them but can increase STL.	844 - 998 Hz
[14]	Ligament Dimensions	Thinner ligaments shift the mass-spring-mass (MSM) resonance dip lower.	MSM resonance (e.g., 187 Hz)
[11]	Cell Angle (θ)	Varying the cell angle across the panel shifts resonance dips.	42 - 124 Hz
[12]	Piezoelectric Stiffness	Resonant shunt circuits damp specific modes, reducing radiated sound power.	Modal frequencies (e.g., 291 Hz)
[16]	Compliant Mechanism Core	Creates broadband attenuation zones via out-of-phase, non-resonant behavior.	3000 - 5500 Hz
[17]	Link Stiffness (k)	Mechanical links create a "bridge," significantly decreasing TL.	Double wall resonance (~339 Hz)
[7]	Panel Configuration	A resonance dip at ~160 Hz was observed for all panels, linked to the connector-facings interaction.	160 Hz
[23]	Length Scale (L)	Band gap frequency scales with 1/L; Distorted scaling can close the band gap.	Band gap frequency

5. Numerical Modeling Approaches for Sound Bridge Analysis

The investigation of sound transmission and vibration characteristics of sandwich panels has been extensively pursued through various numerical modeling approaches. These numerical modeling approaches vary from detailed 3D finite element models to more simplified models, each having its own merits and demerits depending upon the research objectives of individual studies. In this section, various numerical modeling approaches adopted by different authors from the literature are synthesized according to the most dominant numerical models adopted by individual researchers. However, mostly these models are analogies based on idealized geometries or lightweight materials with a lack of experimental verification. Moreover, common modelling simplifications like 2D plane strain and homogenized cores mostly overlook the significant mass and material damping specific to concrete wythes.

Figure 2 shows the conceptual sound insulation loss curve of the sandwich panel, illustrating the frequency ranges where different numerical modeling approaches are most suitable. Detailed finite element methods (FEM) resolve low-frequency modal behavior; coupled FE-boundary element or hybrid methods address the mid-frequency transition; and high-frequency techniques such as the Transfer Matrix Method (TMM) or statistical energy analysis (SEA) capture average trends efficiently. The annotated dips represent typical resonance phenomena (panel modes, core resonances, coincidence effect).

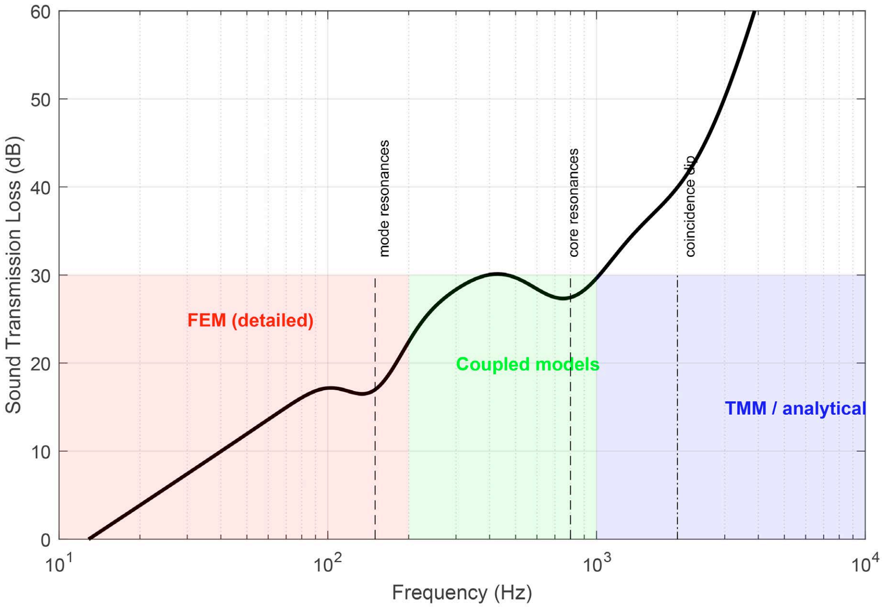

Figure 2. Conceptual sound transmission loss curve for a sandwich panel.

5.1. Finite Element Modeling (FEM)

Finite Element Modeling appears to be the most widely accepted numerical method for the vibro-acoustic characterization of sandwich panels' performance, with ABAQUS, ANSYS, LS-DYNA, and COMSOL Multiphysics being the most popular commercially available software packages widely utilized for the purpose [1] [2] [20]. While the development of a valid FE model may result in more realistic predictions compared to simplified analytical approaches and may minimize the need for extensive experimentation, the available numerical studies are mostly limited to the individual component performance evaluation instead of system performance evaluation. The choice of finite elements plays a critical role in the accuracy of the solution. For sandwich panels, shell elements are often used for the face sheets, beam elements for the core struts, and acoustic elements for the fluid regions, along with the corresponding damage criteria such as the Hashin failure criteria and Cohesive Zone Models. However, computational costs become prohibitively expensive with large-scale models or high-frequency calculations, and validation against experimental results rather than numerical results remains an important tool in ensuring the reliability of predictive calculations across the studies reviewed [2] [12].

5.2. Vibro-Acoustic Coupled Models

Coupled fluid-structure interaction models have also been proposed to simultaneously address structural vibrations and acoustic radiation using specialized software packages such as ACTRAN and LMS Virtual. Lab, and COMSOL Multiphysics with periodic boundary conditions implemented in the code [9] [14]. These methods generally employ equivalent core representations of complex geometries involving honeycomb or truss cores modeled as an orthotropic material using infinite baffle approximations and Perfectly Matched Layer techniques in the acoustic domain [9] [24]. The Transfer Matrix Method provides a computationally efficient method, but is restricted to flat panel geometries and high-frequency solutions where modal effects are negligible in the acoustic domain [17]. In contrast, validation of these methods against experimental results appears to be surprisingly absent in the literature, with most studies only comparing results with other numerical models or theoretical results, with simplifying assumptions in the core modeling potentially masking important local effects critical in accurate transmission loss calculations [9] [14] [24].

5.3. Simplified Analytical and Hybrid Models

Simplified analytical methods, from one-dimensional spectral elements to two-dimensional equivalent plate approaches, have been proposed for the compromise between solution accuracy and computational efficiency for optimization and parameter studies [11] [13] [15]. Spectral beam elements with the Wittrick-Williams method are useful for efficient eigenvalue extraction without any mode skipping, and equivalent single-layer approaches based on Third-order Shear Deformation Theory are exact for simply supported boundary conditions [11] [13]. Averaging of tolerances is useful for microstructure changes by redefining the periodic cell function rather than redefining the entire model, though accuracy is sacrificed for higher vibration modes [22]. However, all simplified methods universally suffer from a compromise in solution accuracy, whether through two-dimensional approximations, "hard" core approximations, or inability to capture joint continuity effects, and generally validate against other numerical methods rather than experimental data, thus limiting confidence in predictive capabilities [10] [13] [16].

However, determining the right type of numerical technique for sound-bridge analysis depends greatly on balancing detail and efficiency within particular frequencies. FEM is best used for low-frequency analysis in that it can describe specific modal behavior through shell and beam element details, but it is typically limited to individual components due to the prohibitive computational costs of large-scale, high-frequency simulations. Coupled vibro-acoustics modeling addresses the middle frequency transition by considering both fluid and structure at once, but it uses simplified core structures and infinite baffles, in that it fails to take into consideration important localized effects. The Transfer Matrix Method (TMM) provides high efficiency for high-frequency solutions where modal effects are negligible, but it is strictly restricted to flat panel geometries and captures only average acoustic trends. Lastly, simplified analytical and hybrid models such as 1D spectral element method and 2D equivalent plates are ideal for quick parameterization in low to middle frequencies, but make use of idealized boundary conditions (simply supported), and do not consider joint continuity and higher vibration modes. However, all these methods currently suffer from a notable lack of experimental validation, specifically regarding concrete sandwich systems.

6. Vibro-Acoustic Coupling and Boundary Conditions

This section synthesizes literature on the critical role of fluid-structure interaction and edge constraints in sound propagation. While the structural parameters discussed previously are vital, the vibro-acoustic coupling mechanism and boundary conditions govern how vibrational energy is converted into acoustic radiation. However, most existing literature generates results based on idealized analogies such as simply supported or clamped edges in infinite rigid baffles, which fail to capture the behavior of concrete panels; specifically, the large mass and inherent damping of concrete wythes, combined with "rigid baffle" leakage found in physical test holes, create significantly different vibro-acoustic signatures than the lightweight models typically cited.

6.1. Connector Material Properties

In the context of vibro-acoustic coupling, the core acts as a "connector," and its properties are crucial in influencing the dynamic interaction between the two face sheets. The core's stiffness and damping properties directly influence the energy transfer from the excited face sheet to the other. Research based on completely coupled fluid-structure interaction models has investigated various core materials. For example, Fu *et al.* [9] and Fu *et al.* [18] have analyzed metallic cores, such as aluminum and steel truss structures, under various conditions, showing the core's elastic modulus to be a significant factor in influencing the dynamic response of the panel and its sound radiation. However, the use of lighter and stiffer materials, such as aluminum, as in most research [10] [11] [15] [16], is intended to increase the specific stiffness, but at the expense of internal damping, possibly resulting in reduced damping of the structural vibrations at resonance.

The advent of advanced composites has added a further dimension to core material properties. Arunkumar *et al.* [13] studied a magneto-electro-elastic (MEE) composite core material, where the intrinsic coupling between electric and magnetic fields in the core material was shown to be used to control vibrations and hence sound radiation. This is a step change from passive material behavior to active material behavior. Additionally, the advent of polymer-based cores such as Nylon PA12 used in the 3D-printed panel studied by Gazzola *et al.* [14] has shown that there is scope to leverage base material damping. The work by Gazzola *et al.* was experimentally validated and showed that the viscoelastic properties of the polymer had considerable scope to contribute to acoustic insulation, especially with a periodic structure. However, there is a major gap in knowledge that needs to be filled: whereas the impact of core material effective properties is well understood, there is a lack of work on how the impact of the material's intrinsic damping coefficient used in the connector affects STL, especially in relation to geometry effects.

6.2. Geometric Parameters

The geometry of the core, whether a truss, honeycomb, or corrugated configuration, is the most extensively studied parameter in vibro-acoustic coupling. The geometry of the core determines the paths of the structure-borne sound and the frequencies at which the panel is most efficient in radiating noise.

Significant research has been dedicated to the study of truss lattice cores. Moosavimehr & Phani [20] have successfully validated their models using historical data on shear panels, providing a framework for understanding the impact of core geometry on STL. Fu *et al.* [9] and Kabiripoor *et al.* [15] both investigated the impact of geometry on the truss core, with the latter also demonstrating the potential for optimizing a truss-like geometry for improved STL in broadband low-frequency domains. This is a fundamental aspect in understanding the impact of geometry on STL, as the dimensions of the unit cell and strut angles directly impact the position of the stop band and the coupling stiffness. Guo *et al.* [12] also used the core geometry for the attachment of resonant shunt circuits, directly impacting the acoustic radiation of specific modes. This is a fundamental aspect in understanding the impact of geometry on STL, as the geometry is not simply a medium for wave propagation but also a medium for impact.

Other geometric configurations exhibit alternative coupling characteristics. For example, Yang *et al.* in reference [10] studied a double-wall structure with interconnected trapezoidal acoustic cavities. This geometry, in itself, inherently promotes a more complex FSI due to the presence of acoustic cavities that resonate. Another study on woven lattice truss structures was conducted by Wan *et al.* in reference [7] and Yan *et al.* in reference [8]. This study promotes an even more intricate geometry, whereby the geometry of the core is multifunctional, promoting load-carrying and sound absorption characteristics. It is, however, interesting to note that in all these studies, the method of coupling was dictated by the geometric complexities. For simpler geometries, particularly those that are periodic, the Rayleigh integral method was adequate in determining sound radiation characteristics, as was shown in references [11] [13] [19] [24]. For more complex geometries, such as those involving interconnected cavities [5] and intricate trusses [14] [20], coupled FE models were necessary in determining sound radiation characteristics. This, therefore, suggests that the method of coupling is not independent of the geometric parameters under investigation.

6.3. Panel Configuration Parameters

Aside from that, the total configuration of the panel itself, along with its boundary conditions, layering, and the presence of facing layers, greatly impacts its acoustic signature. The literature shows that a range of modeling assumptions as well as experimental configurations is employed, which is difficult to compare directly but is also enlightening.

Boundary conditions are a key aspect of a configurational parameter that plays a significant role in the acoustic response. Research covers a broad spectrum from the assumption of infinite panels to the assumption of simply supported edges. A considerable number of analytical and numerical studies, particularly those dealing with method development, employ simply supported edges [9]-[11] [13] [17] [18] and clamped edges [3] [12] [16] [24], assuming infinite rigid baffle boundary conditions [12] [13] [24]. This is done to facilitate a comparison with the classical solution. However, as Wang in [3] explicitly compared the boundary conditions (CCCC and SSSS), the boundary conditions significantly affect the stiffness of the panel and the mode shapes, which in turn affect the sound radiation and STL. In the case of experiments, the panels are necessarily placed in a test hole between reverberation chambers [7] and impedance tubes [2] [8] [14]. The disparity between the numerical boundary assumptions and the actual boundary assumptions is a critical drawback. For instance, the assumption of a rigid baffle does not consider the effect of sound radiation from the edges and the possibility of leakage.

The configuration of the panel in multiple layers is another important parameter. While the traditional sandwich concept consists of only three layers, there have been some investigations into more complex configurations. Franco *et al.* in reference [19] have investigated a top and bottom composite sheet, which represents the most basic configuration. Atalla, in reference [17], has developed an extensive modeling framework for complex multilayered configurations, including those with noise control materials, showing that each additional layer has an impact on the transfer matrix and hence on the transmission loss. Recent research on gradient and multi-layer woven structures in reference [7] [8] takes this concept even further, showing that by modifying the properties in each layer, it is possible to create multifunctional materials that can meet both structural and acoustic requirements. The research on wave propagation in profile strips in reference [21] by Kohrs & Petersson suggests that even the periodicity of the core itself can be considered an important configurational parameter, where any variation in periodicity can be an important tool in influencing vibro-acoustic behavior, an aspect that is also related to phononic crystals and metamaterials, as described in reference [23].

Figure 3. summarizes the quantitative data from 25 studies: distribution in terms of (a) the method for the coupled problem (not addressed, one-way, two-way FSI); (b) the type of boundary condition (not specified, simply supported, clamped); (c) the core geometric parameter (not specified, truss/lattice, honeycomb, corrugated/woven); and (d) the validation method (not addressed, numerical only, experiments). The bars in the figure show the number of studies for a specific category. The figure offers a general view of the overall trends in the literature regarding vibro-acoustic coupling in sandwich panels.

7. Key Design Parameters Affecting Sound Bridging

The sound bridging in sandwich construction occurs due to the stiff connections between the two wythes, enabling sound vibration. This happens at the expense of the insulation core. It has been observed that the parameters associated with sound bridging vary from material properties to geometrical optimization. This section aims to present an overview of the important parameters that affect sound bridging in sandwich construction, including connector properties, layout, damping, and recent design recommendations.

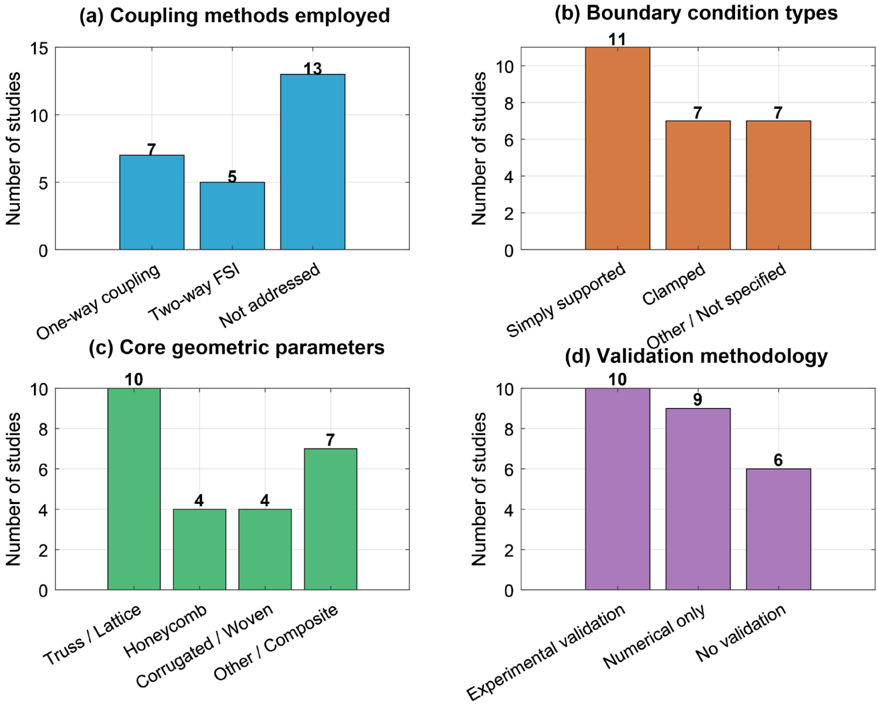

Figure 3. Quantitative summary of the 25 reviewed studies.

Figure 4 shows the key design parameters on sound bridging in the sandwich panel: (a) effect of the connector's elastic modulus on the resonance frequency of the double-wall resonance (lower elastic modulus results in a lower resonance frequency); (b) effect of the connector inclination angle on the sound transmission loss (peak improvement is found for an angle close to 45˚); (c) effect of the structural damping on the smoothing of the resonance dip in the transmission loss curve; (d) comparison of the STL performance of different core topologies with the Kagome core (adapted from Moosavimehr & Phani [20]).

7.1. Low-Stiffness and FRP Connectors

The axial stiffness of these connectors is arguably the fundamental parameter that is critical to sound bridging, as stiffer connectors are more efficient in transferring vibrational waves between the facings. Steel-based connectors are known to cause severe acoustic short circuits owing to their high modulus of elasticity. On the contrary, Fiber-Reinforced Polymer (FRP) connectors are seen to offer considerable advantages over steel-based connectors owing to their lower stiffness. Silva and Lameiras [5] found that the longitudinal modulus for GFRP-based connectors is 12.56 GPa. This is much lower than that of steel, which is 210 GPa. de Sousa *et al.* [6] found that this modulus varied from 10.4 GPa to 58.4 GPa for various fiber architectures. This allows for the optimization of stiffness for thermal as well as acoustic purposes, as FRPs are known to be poor thermal conductors, hence minimizing thermal bridging while possibly enhancing acoustic bridging. However, Sah *et al.* [1] found in their exhaustive review that the acoustic behavior of FRP-based connectors is seldom quantified.

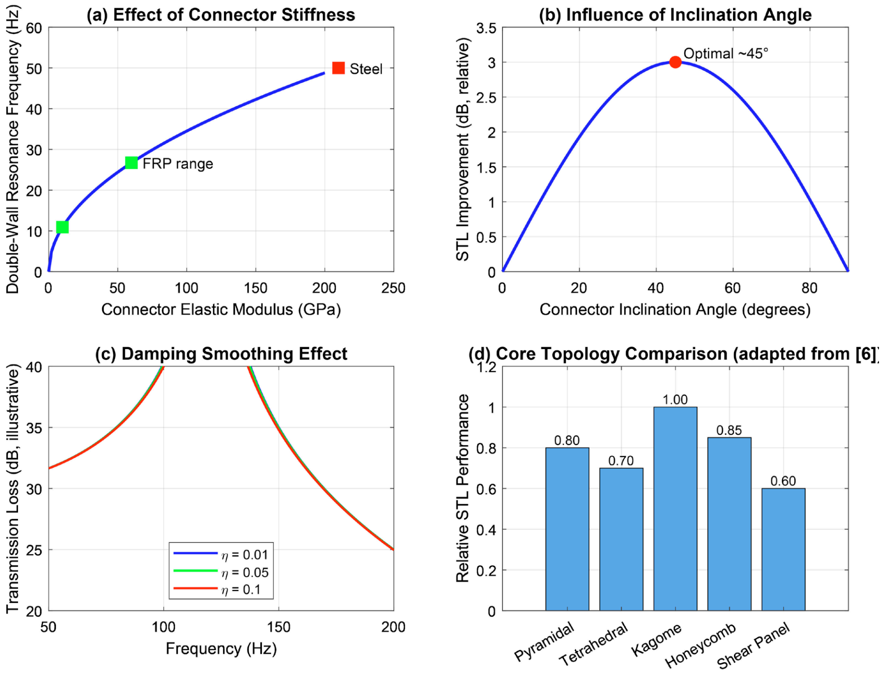

Figure 4. Key design parameters affecting sound bridging in sandwich panels.

The mass law creates a framework through which the aforementioned aspects may be understood. As emphasized by Atalla [17], the stiffness of the connector (k) is a critical parameter in the case of a double-wall system. A stiffer connector results in a larger degradation of transmission loss due to the elevation of the resonance frequency of the double wall into the problem zone. However, the relationship between the connector stiffness and the acoustic performance is not as clear-cut. For instance, the connector must not only provide adequate decoupling from the acoustic performance but must also maintain structural integrity. Haffke *et al.* [4] observed that although the GFRP connector retains structural integrity during fire exposure, the acoustic performance of the connector when subjected to extreme loading conditions remains uninvestigated. It is apparent that the entire field of FRPs is yet to be fully explored in terms of the acoustic performance of the connector over the entire range of achievable moduli. Such a gap represents a critical area of research. It is proposed that future studies must be devoted to the characterization of sound bridging for moduli below 10 GPa, as this represents the area with the highest potential for optimization.

7.2. Optimized Connector Layouts

Apart from the material properties of the connectors, the geometry of the connectors' arrangement and their orientation also provides scope for controlling the sound bridging. The effect of the inclination of the connectors has been investigated. Yang *et al.* [10] showed that an increase in the inclination of the connectors improves the sound insulation due to an added stiffness effect. Fu *et al.* [9] varied the inclination angle of the pyramidal cores between 30 and 60 degrees. They showed that the inclination of the connectors changes the stiffness of the core and, therefore, must be affecting the sound bridging. A more advanced method of controlling the STL curve is the use of hybrid cores. Li and Yang varied the angle of the cells within the core. This method was employed to tune the STL curve by shifting the dips of the curve. They showed that the optimization of the angle distribution improves the STL performance compared to the uniform angle case.

Moreover, it has been shown by Moosavimehr and Phani [20] that topology itself determines wave propagation properties by comparing tetrahedral, pyramidal, double pyramidal, Kagome, hexagonal honeycomb, and shear panel cores. The results indicate that topology has a major effect on wave propagation properties, coincidence frequencies, and ultimately STL; thus, Kagome has a good compromise between high stiffness and high STL. Kabiripoor *et al.* [15] also found that core height and aspect ratio are important parameters affecting STL; conversely, the effect of the interior angle is negligible. However, it is obvious that not all parameters are equally important. The effect of periodicity is a bit more complicated; Kohrs and Petersson [21] have shown that periodic length determines fundamental wavenumber as well as spacing of space harmonics; moreover, purposeful periodicity perturbations can cause a smearing effect of wavenumber spectra and thus disturb sound bridging paths. The problem is that it is difficult to apply this knowledge to practical design; thus, Gazzola *et al.* [14] proposed optimization of periodic cores for specific acoustic phenomena while taking into account manufacturing constraints. The effect of different geometric parameters interacting with each other should be studied more thoroughly; thus, hybrid structures should be analyzed more systematically.

7.3. Damping Layers and Interface Treatments

While the stiffness of a connector and its layout influence the path that vibrational waves take, damping treatments affect the efficiency with which vibrational waves are dissipated once they are introduced into those paths. In a more systematic approach, Franco *et al.* [19] showed that as structural damping is increased from 0.01 to 0.1, it smooths out the transmission loss curve by minimizing deep troughs that are associated with resonant sound bridging. The importance of this is that sound bridging is most likely to be a problem at particular resonance frequencies; by incorporating a damping effect, it is possible to smooth out resonances to ensure that acoustic properties are more uniform. Wang [3] has shown that it is possible to enhance a damped effect by incorporating absorption materials into the core of a connector. These materials can include PUF foams or wood-based materials; wood-based materials have equivalent insulation properties to synthetic foams while also having sustainability advantages. Air flow resistivity was found to be a significant factor.

The source and method of damping have significant implications in practical applications. Wang, Dai, and Hu in [24] determined that filler materials have significant effects on resonance peaks and STL. Triangle-shaped cores provided optimal results when combined with wood-based fillers. This study suggests that the geometry between core materials and fillers has significant implications for damping. Active methods provide further opportunities, as demonstrated in Guo, Jiang, and Xu in [12], in which shunt circuits can be utilized to provide frequency-dependent complex impedances, thereby achieving significant additional damping up to 0.0407. This method can control individual vibration modes. This method specifically targets those modes that are most likely involved in sound bridging, unlike general damping. Another significant source of damping is between the connector and the facing, where Fu *et al.* in [18] suggest that shear foundation stiffness could be more significant than translation stiffness in sound bridging. Atalla [17] stresses that damping treatments should be considered as an integrated package that takes into account the combined effect of facings, connectors, and core materials since the poroelastic properties of the fill material control the combined effect of the airborne and structural paths. Future research should be conducted on interface treatments and their durability. Additionally, the optimal placement of damping material within the core and the connectors should be studied.

7.4. Design Recommendations from Standards and Research

To synthesize the literature in a manner that provides useful design recommendations, it is necessary to understand both what is known and what is not known. With regard to the material science of the problem, FRP connectors have clear advantages over steel in reducing sound bridging; however, the range of possible moduli (10 - 60 GPa) means that the choice of material must be considered carefully, with softer moduli likely more beneficial in acoustic terms but stiffer options potentially necessary in terms of structural performance. Hybrid solutions in which the stiffness of the material is varied along the length of the connector or in a hybrid fiber arrangement have yet to be explored in acoustic terms but represent an interesting avenue of future work. Geometrically, inclined connectors and truss structures have been shown to have benefits in acoustic terms; however, there is no clear agreement in the literature regarding the optimal angle of the connectors, with angles of 30˚ - 60˚ having been explored. Similarly, the concept of a hybrid core in which angles vary across the panel represents a promising avenue of future work.

The biggest gap in existing design standards is that no requirements are given for acoustic behavior within existing standards for connectors or building codes. Sah *et al.* [1] already stated that the material used for cores is primarily considered to be important for thermal and fire behavior within existing standards, whereas acoustic behavior is seen as secondary. This is now changing as multifunctional design is becoming more accepted [6]-[8], but no requirements are given within major international standards regarding acoustic behavior for connectors. Future research should be aimed at experimental determination of sound bridging behavior for various types of connectors, development of models to describe sound bridging behavior considering various effects such as stiffness, layout, and damping, and integration of research outcomes into design standards. For now, however, designers should apply fundamental principles such as minimizing stiffness, optimizing layout for certain ranges of interest, and providing adequate damping. Verification of acoustic behavior through testing is then required. The future is seen in multifunctional design, where acoustic behavior must be provided in combination with structural behavior, thermal behavior, fire behavior, and durability behavior.

8. Limitations of Existing Studies and Research Gaps

A critical analysis of the literature reveals that there are some general shortcomings that limit the advancement and use of advanced sandwich panels. The most important and general limitation is the absence of comprehensive design tools and regulatory validation. As emphasized by Haffke *et al.* [4] and Sah *et al.* [1], the normative regulations lack comprehensive provisions, especially regarding the fire properties and the structural behavior of the material. The lack of standardized design tools and guidelines forces the designers to use proprietary data and tools. This situation limits the use of material- and cost-efficient composite materials. Furthermore, research is often very context-dependent, and results can only be generalized within very limited boundaries. For example, research on fire resistance might be dependent on certain types of insulation materials, like mineral wool, applied in the research [4]. Moreover, mechanical characterization might be dependent on certain types of connector geometries, like those in lower-grade materials, while there is no information on how they would perform in alternative materials, even if they are of superior quality and sustainability, as highlighted in [3] [24]. This disconnection in information, combined with an evident lack of research on critical issues like curved panel behavior, hybrid steel-FRP connector behavior under fire and long-term loading, and dynamic behavior under blast and impact loading, represents significant obstacles.

Moreover, the applicability of acoustic results obtained for the lightweight sandwich structures is fundamentally hindered by the physical properties of concrete wythes. The relatively large mass and thickness of concrete wythes in comparison to the light face sheets used in lightweight structures lead to changes in the acoustic penalty and, most importantly, a shift in critical resonance frequencies, such as the MSM dip. Furthermore, in contrast to lightweight metallic materials with high modulus-to-density ratios, concrete materials have material damping which acts to reduce resonance troughs in the STL curves. Another feature of the acoustic behavior of the insulation type interacting with concrete wythes lies in the poroelastic nature of core filling materials and the dominance of their contribution to vibro-acoustic phenomena at certain frequencies. Thus, interaction between dense wythes and insulation leads to different vibrational behavior compared to the interaction of lightweight counterparts. In this regard, although the qualitative conclusions regarding acoustic performance still hold, quantitative conclusions about the acoustics depending on the frequencies should be adjusted accordingly.

In addition to the knowledge gaps, the literature is marred by substantial methodological limitations that affect the reliability of the results. A large majority of the works, especially in the vibro-acoustic field, are based on numerical simulations with little or no experimental verification [9]-[12] [19] [20] [24]. Although the models are useful, the effectiveness of optimized designs for truss lattice cores [20], metamaterials [12] [14], and wood-filled panels [24] is questionable and requires experimental verification. This situation is further exacerbated by the fact that most of these simulations use basic representations of the structure and the field, such as the use of 2D plane strain representations of the structure [10] [11] [15], the use of homogenized cores that ignore the effects of the material properties on the core [9] [18], and the use of normal incidence sound waves rather than the more representative diffuse field [11] [14]. Moreover, most of the idealized numerical and analytical simulations ignore important factors that play significant roles in the performance of the structure and the material, such as manufacturing defects [16] [20], statistical variations in material properties [24], the precise tuning of the system for active control [12], and the significant effects of uncontrollable factors such as moisture content on the performance of the material in fires [4]. To overcome these gaps, a concerted future research agenda is needed to: 1) advance strong and experimentally verified design rules that consider full-scale performance and multiple load cases (e.g., fire, blast, thermal) [1] [2] [18]; 2) advance beyond simplified approaches and move toward high-fidelity simulations that are experimentally verified against representative prototype test data [9] [10] [14] [20]; 3) study the acoustic performance of sandwich panels in the low-frequency range, a critical gap in the field that is widely acknowledged [3] [15]; and 4) exploit new and environmentally friendly materials and manufacturing techniques, such as 4D printing and AI-assisted design, as well as the development of strong damage detection techniques for health monitoring.

9. Conclusions

As may be seen in this review, the sound bridge effects of mechanical connectors in concrete sandwich panels are fundamentally a function of their stiffness, geometric configuration, properties of their constitutive materials, and frequency dependence of vibro-acoustic coupling. Various studies have confirmed that connectors with high elastic modulus, particularly those made of steel trusses, can establish efficient paths for structure-borne sound transmission, bypassing the insulating core, and causing a significant degradation of sound transmission loss, especially at critical resonance frequencies such as those for mass-spring-mass dip and panel mode frequencies. Other studies have confirmed that numerical modeling techniques, such as finite element method (FEM), transfer matrix method (TMM), and coupled fluid-structure interaction models, are potentially powerful tools for predicting acoustic performance, although they are still limited by simplifications, such as homogenization of core properties, boundary conditions, and normal incidence waves, which ignore actual effects of manufacturing tolerances, damping, and diffuse fields.

To create optimized systems of connection that take into account composite action and acoustic insulation properties, experimental validation of existing numerical predictions is an urgent need, together with the development of standard testing protocols that consider real boundary conditions, diffuse sound fields, and full-scale panels. In addition, the integration of detailed experimental data into existing high-fidelity numerical simulations, including connectors of FRP type over their possible range of modulus, will create a simulation environment that is closer to reality, allowing for an accurate prediction of vibro-acoustic properties of sandwich panels under service conditions. This is seen as a promising step toward creating predictive models that could be used for the expanded use of these systems in building envelopes, transport applications, etc.

Apart from the acoustic properties, the concept of multifunctional concrete sandwich panels holds a number of connotations with respect to the sustainability of buildings, the comfort of the users, as well as the robustness of the structures against noise pollution. By addressing the research gaps identified, the rational design of the connector systems, which can meet the requirements from the structural, thermal, and acoustic points of view, can be achieved, thereby unlocking the potential of the sandwich panel concept in modern engineering structures.

Conflicts of Interest

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

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