

Article

Analytical Modeling and Acoustic Optimization of Sound Insulation Performance of Finite-Sized Insulated Concrete Sandwich Panels

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Abstract

Insulated concrete sandwich panels (ICSPs) are widely utilized in modern building structures due to their excellent combination of energy efficiency and structural load-bearing capacity. However, compared to their mechanical and thermal properties, the sound insulation characteristics of ICSPs remain insufficiently studied, presenting a scientific deficit. In practical engineering, insufficient consideration of these acoustic properties—particularly the “acoustic bridging” induced by connectors—often leads to unpredictable noise transmission, making it difficult for building envelopes to meet stringent modern acoustic codes. To further investigate their acoustic characteristics, this paper extends existing theories on infinite periodic ICSPs to study the airborne sound insulation performance of finite-sized ICSPs. First, analytical models for ICSPs under simply supported on all edges (SS) and clamped on all edges (CC) boundary conditions are derived, wherein the connectors are equivalently modeled as elastic media and discrete elastic springs, respectively. Subsequently, the accuracy and applicability of the analytical models are verified through finite element (FE) models and an airborne sound insulation experiment. Finally, based on the analytical models, a parametric study is conducted to explore the effects of the stiffness of connectors, boundary conditions, and the thickness of the core layer on the sound insulation performance of the ICSPs. The results indicate that connector stiffness has a non-monotonic influence on the sound insulation performance of ICSPs. As the connector stiffness increases, the R_w first decreases and then increases, and the sound insulation performance gradually stabilizes when the connector stiffness becomes sufficiently high. Boundary conditions have a significant effect on the acoustic response. For the reference ICSPs, changing the boundary condition from SS to CC increases the R_w from 49 dB to 62 dB, corresponding to an increment of 13 dB and an approximately 95.0% reduction in the equivalent sound transmission coefficient. When the total panel thickness is kept constant, reducing the core layer thickness from 80 mm to 40 mm increases the R_w from 49 dB to 55 dB under SS boundary conditions and from 62 dB to 66 dB under CC boundary conditions, corresponding to increments of 6 dB and 4 dB, respectively. These improvements are equivalent to reductions of approximately 74.9% and 60.2% in the sound transmission coefficient, though this must be weighed against the inevitable reduction in thermal insulation capacity. Although the sound insulation performance of ICSPs is inferior to that of solid concrete panels (SCPs) of equivalent thickness, with reasonable parameter optimization, their sound insulation indices can significantly exceed the latest requirements of current building codes. By fully

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accounting for boundary effects in practical engineering, this study provides an analytical basis for the acoustic performance prediction and engineering-oriented optimization of finite-sized ICSPs.

Keywords: finite-sized; insulated concrete sandwich panel; analytical model; sound transmission loss; finite element analysis; experiment

1. Introduction

As urbanization accelerates and transportation networks become increasingly dense, noise pollution has emerged as a significant factor affecting the quality of the living environment, thereby imposing stricter demands on the acoustic insulation performance of modern building envelopes. Simultaneously, driven by the rapid advancement of building industrialization, Insulated Concrete Sandwich Panels (ICSPs) have been extensively adopted in prefabricated construction. This is due to their ability to integrate load-bearing capacity, thermal insulation, and highly efficient factory prefabrication into a single system. Generally, an ICSP consists of internal and external concrete wythes, a core layer of lightweight thermal insulation (such as EPS, XPS, or polyurethane foam), and shear connectors that penetrate the insulation to structurally link the two concrete layers [1]. This sandwich configuration not only endows the ICSP with exceptional thermal and mechanical performance, but also theoretically provides them with immense potential to bypass the limitations of the “mass law” associated with single-layer materials, thereby achieving highly efficient acoustic insulation.

To date, research on the vibro-acoustic characteristics of sandwich structures has yielded fruitful results across various interdisciplinary fields. The focus of these studies has undergone an evolutionary transition from lightweight, high-strength materials toward heavy-duty building components. Early theoretical explorations often originated from fundamental double-leaf panels, establishing cavity resonance and sound transmission prediction theories based on “mass-air/spring-mass” models [2,3]. Subsequently, in the aerospace, marine, and transportation sectors, lightweight metal and composite sandwich panels featuring continuous cores (such as those with aluminum face sheets [4–6], honeycomb cores [7,8], or corrugated cores [9,10]) became the focus of academic inquiry. These investigations elucidated the critical coincidence effects and broadband sound transmission laws inherent in such structures. To further meet the increasingly stringent demands for mechanical load-bearing capacity as well as vibration and noise reduction, stiffened panels (such as stiffened single panels [11,12], stiffened double-leaf panels [13,14], orthogonally stiffened panels [15], and stiffened multi-layer panels [16]) have progressively become a research hotspot in the field of vibro-acoustic coupling. The incorporation of stiffeners causes the structure to exhibit differentiated vibration characteristics across various frequency bands: in the low-frequency range, acoustic waves easily excite the global modal resonance of the structure; whereas in the mid-to-high frequency ranges, the stiffeners divide the panel into multiple sub-regions, readily exciting local structural vibrations. The addition of stiffeners has broadened the horizons for structural vibration and noise reduction; however, the accompanying “acoustic bridging” effect has concurrently emerged as a major challenge, as the high-stiffness connecting components create strong structure-borne sound transmission paths within the flexible interlayer [17]. This effect reveals the degradation mechanism of the structure’s high-frequency sound insulation performance, concurrently laying the groundwork for complex structural-acoustic analyses. In recent years, in the pursuit of superior vibration mitigation and sound insulation, a proliferation of optimized designs has emerged. These include functionally

graded panels [18,19], acoustic black hole (ABH) panels [20,21], profiled connectors [22,23], and core layers featuring negative Poisson's ratios and negative stiffness [18,24,25]. Such advancements have provided novel approaches for sound insulation and noise reduction in panel structures.

In the field of civil engineering, the noise reduction analysis of building envelopes originated with basic single-material walls. Litvin et al. [26] evaluated the sound insulation ratings of cast-in-place concrete walls and lightweight concrete block walls under various surface treatments (including gypsum board, rock wool, studs, etc.), thereby providing a crucial reference for analyzing the acoustic performance of building envelopes. Guided by the principles of lightweighting and waste utilization, the incorporation of materials, such as lightweight aggregates [27], coal bottom ash [28], Miscanthus fibers [29], hemp stalks, and foam [30], into concrete to fabricate modified or lightweight concrete walls has offered diversified solutions for the optimization of architectural acoustic design. As building energy efficiency standards have continuously escalated, sandwich structures have been integrated into civil envelope systems, fostering the development of lightweight architectural sandwich components, such as metal-faced glass wool sandwich wall panels [31] and lightweight double-leaf gypsum sandwich wall panels [32–34]. Building upon this foundation, Min et al. [35] further investigated the impact of varying stud types and materials on the sound insulation performance of lightweight sandwich wall panels. Functioning as non-load-bearing infill walls, these lightweight sandwich panels have demonstrated highly promising application prospects in successfully balancing cost control with thermal insulation performance.

Concurrently with the advancement of prefabricated construction, when the aforementioned sandwich technologies are applied to ICSPs, which integrate load-bearing capacity and thermal insulation, their physical properties and acoustic boundaries undergo a fundamental transformation. In stark contrast to lightweight sandwich wall panels or lightweight stiffened structures, ICSPs feature massive wythes characterized by exceptionally high surface mass density and flexural stiffness. Furthermore, their internal and external wythes achieve composite structural action via shear connectors that penetrate the thick thermal insulation layer. To date, researchers worldwide have made notable progress in the study of ICSPs; however, the majority of existing literature remains predominantly focused on structural mechanical properties, such as flexural behavior under out-of-plane loading [1,36,37], mechanical performance under vertical axial and eccentric compression [38,39]), recent investigations have further extended to thermal resistance [40] and the influence of connectors on thermal performance [41–43]. Meanwhile, considerable attention has been paid to the mechanical behavior of different connector systems, including FRP [44], BFRP [45], stainless-steel plate [46], CFRP grid [47], stainless steel-GFRP [48], S-type [49], etc. Recent studies have also highlighted the increasing integration of analytical, numerical, experimental, and data-driven approaches in the characterization and performance assessment of composite panel systems [50]. Such developments provide useful tools for understanding the multi-physics behaviour of layered structural components and for improving the reliability of performance prediction and design optimization [51]. Although these studies are not specifically focused on airborne sound insulation, they offer a broader methodological context for the modelling and evaluation of complex panel systems.

Conversely, research concerning the sound insulation performance of ICSP remains a significant gap in the literature. This scientific deficit has critical practical consequences: ignoring the acoustic characteristics during the design phase, especially the structure-borne noise transmitted through shear connectors (acoustic bridging), often results in prefabricated envelopes failing to comply with modern residential noise regulations. In light of the limitations of lightweight sandwich wall panels regarding structural load-bearing

capacity, ICSP holds an indispensable position within modern prefabricated structural frameworks. Therefore, this paper investigates the sound insulation performance of ICSP with finite boundary conditions. First, an analytical prediction model for ICSP is established based on vibro-acoustic coupling theory, and the accuracy of this theoretical model is validated through Finite Element (FE) simulations and experimental results. Subsequently, the effects of various boundary conditions, such as simply supported on all edges (SS) and clamped on all edges (CC) boundary conditions, along with key structural parameters on the acoustic insulation performance of ICSP are analyzed. Finally, the applicability of the proposed theory to practical engineering applications is demonstrated.

2. Materials and Methods

2.1. Methodological Framework and Material/Data Basis

The methodological framework of this study consists of six main steps. First, the geometric configuration and material composition of a finite-sized insulated concrete sandwich panel (ICSP) are defined. Second, an analytical model is established based on vibro-acoustic coupling theory, in which the concrete wythes, insulation material, and connectors are modeled separately according to their mechanical roles. Third, the governing equations are solved using the Galerkin method under two representative boundary conditions, namely simply supported on all edges (SS) and clamped on all edges (CC). Fourth, a finite element (FE) model is developed to verify the accuracy of the analytical model. Fifth, an airborne sound insulation experiment is used for further validation. Finally, parametric analyses are conducted to evaluate the effects of connector stiffness, boundary condition, and core layer thickness on the sound insulation performance of ICSPs.

The selected materials and modeling assumptions are determined according to the standard engineering practices and building code [52] of ICSPs. The concrete wythes are modeled using Kirchhoff thin-plate theory because the panel thickness is much smaller than the in-plane dimensions, and the airborne sound insulation response is mainly governed by transverse bending vibration. The insulation material is treated as a homogeneous elastic medium to describe the elastic interaction between the two concrete wythes. This assumption is consistent with the role of common thermal insulation materials, such as EPS, XPS, and polyurethane foam, which mainly provide lightweight thermal insulation and transverse elastic coupling in ICSPs. For the connectors, two modeling strategies are adopted. Plate-type or continuous connectors are modeled as elastic media, whereas column-type or stud-type connectors are represented by a mass-spring model. This treatment allows different connector forms used in practical ICSPs to be included in the analytical framework.

The SS and CC boundary conditions are selected to represent two typical constraint states of finite-sized panels in engineering applications. The SS boundary condition reflects a relatively weak edge restraint, while the CC boundary condition represents a stronger constraint with restricted displacement and rotation. The geometric parameters, material properties, and experimental data used in the validation are selected from the tested ICSP specimen and commonly used engineering materials. The evaluation of airborne sound insulation follows the weighted sound reduction index specified in the relevant acoustic standard.

2.2. ICSPs System and Material Assumptions

Figure 1a illustrates the structural schematic of the ICSP, while Figure 1b presents its cross-sectional view in the x - z plane. The system has a length of a along the x -direction, a width of b along the y -direction, and an overall thickness of H . The connectors are arrayed along the x -axis, with their length along the y -axis. The thicknesses of the external panel,

internal panel, and connectors are denoted as h_1 , h_2 , and t_c , respectively; additionally, the clear spacing between the two panels is d , and the spacing between adjacent connectors is L .

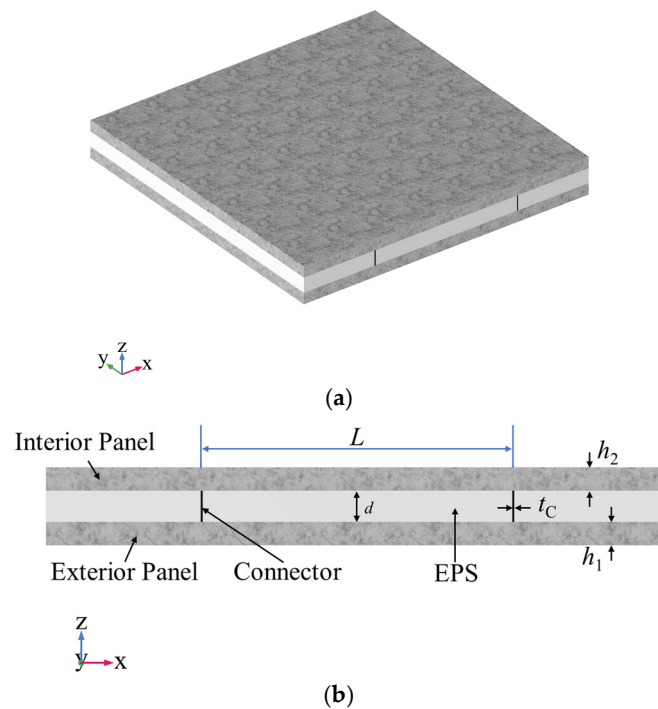


Figure 1. ICSP wall with connectors. (a) Schematic drawing of ICSP; (b) x - z section of an ICSP.

2.3. Theoretical Model of the System

The main symbols used in the analytical model are summarized in Appendix A to improve the readability of the following derivation. Based on the formula derivation process, a brief flowchart is summarized, as shown in Figure 2.

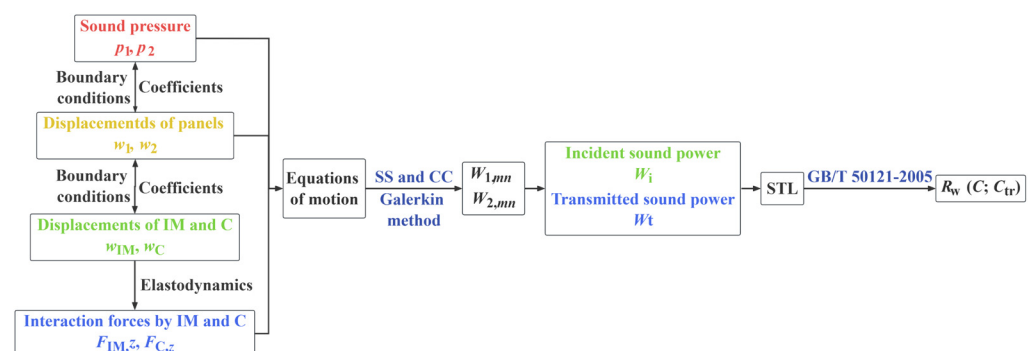


Figure 2. Formula derivation flowchart.

Considering Kirchhoff thin panels, the motions of the two concrete wythes are described by thin-plate theory; meanwhile, the insulation material (IM) filling the core is treated as a homogeneous continuous medium and is modeled using the theory of elastodynamics. For homogeneous and continuous connectors, taking plate-type connectors as a primary example, the introduction of boundary conditions dictates that the vibration modes of the finite structure differ from those of an infinite structure. Consequently, the simplified “mass-spring” model typically applied to infinite structures is rendered inapplicable. Therefore, in order to accurately describe the motion of the connectors, the interaction forces exerted by the connectors on both wythes are similarly modeled employing elastodynamics theory. Thus, under the excitation of plane harmonic acoustic waves, the

global governing equations of motion for a finite ICSP equipped with plate-type connectors are given by:

$$\begin{aligned} D_1 \left(\frac{\partial^4 w_1}{\partial x^4} + 2 \frac{\partial^4 w_1}{\partial x^2 \partial y^2} + \frac{\partial^4 w_1}{\partial y^4} \right) + \rho_1 h_1 \frac{\partial^2 w_1}{\partial t^2} &= p_1 + F_{\text{IM},z1} \\ &+ \sum_j F_{\text{C},z1} H \left[x - \left(x_j - \frac{t_c}{2} \right), x - \left(x_j + \frac{t_c}{2} \right) \right], \\ D_2 \left(\frac{\partial^4 w_2}{\partial x^4} + 2 \frac{\partial^4 w_2}{\partial x^2 \partial y^2} + \frac{\partial^4 w_2}{\partial y^4} \right) + \rho_2 h_2 \frac{\partial^2 w_2}{\partial t^2} &= -p_2 - F_{\text{IM},z2} \\ &- \sum_j F_{\text{C},z2} H \left[x - \left(x_j - \frac{t_c}{2} \right), x - \left(x_j + \frac{t_c}{2} \right) \right], \end{aligned} \quad (1)$$

where w_1 and w_2 , ρ_1 and ρ_2 , h_1 and h_2 represent displacements, densities and thicknesses of panels 1 and 2, respectively; p_1 , p_2 , $F_{\text{IM},z1}$, $F_{\text{IM},z2}$, $F_{\text{C},z1}$, $F_{\text{C},z2}$ denote the incident side sound pressure, transmitted sound pressure, interaction forces exerted by the IM on the two panels, and interaction forces exerted by the connectors on the two panels, respectively; and D_i stands for the bending stiffness of the panel:

$$D_\ell = \frac{E_\ell h_\ell^3 (1 + i\eta_\ell)}{12(1 - \nu_\ell^2)}, \ell = 1, 2, \quad (2)$$

where E_ℓ , ν_ℓ , and η are Young's modulus, Poisson's ratio, and loss factor of the panel, respectively; and i is the imaginary number with $i^2 = -1$.

$H(x)$ is the Heaviside step function, which is utilized to spatially locate the surface forces applied by the connectors onto the panels. The definition of the $H(x)$ function is given in Equation (3), where x_1 represents the coordinate of the connector's center along the x -axis.

$$H(x) = \begin{cases} 1, & x_j - \frac{t_c}{2} \leq x \leq x_j + \frac{t_c}{2} \\ 0, & x < x_j - \frac{t_c}{2} \text{ or } x > x_j + \frac{t_c}{2} \end{cases}. \quad (3)$$

Unlike homogeneous and continuous plate-type connectors, if column-type or stud-type connectors are employed, the "mass-spring" model is utilized. Under these circumstances, the global governing equations of motion are given by

$$\begin{aligned} D_1 \left(\frac{\partial^4 w_1}{\partial x^4} + 2 \frac{\partial^4 w_1}{\partial x^2 \partial y^2} + \frac{\partial^4 w_1}{\partial y^4} \right) + \rho_1 h_1 \frac{\partial^2 w_1}{\partial t^2} + \sum_j \frac{m_c}{2} \frac{\partial^2 w_1}{\partial t^2} \delta(x - x_j) \delta(y - y_j) \\ = p_1 + F_{\text{IM},z1} - \sum_j K_{\text{C},t} (w_1 - w_2) \delta(x - x_j) \delta(y - y_j), \\ D_2 \left(\frac{\partial^4 w_2}{\partial x^4} + 2 \frac{\partial^4 w_2}{\partial x^2 \partial y^2} + \frac{\partial^4 w_2}{\partial y^4} \right) + \rho_2 h_2 \frac{\partial^2 w_2}{\partial t^2} + \sum_j \frac{m_c}{2} \frac{\partial^2 w_2}{\partial t^2} \delta(x - x_j) \delta(y - y_j) \\ = -p_2 - F_{\text{IM},z2} + \sum_j K_{\text{C},t} (w_1 - w_2) \delta(x - x_j) \delta(y - y_j), \end{aligned} \quad (4)$$

where m_c denotes half mass of the connector, and the total mass of the connector is $2m_c$, $K_{\text{C},t}$ is the translational stiffness of the spring, with the expression as follows:

$$K_{\text{C},t} = \frac{E_c A}{d}, \quad (5)$$

where E_c and A are Young's modulus and cross-sectional area of the connectors.

2.4. Solution Procedure of the Theoretical Model

2.4.1. Force and Equation

For brevity in mathematical expressions, the fully simply supported (SS) and fully clamped (CC) boundary conditions are denoted by the subscripts “SS” and “CC”, respectively. Considering the two boundary conditions of SS and CC on all four sides, the transverse displacements of the panels are given by

$$\left\{ \begin{array}{l} \left\{ \begin{array}{l} w_1 = \sum_m \sum_n W_{1,mn} \phi_{SS,mn} e^{i\omega t}, \\ w_2 = \sum_m \sum_n W_{2,mn} \phi_{SS,mn} e^{i\omega t}, \end{array} \right. \quad \text{for SS} \\ \left\{ \begin{array}{l} w_1 = \sum_m \sum_n W_{1,mn} \phi_{CC,mn} e^{i\omega t}, \\ w_2 = \sum_m \sum_n W_{2,mn} \phi_{CC,mn} e^{i\omega t}, \end{array} \right. \quad \text{for CC} \end{array} \right. , \quad (6)$$

where $\phi_{SS,mn}$ and $\phi_{CC,mn}$ are the modal functions for SS and CC, respectively, taking the following forms:

$$\left\{ \begin{array}{l} \phi_{SS,mn} = \sin\left(\frac{m\pi x}{a}\right) \sin\left(\frac{n\pi y}{b}\right), \\ \phi_{CC,mn} = \left[1 - \cos\left(\frac{2m\pi x}{a}\right)\right] \left[1 - \cos\left(\frac{2n\pi y}{b}\right)\right]. \end{array} \right. \quad (7)$$

Letting $k_m = m\pi/a$, $k_n = n\pi/b$, $\alpha_m = 2m\pi/a$, and $\beta_n = 2n\pi/b$, in the incident field, the plane acoustic wave incident upon the surface of the ICSP at an elevation angle θ and an azimuthal angle φ is expressed as

$$p_1 = p_{\text{amp}} e^{i\omega t - ik_x x - ik_y y - ik_z z} + a_1 e^{i\omega t - ik_x x - ik_y y + ik_z z}, \quad (8)$$

where the first and second terms represent the incident and reflected sound pressures, respectively, while p_{amp} and a_1 represent their corresponding amplitudes. Similarly, the expression for the transmitted sound pressure can be written as

$$p_2 = a_2 e^{i\omega t - ik_x x - ik_y y - ik_z z}, \quad (9)$$

where a_2 represents the amplitude of sound pressure, and k_x , k_y and k_z are the wave numbers in the x -, y -, and z -directions, respectively, with the expression as follows:

$$k_x = k_0 \sin \theta \cos \varphi, \quad k_y = k_0 \sin \theta \sin \varphi, \quad k_z = k_0 \cos \theta, \quad (10)$$

where $k_0 = \omega/c_0$ is the acoustic wave number in air and c_0 is the acoustic speed in air.

Elastodynamics is employed to determine the interaction forces of both the IM and the connectors. Regarding the IM, the formulation originates from displacement potential functions:

$$\Phi_{\text{IM}} = a_3 e^{i\omega t - ik_x x - ik_y y - ik_1 z} + a_4 e^{i\omega t - ik_x x - ik_y y + ik_1 z}, \quad (11)$$

where the first and second terms represent the forward-traveling wave and the backward-traveling wave, respectively, where a_3 and a_4 denote the amplitudes of these two waves; and k_1 is the wave number in the z -direction of IM, with the expression as follows:

$$k_1 = \sqrt{k_{\text{IM},l}^2 - k_x^2 - k_y^2}, \quad (12)$$

where $k_{\text{IM},l} = \omega/c_{\text{IM},l}$ is the longitudinal wave number and $c_{\text{IM},l}$ is the longitudinal wave speed of the IM. Based on the relationship between the potential functions and displacements, the displacement expression for the core layer can be derived as

$$w_{\text{IM}} = \frac{\partial \Phi_{\text{IM}}}{\partial z} = ik_1 \left(-a_3 e^{i\omega t - ik_x x - ik_y y - ik_1 z} + a_4 e^{i\omega t - ik_x x - ik_y y + ik_1 z} \right). \quad (13)$$

For the connectors, the two cases of SS and CC on all four sides are considered. Firstly, for the SS condition, the displacement potential function is given by

$$\Phi_C = \sum_m \sum_n \left(a_{5,mn} e^{i\omega t - ik_{2,mn} z} + a_{6,mn} e^{i\omega t + ik_{2,mn} z} \right) \phi_{\text{SS},mn}, \quad (14)$$

where $k_{2,mn}$ is the wave number in the z -direction of connectors, with the expression as follows:

$$k_{2,mn} = \sqrt{k_{\text{C},l}^2 - k_m^2 - k_n^2}, \quad (15)$$

and the displacement expression for the connectors can then be derived as

$$w_C = \frac{\partial \Phi_C}{\partial z} = \sum_m \sum_n ik_{2,mn} \left(-a_{5,mn} e^{i\omega t - ik_{2,mn} z} + a_{6,mn} e^{i\omega t + ik_{2,mn} z} \right) \phi_{\text{SS},mn}. \quad (16)$$

Secondly, for CC conditions, the displacement potential function for the connectors satisfies the following wave equation:

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \right) \Phi_C + \frac{\omega^2}{c_{\text{C},l}^2} \Phi_C = 0. \quad (17)$$

The solution for the displacement potential function is given by

$$\Phi_C = \sum_m \sum_n \left[F_5(z) \psi_5 + F_6(z) \psi_6 + F_7(z) \psi_7 + F_8(z) \psi_8 \right] e^{i\omega t}, \quad (18)$$

where ψ_s ($s = 5, 6, 7, 8$) are obtained from the expansion of $\phi_{\text{CC},mn}$,

$$\psi_5 = 1, \psi_6 = -\cos(\alpha_m x), \psi_7 = -\cos(\beta_n y), \psi_8 = \cos(\alpha_m x) \cos(\beta_n y), \quad (19)$$

and by substituting Equation (19) into Equation (17), we obtain four distinct solutions, namely

$$F_5(z) = a_{5,mn}^+ e^{-ik_{z,5} z} + a_{5,mn}^- e^{ik_{z,5} z}, \quad (20)$$

$$F_6(z) = a_{6,mn}^+ e^{-ik_{z,6} z} + a_{6,mn}^- e^{ik_{z,6} z}, \quad (21)$$

$$F_7(z) = a_{7,mn}^+ e^{-ik_{z,7} z} + a_{7,mn}^- e^{ik_{z,7} z}, \quad (22)$$

$$F_8(z) = a_{8,mn}^+ e^{-ik_{z,8} z} + a_{8,mn}^- e^{ik_{z,8} z}, \quad (23)$$

where a_s^+ and a_s^- ($s = 5, 6, 7, 8$) denote the amplitudes of the forward-traveling and backward-traveling waves, respectively; $k_{z,s}$ are the longitudinal wave numbers of the connectors in z -direction, as follows:

$$\begin{aligned} k_{z,5} &= k_{\text{C},l}, \\ k_{z,6} &= \sqrt{k_{\text{C},l}^2 - \alpha_m^2}, \\ k_{z,7} &= \sqrt{k_{\text{C},l}^2 - \beta_n^2}, \\ k_{z,8} &= \sqrt{k_{\text{C},l}^2 - \alpha_m^2 - \beta_n^2}, \end{aligned} \quad (24)$$

where $k_{\text{C},l} = \omega/c_{\text{C},l}$ is the longitudinal wave number and $c_{\text{C},l}$ is the longitudinal wave speed of the connectors. Then, the simple expression for Φ_C is given by

$$\Phi_C = \sum_m \sum_n \sum_{s=5}^8 \left(a_{s,mn}^+ e^{i\omega t - ik_{z,s} z} + a_{s,mn}^- e^{i\omega t + ik_{z,s} z} \right) \psi_s(x, y). \quad (25)$$

Finally, under the CC boundary condition, the displacement expression for the connectors can be expressed as

$$w_C = \sum_m \sum_n \sum_{s=5}^8 ik_{z,s} \left(-a_{s,mn}^+ e^{i\omega t - ik_{z,s}z} + a_{s,mn}^- e^{i\omega t + ik_{z,s}z} \right) \psi_s(x, y). \quad (26)$$

Through the preceding derivations, the expressions for the sound pressure, as well as the displacements of the IM and the connectors, have been obtained. The unknown coefficients within these expressions are determined by applying the normal velocity continuity and displacement compatibility conditions:

$$\begin{aligned} z = 0: \quad \frac{\partial p_1}{\partial z} &= \rho_0 \omega^2 w_1; \quad z = h_1: \quad w_{IM} = w_1, \quad w_C = w_1, \\ z = H: \quad \frac{\partial p_2}{\partial z} &= \rho_0 \omega^2 w_2; \quad z = h_1 + d: \quad w_{IM} = w_2, \quad w_C = w_2. \end{aligned} \quad (27)$$

For the SS boundary condition, substituting the expressions for the sound pressure and the displacements into the boundary conditions yields

$$a_1 = \frac{\rho_0 \omega^2 \sum 1}{ik_z} e^{ik_x x + ik_y y} + p_{amp}, \quad (28)$$

$$a_2 = -\frac{\rho_0 \omega^2 \sum 2e^{ik_x x + ik_y y + ik_z H}}{ik_z}, \quad (29)$$

$$a_3 = \frac{\left(\sum 2e^{ik_1 h_1} - \sum 1e^{ik_1(h_1+d)} \right) e^{ik_x x + ik_y y}}{ik_1 (e^{ik_1 d} - e^{-ik_1 d})}, \quad (30)$$

$$a_4 = \frac{\left(\sum 2e^{-ik_1 h_1} - \sum 1e^{-ik_1(h_1+d)} \right) e^{ik_x x + ik_y y}}{ik_1 (e^{ik_1 d} - e^{-ik_1 d})}, \quad (31)$$

$$a_{5,mn} = \frac{W_{2,mn} e^{ik_{2,mn} h_1} - W_{1,mn} e^{ik_{2,mn}(h_1+d)}}{ik_{2,mn} (e^{ik_{2,mn} d} - e^{-ik_{2,mn} d})}, \quad (32)$$

$$a_{6,mn} = \frac{W_{2,mn} e^{ik_{2,mn} h_1} - W_{1,mn} e^{ik_{2,mn}(h_1+d)}}{ik_{2,mn} (e^{ik_{2,mn} d} - e^{-ik_{2,mn} d})}, \quad (33)$$

and for the CC boundary condition, substituting the expressions for the sound pressure and the displacements into the boundary conditions yields

$$a_1 = \frac{\rho_0 \omega^2 \sum 3}{ik_z} e^{ik_x x + ik_y y} + p_{amp}, \quad (34)$$

$$a_2 = -\frac{\rho_0 \omega^2 \sum 4e^{ik_x x + ik_y y + ik_z H}}{ik_z}, \quad (35)$$

$$a_3 = \frac{\left(\sum 4e^{ik_1 h_1} - \sum 3e^{ik_1(h_1+d)} \right) e^{ik_x x + ik_y y}}{ik_1 (e^{ik_1 d} - e^{-ik_1 d})}, \quad (36)$$

$$a_4 = \frac{\left(\sum 4e^{-ik_1 h_1} - \sum 3e^{-ik_1(h_1+d)} \right) e^{ik_x x + ik_y y}}{ik_1 (e^{ik_1 d} - e^{-ik_1 d})}, \quad (37)$$

$$a_{s,mn}^+ = \frac{W_{2,mn} e^{ik_{z,s}h_1} - W_{1,mn} e^{ik_{z,s}(h_1+d)}}{ik_{z,s} (e^{ik_{z,s}d} - e^{-ik_{z,s}d})}, \quad (38)$$

$$a_{s,mn}^- = \frac{W_{2,mn} e^{ik_{z,s}h_1} - W_{1,mn} e^{ik_{z,s}(h_1+d)}}{ik_{z,s} (e^{ik_{z,s}d} - e^{-ik_{z,s}d})}, \quad (39)$$

where $\Sigma 1$, $\Sigma 2$, $\Sigma 3$ and $\Sigma 4$ are symbols introduced to simplify the derivation, and their expressions are given by

$$\Sigma 1 = \sum_m \sum_n W_{1,mn} \phi_{SS,mn}, \quad \Sigma 2 = \sum_m \sum_n W_{2,mn} \phi_{SS,mn}, \quad (40)$$

$$\Sigma 3 = \sum_m \sum_n W_{1,mn} \phi_{CC,mn}, \quad \Sigma 4 = \sum_m \sum_n W_{2,mn} \phi_{CC,mn}. \quad (41)$$

At this point, based on the coefficient expressions, the interaction forces exerted by the IM and the connectors on the panels can be derived using the stress-displacement relationship, for the SS boundary condition:

$$F_{IM,z} = -(\lambda_{IM} + 2G_{IM})k_1 \left[\frac{\left(\sum 2e^{ik_1h_1} - \sum 1e^{ik_1(h_1+d)} \right) e^{-ik_1z}}{i(e^{ik_1d} - e^{-ik_1d})} + \frac{\left(\sum 2e^{-ik_1h_1} - \sum 1e^{-ik_1(h_1+d)} \right) e^{ik_1z}}{i(e^{ik_1d} - e^{-ik_1d})} \right], \quad (42)$$

$$F_{C,z} = -(\lambda_C + 2G_C) \sum_m \sum_n k_{2,mn} \left[\frac{\left(W_{2,mn} e^{ik_{2,mn}h_1} - W_{1,mn} e^{ik_{2,mn}(h_1+d)} \right) e^{-ik_{2,mn}z}}{i(e^{ik_{2,mn}d} - e^{-ik_{2,mn}d})} + \frac{\left(W_{2,mn} e^{-ik_{2,mn}h_1} - W_{1,mn} e^{-ik_{2,mn}(h_1+d)} \right) e^{ik_{2,mn}z}}{i(e^{ik_{2,mn}d} - e^{-ik_{2,mn}d})} \right] \phi_{SS,mn}, \quad (43)$$

and for the CC boundary condition,

$$F_{IM,z} = -(\lambda_{IM} + 2G_{IM})k_1 \left[\frac{\left(\sum 4e^{ik_1h_1} - \sum 3e^{ik_1(h_1+d)} \right) e^{-ik_1z}}{i(e^{ik_1d} - e^{-ik_1d})} + \frac{\left(\sum 4e^{-ik_1h_1} - \sum 3e^{-ik_1(h_1+d)} \right) e^{ik_1z}}{i(e^{ik_1d} - e^{-ik_1d})} \right], \quad (44)$$

$$F_{C,z} = -(\lambda_C + 2G_C) \sum_m \sum_n \sum_{s=5}^8 \left[\frac{k_{z,s} (W_{2,mn} e^{ik_{z,s}d} - W_{1,mn} e^{ik_{z,s}(h_1+d)}) e^{-ik_{z,s}z}}{i(e^{ik_{z,s}d} - e^{-ik_{z,s}d})} + \frac{k_{z,s} (W_{2,mn} e^{-ik_{z,s}d} - W_{1,mn} e^{-ik_{z,s}(h_1+d)}) e^{ik_{z,s}z}}{i(e^{ik_{z,s}d} - e^{-ik_{z,s}d})} \right] \psi_s(x, y). \quad (45)$$

By substituting the expressions for the panel displacements, sound pressure, and interaction forces into Equations (1) and (4), the equations are subsequently solved utilizing the Galerkin method, based on the principle of weighted residuals:

$$\int_0^b \int_0^a \left\{ \begin{aligned} & D_1 \nabla^4 w_1 + \rho_1 h_1 \frac{\partial^2 w_1}{\partial t^2} - p_1 - F_{IM,z1} \\ & - \sum_j F_{C,z1} H \left[x - \left(x_j - \frac{t_C}{2} \right), x - \left(x_j + \frac{t_C}{2} \right) \right] = 0 \end{aligned} \right\} \cdot \phi_{SS,pq} dx dy, \quad (46)$$

$$\int_0^b \int_0^a \left\{ \begin{aligned} & D_2 \nabla^4 w_2 + \rho_2 h_2 \frac{\partial^2 w_2}{\partial t^2} + p_2 + F_{IM,z2} \\ & + \sum_j F_{C,z2} H \left[x - \left(x_j - \frac{t_C}{2} \right), x - \left(x_j + \frac{t_C}{2} \right) \right] = 0 \end{aligned} \right\} \cdot \phi_{SS,pq} dx dy,$$

and

$$\int_0^b \int_0^a \left\{ \begin{aligned} & D_1 \nabla^4 w_1 + \rho_1 h_1 \frac{\partial^2 w_1}{\partial t^2} + \sum_j \frac{m_C}{2} \frac{\partial^2 w_1}{\partial t^2} \delta(x - x_j) \delta(y - y_j) \\ & - p_1 - F_{IM,z1} + \sum_j K_{C,t} (w_1 - w_2) \delta(x - x_j) \delta(y - y_j) = 0 \end{aligned} \right\} \cdot \phi_{CC,pq} dx dy, \quad (47)$$

$$\int_0^b \int_0^a \left\{ \begin{aligned} & D_2 \nabla^4 w_2 + \rho_2 h_2 \frac{\partial^2 w_2}{\partial t^2} + \sum_j \frac{m_C}{2} \frac{\partial^2 w_2}{\partial t^2} \delta(x - x_j) \delta(y - y_j) \\ & + p_2 + F_{IM,z2} - \sum_j K_{C,t} (w_1 - w_2) \delta(x - x_j) \delta(y - y_j) = 0 \end{aligned} \right\} \cdot \phi_{CC,pq} dx dy,$$

where p and q represent the Galerkin projection order.

Rearranging Equations (46) and (47) yields an infinite system of algebraic equations.

Under the SS boundary condition, in the case of homogeneous continuous connectors:

$$\left\{ \left[D_1 (k_m^2 + k_n^2)^2 - \rho_1 h_1 \omega^2 \right] - \frac{\rho_0 \omega^2}{ik_z} - \frac{k_1 (\lambda_{IM} + 2G_{IM}) (e^{ik_1 d} + e^{-ik_1 d})}{i(e^{ik_1 d} - e^{-ik_1 d})} \right\} W_{1,mn} + \frac{2k_1 (\lambda_{IM} + 2G_{IM})}{i(e^{ik_1 d} - e^{-ik_1 d})} W_{2,mn} \\ - \frac{2}{a} \sum_j \sum_m I_{mp,x_j} \frac{(\lambda_C + 2G_C) k_{2,mn} (e^{ik_{2,mn} d} + e^{-ik_{2,mn} d})}{i(e^{ik_{2,mn} d} - e^{-ik_{2,mn} d})} W_{1,mn} + \frac{2}{a} \sum_j \sum_m I_{mp,x_j} \frac{2(\lambda_C + 2G_C) k_{2,mn}}{i(e^{ik_{2,mn} d} - e^{-ik_{2,mn} d})} W_{2,mn} = \frac{8p_{amp} P_{SS,mn}}{ab}, \quad (48)$$

$$\frac{2k_1 (\lambda_{IM} + 2G_{IM})}{i(e^{ik_1 d} - e^{-ik_1 d})} W_{1,mn} + \left\{ \left[D_2 (k_m^2 + k_n^2)^2 - \rho_2 h_2 \omega^2 \right] - \frac{\rho_0 \omega^2}{ik_z} - \frac{k_1 (\lambda_{IM} + 2G_{IM}) (e^{-ik_1 d} + e^{ik_1 d})}{i(e^{ik_1 d} - e^{-ik_1 d})} \right\} W_{2,mn} \\ + \frac{2}{a} \sum_j \sum_m I_{mp,x_j} \frac{2(\lambda_C + 2G_C) k_{2,mn}}{i(e^{ik_{2,mn} d} - e^{-ik_{2,mn} d})} W_{1,mn} - \frac{2}{a} \sum_j \sum_m I_{mp,x_j} \frac{(\lambda_C + 2G_C) k_{2,mn} (e^{-ik_{2,mn} d} + e^{ik_{2,mn} d})}{i(e^{ik_{2,mn} d} - e^{-ik_{2,mn} d})} W_{2,mn} = 0,$$

and in the case of the “mass-spring” model,

$$\left\{ \left[D_1 (k_m^2 + k_n^2)^2 - \rho_1 h_1 \omega^2 \right] - \frac{\rho_0 \omega^2}{ik_z} - \frac{k_1 (\lambda_{IM} + 2G_{IM}) (e^{ik_1 d} + e^{-ik_1 d})}{i(e^{ik_1 d} - e^{-ik_1 d})} \right\} W_{1,mn} + \frac{2k_1 (\lambda_{IM} + 2G_{IM})}{i(e^{ik_1 d} - e^{-ik_1 d})} W_{2,mn} \\ + \left(\frac{4K_{C,t} - 2m_C \omega^2}{ab} \right) \sum_j \left\{ \left[\phi_{SS,mn}(x_j, y_j) \right] \sum_p \sum_q W_{1,pq} \left[\phi_{SS,pq}(x_j, y_j) \right] \right\} \\ - \frac{4K_{C,t}}{ab} \sum_j \left\{ \left[\phi_{SS,mn}(x_j, y_j) \right] \sum_p \sum_q W_{2,pq} \left[\phi_{SS,pq}(x_j, y_j) \right] \right\} = \frac{8p_{amp} P_{SS,mn}}{ab}, \quad (49)$$

$$\frac{2k_1 (\lambda_{IM} + 2G_{IM})}{i(e^{ik_1 d} - e^{-ik_1 d})} W_{1,mn} + \left\{ \left[D_2 (k_m^2 + k_n^2)^2 - \rho_2 h_2 \omega^2 \right] - \frac{\rho_0 \omega^2}{ik_z} - \frac{k_1 (\lambda_{IM} + 2G_{IM}) (e^{ik_1 d} + e^{-ik_1 d})}{i(e^{ik_1 d} - e^{-ik_1 d})} \right\} W_{2,mn} \\ - \frac{4K_a}{ab} \sum_j \left\{ \left[\phi_{SS,mn}(x_j, y_j) \right] \sum_p \sum_q W_{1,pq} \left[\phi_{SS,pq}(x_j, y_j) \right] \right\} \\ + \left(\frac{4K_a - 2m_C \omega^2}{ab} \right) \sum_j \left\{ \left[\phi_{SS,mn}(x_j, y_j) \right] \sum_p \sum_q W_{2,pq} \left[\phi_{SS,pq}(x_j, y_j) \right] \right\} = 0,$$

where j denotes the number of connectors, and $I_{mp,xj}$ is obtained by integrating the Heaviside function. Its specific form is given by

$$\begin{aligned} m \neq p, I_{mp,xj} &= \frac{a}{(m-p)\pi} \cos \left[\frac{(m-p)\pi x_j}{a} \right] \sin \left[\frac{(m-p)\pi t_c}{a} \right] \\ &\quad - \frac{a}{(m+p)\pi} \cos \left[\frac{(m+p)\pi x_j}{a} \right] \sin \left[\frac{(m+p)\pi t_c}{a} \right], \\ m = p, I_{mp,xj} &= t_c - \frac{a}{2m\pi} \cos \left(\frac{2m\pi x_j}{a} \right) \sin \left(\frac{2m\pi t_c}{a} \right). \end{aligned} \quad (50)$$

P_{mn} represents the projection of the incident sound pressure onto the modal space under the SS boundary condition, and its specific form is given by

$$P_{SS,mn} = \frac{abmn\pi^2 \left[e^{-ik_x a} \cos(m\pi) - 1 \right] \left[e^{-ik_y b} \cos(n\pi) - 1 \right]}{\left[(k_x a)^2 - (m\pi)^2 \right] \left[(k_y b)^2 - (n\pi)^2 \right]}. \quad (51)$$

Under the CC boundary condition, in the case of homogeneous continuous connectors,

$$\begin{aligned} &\text{ors,} \\ D_1 \sum_m \sum_n &\left[\frac{ab}{2} \alpha_m^4 \delta_{mp} \left(1 + \frac{1}{2} \delta_{nq} \right) + \frac{ab}{2} \alpha_m^2 \beta_n^2 \delta_{mp} \delta_{nq} + \frac{ab}{2} \beta_n^4 \delta_{nq} \left(1 + \frac{1}{2} \delta_{mp} \right) \right] W_{1,mn} \\ &- \sum_m \sum_n \left[\rho_1 h_1 \omega^2 ab + \frac{\rho_0 \omega^2 ab}{ik_z} + \frac{abk_1 (\lambda_{IM} + 2G_{IM}) (e^{ik_1 d} + e^{-ik_1 d})}{i(e^{ik_1 d} - e^{-ik_1 d})} \right] W_{1,mn} \left(1 + \frac{1}{2} \delta_{mp} \right) \left(1 + \frac{1}{2} \delta_{nq} \right) \\ &+ \frac{2k_1 (\lambda_{IM} + 2G_{IM})}{i(e^{ik_1 d} - e^{-ik_1 d})} ab \sum_m \sum_n W_{2,mn} \left(1 + \frac{1}{2} \delta_{mp} \right) \left(1 + \frac{1}{2} \delta_{nq} \right) \\ &+ (\lambda_c + 2G_c) \sum_j \sum_m \sum_n Q_{1,mnpq} = P_{CC,mn}, \\ &\frac{2k_1 (\lambda_{IM} + 2G_{IM})}{i(e^{ik_1 d} - e^{-ik_1 d})} ab \sum_m \sum_n W_{1,mn} \left(1 + \frac{1}{2} \delta_{mp} \right) \left(1 + \frac{1}{2} \delta_{nq} \right) \\ &+ D_2 \sum_m \sum_n \left[\frac{ab}{2} \alpha_m^4 \delta_{mp} \left(1 + \frac{1}{2} \delta_{nq} \right) + \frac{ab}{2} \alpha_m^2 \beta_n^2 \delta_{mp} \delta_{nq} + \frac{ab}{2} \beta_n^4 \delta_{nq} \left(1 + \frac{1}{2} \delta_{mp} \right) \right] W_{2,mn} \\ &- \sum_m \sum_n \left[\rho_2 h_2 \omega^2 ab + \frac{\rho_0 \omega^2 ab}{ik_z} + \frac{abk_1 (\lambda_{IM} + 2G_{IM}) (e^{-ik_1 d} + e^{ik_1 d})}{i(e^{ik_1 d} - e^{-ik_1 d})} \right] W_{2,mn} \left(1 + \frac{1}{2} \delta_{mp} \right) \left(1 + \frac{1}{2} \delta_{nq} \right) \\ &- (\lambda_c + 2G_c) \sum_j \sum_m \sum_n Q_{2,mnpq} = 0. \end{aligned} \quad (52)$$

where P_{mn} represents the projection of the incident sound pressure onto the modal space under the CC boundary condition, and its specific form is given by

$$P_{CC,mn} = \begin{cases} 2P_0 ab, & k_x = 0, k_y = 0 \\ \frac{8iP_0 an^2 \pi^2 (1 - e^{-ik_y b})}{k_y (k_y^2 b^2 - 4n^2 \pi^2)}, & k_x = 0, k_y \neq 0 \\ \frac{8iP_0 bm^2 \pi^2 (1 - e^{-ik_x a})}{k_x (k_x^2 a^2 - 4m^2 \pi^2)}, & k_x \neq 0, k_y = 0 \\ -\frac{32P_0 \pi^4 m^2 n^2 (1 - e^{-ik_x a})(1 - e^{-ik_y b})}{k_x k_y (k_x^2 a^2 - 4m^2 \pi^2)(k_y^2 b^2 - 4n^2 \pi^2)}, & k_x \neq 0, k_y \neq 0 \end{cases} \quad (53)$$

$Q_{1,mnpq}$ and $Q_{2,mnpq}$ are defined as

$$\begin{aligned}
Q_{1,mnpq} = & -\frac{k_{z,5} \left(e^{ik_{z,5}d} + e^{-ik_{z,5}d} \right)}{i \left(e^{ik_{z,5}d} - e^{-ik_{z,5}d} \right)} bC_0 W_{1,mn} + \frac{2k_{z,5}}{i \left(e^{ik_{z,5}d} - e^{-ik_{z,5}d} \right)} bC_0 W_{2,mn} \\
& + \frac{k_{z,6} \left(e^{ik_{z,6}d} + e^{-ik_{z,6}d} \right)}{i \left(e^{ik_{z,6}d} - e^{-ik_{z,6}d} \right)} bC_1 W_{1,mn} - \frac{2k_{z,6}}{i \left(e^{ik_{z,6}d} - e^{-ik_{z,6}d} \right)} bC_1 W_{2,mn} \\
& - \frac{k_{z,7} \left(e^{ik_{z,7}d} + e^{-ik_{z,7}d} \right)}{i \left(e^{ik_{z,7}d} - e^{-ik_{z,7}d} \right)} \frac{b}{2} \delta_{nq} C_0 W_{1,mn} + \frac{2k_{z,7}}{i \left(e^{ik_{z,7}d} - e^{-ik_{z,7}d} \right)} \frac{b}{2} \delta_{nq} C_0 W_{2,mn} \\
& + \frac{k_{z,8} \left(e^{ik_{z,8}d} + e^{-ik_{z,8}d} \right)}{i \left(e^{ik_{z,8}d} - e^{-ik_{z,8}d} \right)} \frac{b}{2} \delta_{nq} C_1 W_{1,mn} - \frac{2k_{z,8}}{i \left(e^{ik_{z,8}d} - e^{-ik_{z,8}d} \right)} \frac{b}{2} \delta_{nq} C_1 W_{2,mn},
\end{aligned} \quad (54)$$

$$\begin{aligned}
Q_{2,mnpq} = & -\frac{2k_{z,5}}{i \left(e^{ik_{z,5}d} - e^{-ik_{z,5}d} \right)} bC_0 W_{1,mn} + \frac{k_{z,5} \left(e^{-ik_{z,5}d} + e^{ik_{z,5}d} \right)}{i \left(e^{ik_{z,5}d} - e^{-ik_{z,5}d} \right)} bC_0 W_{2,mn} \\
& + \frac{2k_{z,6}}{i \left(e^{ik_{z,6}d} - e^{-ik_{z,6}d} \right)} bC_1 W_{1,mn} - \frac{k_{z,6} \left(e^{-ik_{z,6}d} + e^{ik_{z,6}d} \right)}{i \left(e^{ik_{z,6}d} - e^{-ik_{z,6}d} \right)} bC_1 W_{2,mn} \\
& - \frac{2k_{z,7}}{i \left(e^{ik_{z,7}d} - e^{-ik_{z,7}d} \right)} \frac{b}{2} \delta_{nq} C_0 W_{1,mn} + \frac{k_{z,7} \left(e^{-ik_{z,7}d} + e^{ik_{z,7}d} \right)}{i \left(e^{ik_{z,7}d} - e^{-ik_{z,7}d} \right)} \frac{b}{2} \delta_{nq} C_0 W_{2,mn} \\
& + \frac{2k_{z,8}}{i \left(e^{ik_{z,8}d} - e^{-ik_{z,8}d} \right)} \frac{b}{2} \delta_{nq} C_1 W_{1,mn} - \frac{k_{z,8} \left(e^{-ik_{z,8}d} + e^{ik_{z,8}d} \right)}{i \left(e^{ik_{z,8}d} - e^{-ik_{z,8}d} \right)} \frac{b}{2} \delta_{nq} C_1 W_{2,mn},
\end{aligned} \quad (55)$$

and C_0, C_1 are defined as

$$C_0 = t_c - \frac{\sin(\alpha_p x_B) - \sin(\alpha_p x_A)}{\alpha_p}, \quad (56)$$

$$C_1 = \begin{cases} \frac{\sin(\alpha_m x_B) - \sin(\alpha_m x_A)}{\alpha_m} - \frac{1}{2} \left\{ \frac{\sin[(\alpha_m + \alpha_p) x_B] - \sin[(\alpha_m + \alpha_p) x_A]}{\alpha_m + \alpha_p} + \frac{\sin[(\alpha_m - \alpha_p) x_B] - \sin[(\alpha_m - \alpha_p) x_A]}{\alpha_m - \alpha_p} \right\}, & m \neq p \\ \frac{\sin(\alpha_m x_B) - \sin(\alpha_m x_A)}{\alpha_m} - \frac{1}{2} \left[t_c + \frac{\sin(2\alpha_m x_B) - \sin(2\alpha_m x_A)}{2\alpha_m} \right], & m = p \end{cases}, \quad (57)$$

where $x_A = x_j - tc/2$ and $x_B = x_j + tc/2$ denote the lower and upper limits of integration, respectively.

When the case is a “mass-spring” model,

$$\begin{aligned}
& D_1 \sum_m \sum_n \left[\frac{ab}{2} \alpha_m^4 \delta_{mp} \left(1 + \frac{1}{2} \delta_{nq} \right) + \frac{ab}{2} \alpha_m^2 \beta_n^2 \delta_{mp} \delta_{nq} + \frac{ab}{2} \beta_n^4 \delta_{nq} \left(1 + \frac{1}{2} \delta_{mp} \right) \right] W_{1,mn} \\
& - \sum_m \sum_n \left[\rho_1 h_1 \omega^2 ab + \frac{\rho_0 \omega^2 ab}{ik_z} + \frac{abk_1 (\lambda_{IM} + 2G_{IM}) (e^{ik_1 d} + e^{-ik_1 d})}{i(e^{ik_1 d} - e^{-ik_1 d})} \right] W_{1,mn} \left(1 + \frac{1}{2} \delta_{mp} \right) \left(1 + \frac{1}{2} \delta_{nq} \right) \\
& + \sum_j \left(K_{C,t} - \frac{m_c \omega^2}{2} \right) [\phi_{CC,pq}(x_j, y_j)] \left\{ \sum_m \sum_n W_{1,mn} [\phi_{CC,mn}(x_j, y_j)] \right\} \\
& + \frac{2abk_1 (\lambda_{IM} + 2G_{IM})}{i(e^{ik_1 d} - e^{-ik_1 d})} \sum_m \sum_n W_{2,mn} \left(1 + \frac{1}{2} \delta_{mp} \right) \left(1 + \frac{1}{2} \delta_{nq} \right) \\
& - \sum_j K_{C,t} [\phi_{CC,pq}(x_j, y_j)] \left\{ \sum_m \sum_n W_{2,mn} [\phi_{CC,mn}(x_j, y_j)] \right\} = P_{CC,mn},
\end{aligned} \tag{58}$$

$$\begin{aligned}
& \frac{2abk_1 (\lambda_{IM} + 2G_{IM})}{i(e^{ik_1 d} - e^{-ik_1 d})} \sum_m \sum_n W_{1,mn} \left(1 + \frac{1}{2} \delta_{mp} \right) \left(1 + \frac{1}{2} \delta_{nq} \right) \\
& - \sum_j K_{C,t} [\phi_{CC,pq}(x_j, y_j)] \left\{ \sum_m \sum_n W_{1,mn} [\phi_{CC,mn}(x_j, y_j)] \right\} \\
& + D_2 \sum_m \sum_n \left[\frac{ab}{2} \alpha_m^4 \delta_{mp} \left(1 + \frac{1}{2} \delta_{nq} \right) + \frac{ab}{2} \alpha_m^2 \beta_n^2 \delta_{mp} \delta_{nq} + \frac{ab}{2} \beta_n^4 \delta_{nq} \left(1 + \frac{1}{2} \delta_{mp} \right) \right] W_{2,mn} \\
& - \sum_m \sum_n \left[\rho_2 h_2 \omega^2 ab + \frac{\rho_0 \omega^2 ab}{ik_z} + \frac{abk_1 (\lambda_{IM} + 2G_{IM}) (e^{-ik_1 d} + e^{ik_1 d})}{i(e^{ik_1 d} - e^{-ik_1 d})} \right] W_{2,mn} \left(1 + \frac{1}{2} \delta_{mp} \right) \left(1 + \frac{1}{2} \delta_{nq} \right) \\
& + \sum_j \left(K_{C,t} - \frac{m_c \omega^2}{2} \right) [\phi_{CC,pq}(x_j, y_j)] \left\{ \sum_m \sum_n W_{2,mn} [\phi_{CC,mn}(x_j, y_j)] \right\} = 0.
\end{aligned}$$

Equations (48), (49), (52) and (58) are all infinite systems of algebraic equations. To facilitate the solution, convergent solutions can be obtained by truncating the values of m and n .

2.4.2. Sound Transmission Loss

The sound insulation performance of the ICSP is evaluated by the sound transmission loss (STL), which is calculated from the incident sound power W_i and the transmitted sound power W_t :

$$STL = 10 \log_{10} \frac{1}{\tau} = 10 \log_{10} \frac{W_i}{W_t}, \tag{59}$$

where τ is the transmission coefficient, W_i and W_t are defined as

$$\begin{aligned}
W_i &= \frac{1}{2} \int_0^b \int_0^a \text{Re}(p_i v_i^*) dx dy, \\
W_t &= \frac{1}{2} \int_0^b \int_0^a \text{Re}(p_t v_t^*) dx dy,
\end{aligned} \tag{60}$$

The STL calculation procedure described above applies only to a single specific incident direction, defined by the elevation angle θ and azimuthal angle φ . When considering a diffuse sound field, it is given by [20]:

$$\bar{\tau}_{\text{diff}} = \frac{\int_0^{\pi/2} \int_0^{78^\circ} \tau(\theta, \varphi) \sin \theta \cos \theta d\theta d\varphi}{\int_0^{\pi/2} \int_0^{78^\circ} \sin \theta \cos \theta d\theta d\varphi}, \tag{61}$$

where 78° denotes the upper limit angle of the incident sound field, determined empirically. Consequently, the new STL is defined as

$$STL = 10 \log_{10} \left(\frac{1}{\bar{\tau}_{\text{diff}}} \right). \tag{62}$$

3. Verifications

3.1. Finite Element Model

To verify the accuracy of the analytical model for the airborne sound insulation of finite structures, a symmetric acoustic-structure coupled FE model is established using the COMSOL 6.4 software, as shown in Figure 3. In this model, the face sheets, IM, and plate-type connectors are modeled using the “Solid Mechanics” physics interface, while the pin-type connectors are modeled using the “Beam” physics interface. The “Acoustic-Structure Boundary” condition is applied at the interface between the solid mechanics and pressure acoustics domains. By utilizing the symmetry of the structure with respect to the planes $x = a/2$ and $y = b/2$, only a quarter model is constructed, and “Symmetry” boundary conditions are assigned to the symmetry planes. For the SS boundary condition, the displacements in the y - and z -directions are constrained on the boundaries perpendicular to the x -axis, and the displacements in the x - and z -directions are constrained on the boundaries perpendicular to the y -axis. For the CC boundary condition, the “Fixed Constraint” in COMSOL is directly applied. Regarding the mesh size, the maximum and minimum mesh sizes are set to $\lambda_{\min}/6$ and $\lambda_{\min}/10$, respectively, with reference to the COMSOL Application Libraries or technical support documentation. The parameters used in the analysis are listed in Table 1.

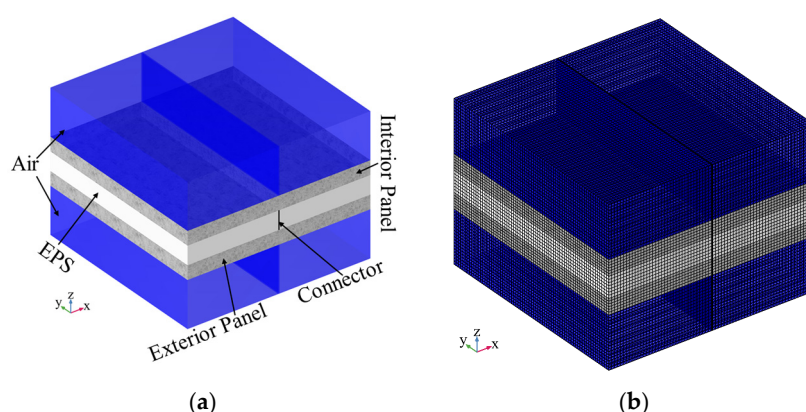


Figure 3. FE model of ICSP. (a) Schematic of the FE model; (b) meshing of the FE model.

Table 1. Analysis Parameters.

h_1 (m)	0.06	h_2 (m)	0.06	t_c (m)	0.005
d (m)	0.08	H (m)	0.2	c_0 (m/s)	343
ρ_0 (kg/m ³)	1.21	ρ_1 (kg/m ³)	2400	ρ_2 (kg/m ³)	2400
ρ_{IM} (kg/m ³)	20.4	E_1 (GPa)	32.5	E_2 (GPa)	32.5
E_C (GPa)	210	E_{IM} (MPa)	4	ν_1	0.2
ν_2	0.2	ν_{IM}	0.1	η_1	0.06
η_2	0.06	η_{IM}	0.2	η_C	0.01

The comparison between the theoretical and FE results is illustrated in Figure 4. As shown in Figure 4a, for the ICSP with plate-type connectors in the low-frequency band (<500 Hz), the overall trends and the frequencies corresponding to the sound insulation dips of the theoretical and FE results show good agreement, particularly at the first-order resonance dip, which demonstrates the accuracy of the theoretical model. In the mid-to-high frequency band (>500 Hz), the macroscopic trends of the two curves remain consistent, exhibiting similar fluctuation characteristics; however, the frequency positions corresponding to the resonance dips begin to shift. This discrepancy arises because, as the frequency increases and the wavelength decreases, the structural vibration transitions

from “global bending” to “local panel resonance” between the connectors. Furthermore, based on the thin-plate assumption, the theoretical model neglects in-plane displacements, thereby ignoring the shear effects of the face sheets, the IM, and the connectors. Consequently, the theoretical model is stiffer than the FE model, leading to higher STL values for the structure.

As shown in Figure 4b, for the ICSP with column-type connectors in the low-frequency band (<500 Hz), the theoretical results agree well with the FE results, particularly regarding the resonance peaks and dips around 90 Hz and 300–400 Hz, which demonstrates the accuracy of the theoretical model. The discrepancy around 200 Hz is similarly attributed to factors such as the neglect of shear stiffness. In the low-frequency band, where the wavelength is relatively long, the structural vibration is dominated by the global bending stiffness, and the axial stiffness of the springs can adequately represent the contribution of the connectors to the global stiffness of the structure. In the mid-to-high frequency band (>500 Hz), while the general trends remain consistent, the theoretical results are overall lower than the FE results. As the frequency increases and the wavelength decreases, higher-order local modes begin to appear in the face sheets. The beam elements used in the FE model possess bending stiffness; therefore, the rotation and transverse displacement of the face sheets are constrained by the beam elements, reducing energy radiation. In contrast, the theoretical model, which only considers the axial stiffness of the springs, fails to constrain the local displacements of the face sheets. This underestimates the actual constraint effect of the connectors on the structure, leading to larger predicted structural displacements in the theoretical model and, consequently, a lower STL.

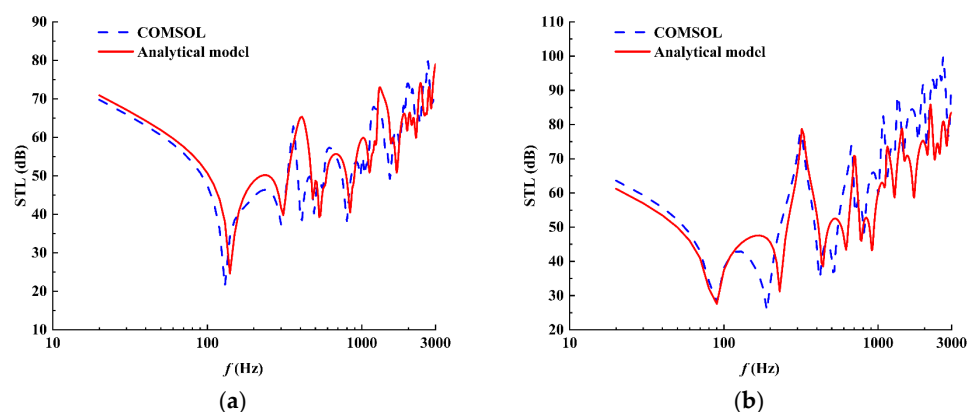


Figure 4. Comparison of FE and theoretical results under SS boundary condition. (a) Plate-type connectors; (b) column-type connectors.

3.2. Experimental Results

To further verify the accuracy of the theoretical model, an ICSP specimen was fabricated, and an airborne sound insulation test was conducted. The in-plane dimensions of the specimen were 1600 mm × 1600 mm, with a total thickness of 150 mm. The upper and lower face sheets were 70 mm and 60 mm thick concrete panels, respectively, with a design grade of C40. The intermediate IM was a 20 mm thick polyurethane foam. The connectors were circular tubular FRP pillars with an outer diameter of 70 mm and a wall thickness of 6.4 mm. The specimen and its installation are shown in Figure 5.

During the installation of the specimen, low-strength cement mortar was used to seal the boundaries. This low-strength mortar cannot provide ideal constraints, approximating the SS boundary condition, as shown in Figure 5b. Therefore, the SS boundary condition was applied in the theoretical and FE models. However, the actual edge stiffness of the specimen was not directly measured; thus, this boundary condition should be regarded

as an approximate representation of the experimental constraint. The theoretical and experimental results in the diffuse sound field are presented in Figure 6. As shown in the figure, the theoretical results are relatively close to the FE and experimental results. In particular, the analytical results can accurately capture the resonance dip around 80 Hz observed in the experimental results.



Figure 5. The specimen and its installation. (a) The ICSP specimen; (b) specimen installation.

To quantitatively evaluate the differences shown in Figure 6, based on the deviations of the analytical model-SS from COMSOL-SS and experimental results at each one-third octave center frequency, the mean absolute deviation (MAD) and maximum absolute deviation (MaxAD) were calculated, as shown in Table 2. The MAD between the analytical model and the FE result is 3.99 dB, and the corresponding MaxAD is 9.98 dB. This indicates that the analytical model is generally consistent with the FE model under the same idealized SS boundary condition. In comparison, the MAD between the analytical model and the experimental result increases to 6.89 dB, and the MaxAD reaches 17.58 dB, indicating larger local discrepancies in some frequency bands.

Overall, the experimental results are lower and exhibit a smoother curve because the analytical model neglects shear deformation and employs a “mass-spring” simplification, leading to a lower overall stiffness. Consequently, in the low-frequency band governed by global bending, the FE model exhibits a higher global bending stiffness, thereby yielding higher STL values. In the mid-to-high frequency bands, the local deformation of the face panels dominates. The comparison indicates that the analytical model can reasonably predict the sound insulation trend of the tested ICSP specimen. Nevertheless, since only one airborne sound insulation experiment was conducted and the actual edge stiffness was not measured, the validation should be interpreted within the scope of the present specimen and the approximate SS boundary assumption.

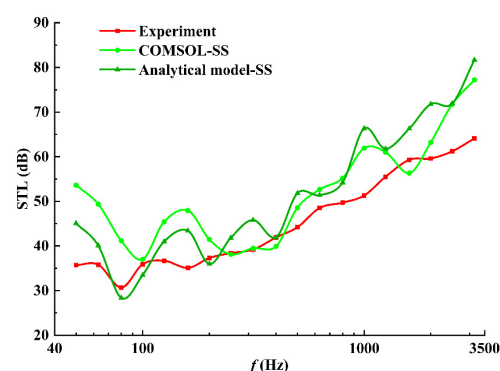


Figure 6. Comparison of theoretical, FE, and experimental results.

Table 2. Frequency-band deviation metrics.

Comparison	MAD (dB)	MaxAD (dB)
Analytical-SS vs. COMSOL-SS	3.99	9.98
Analytical-SS vs. Experiment	6.89	17.58

The Chinese National Standard GB/T 50121-2005 [53] provides an index for evaluating the sound insulation performance of structures, namely the weighted sound reduction index R_w . Following the calculation method for R_w specified in the standard, the experimental, FE, and theoretical results are evaluated, with the results summarized in Table 3. It can be observed that, considering the R_w , the theoretical result (53 dB) is close to the experimental result (49 dB), with a difference of 4 dB. When incorporating the spectrum adaptation terms, the three results become remarkably close in terms of the $R_w + C$ metric (48 dB, 50 dB, 51 dB, respectively), with a maximum difference of 3 dB. Furthermore, they are also very close in the $R_w + C_{tr}$ metric, with a maximum difference of 2 dB. This phenomenon originates from the inherent nature of the rating procedure: R_w penalizes sound insulation dips without rewarding the peaks. Although the SS boundary condition confers a higher global stiffness to the analytical and FE models, thereby substantially elevating the broadband sound insulation level, the resonance dips captured by the evaluation criteria coincidentally fall within the mid-to-high and low-to-mid frequency ranges, which are specifically emphasized by the spectrum adaptation terms C and C_{tr} , respectively. Consequently, under the comprehensive assessment using $R_w + C$ or $R_w + C_{tr}$, the overestimation inherent to relying solely on the single R_w rating is effectively compensated for, ultimately yielding excellent agreement between the predictions of various computational cases and the experimental results. Conversely, the experimental curve is generally smoother without prominent dips, leading to a smaller magnitude of correction. The convergence of the three results after adaptation indicates reasonable predictive capability.

Table 3. Comparison of R_w .

Type	R_w (C; C_{tr}) (dB)
Experiment	49 (−1; −4) = (48; 45)
COMSOL-SS	52 (−2; −5) = (50; 47)
Analytical model-SS	53 (−2; −6) = (51; 47)

R_w is the weighted sound insulation index. C is the pink noise spectrum adaptation term. C_{tr} is the traffic noise spectrum adaptation term.

4. Parametric Analysis

Based on the verified theoretical model, this section will analyze the effects of the stiffness of the connector, boundary conditions, and thickness of IM on the sound insulation performance of the ICSP. The remaining parameters are listed in Table 1. Based on the thin-plate assumption, the thickness of the connectors is extremely small, and their shear contribution is negligible. Instead, they primarily bear axial loads. Consequently, even for discretely distributed connectors, their macroscopic mechanical behavior can be equivalently modeled as homogeneous plate-type connectors. Taking these factors into consideration, the calculation procedure for plate-type connectors is uniformly adopted for the subsequent parametric analysis.

4.1. Stiffness of the Connectors

As a crucial component connecting the two face sheets, the connectors affect the load-bearing capacity of the structure. A higher connector stiffness leads to an enhanced load-bearing capacity. Conversely, from an acoustic perspective, high-stiffness connectors can

act as a medium for energy transmission—a phenomenon known as the “acoustic bridging” effect—which significantly degrades the sound insulation performance of the structure. Therefore, analyzing the stiffness of the connectors plays a vital role in the design optimization of the structure.

The stiffness of the connectors is primarily characterized by the elastic modulus E_c , which is considered in this study. The lower limit of E_c is determined by the elastic modulus of the core layer IM, E_{IM} . When the stiffness of the connectors is sufficiently high, the transverse displacements of the two face sheets tend to be identical, which dictates the upper limit. It should be noted that the selected E_c values are not intended to correspond one-to-one to specific connector materials. Instead, E_c is used here as an equivalent stiffness parameter to describe different levels of mechanical coupling between the two concrete wythes. In practical ICSPs, connectors may be made of different materials and structural forms, such as GFRP, CFRP, steel, plate-type connectors, tubular connectors, or stud-type connectors. The Young’s moduli of common connector materials are generally on the order of 10^{10} Pa– 10^{11} Pa, e.g., approximately 40 GPa–60 GPa for GFRP, 120 GPa–145 GPa for CFRP, and 190 GPa–215 GPa for steel. The range from 10^6 to 10^{12} Pa was selected to cover the transition from weak inter-panel coupling to a nearly rigid connection limit. Therefore, the parametric results should be interpreted as a design-oriented stiffness range that can help designers select connector materials and geometrical configurations according to the required equivalent stiffness level and acoustic performance.

As observed in Figure 7a, the solid concrete panel (SCP) exhibits superior sound insulation performance. The performance of the ICSP only approaches that of the SCP in the mid-to-high frequency range when $E_c = 10^6$ Pa, which is attributed to the higher surface mass density and stiffness of the SCP. The sound insulation dip around 250 Hz corresponds to the first-order resonance frequency of the SCP.

As E_c increases, the first resonance dip of the ICSPs shifts toward higher frequencies. The low-frequency band (<500 Hz) is stiffness-controlled; increasing the stiffness of the connectors enhances the overall bending stiffness of the system and the first-order resonance frequency, while simultaneously yielding a significant increase in the STL. In the mid-to-high frequency band (>500 Hz), as the wavelength decreases, the local panel vibration and acoustic bridging begin to dominate. Low-stiffness connectors ($E_c = 10^6$ Pa and 10^8 Pa) act as an impedance mismatch. Combined with the high damping characteristics of the IM, this reduces energy transmission between the two face sheets, thereby exhibiting better sound insulation performance in the mid-to-high frequency range. When E_c reaches 10^{10} Pa and above, the sound insulation performance of the structure stabilizes. Particularly for $E_c = 10^{12}$ Pa, the STL curves across the entire frequency band tend to converge. At this stage, energy propagates primarily through “acoustic bridging”, causing the sound insulation capacity of the structure to deteriorate, falling not only below that of low-stiffness ICSPs but also significantly below that of the SCP.

As observed in Figure 7b, under the CC boundary condition, the variation trends of the curves are generally consistent with those under the SS boundary condition. The low-frequency range is dominated by stiffness, while the mid-to-high frequency range is dominated by local panel vibration and acoustic bridging. The CC boundary condition enhances the structural stiffness, causing the first-order resonance frequency of the SCP to shift to approximately 500 Hz; correspondingly, the sound insulation dips of the ICSPs also undergo a significant shift to the right. The differences are that for $E_c = 10^6$ Pa and 10^8 Pa, the ICSPs exhibit superior sound insulation performance compared to the SCP across multiple frequency bands; and for $E_c = 10^{12}$ Pa, the curve still exhibits multiple sound insulation dips in the mid-to-high frequency band. However, since $E_c = 10^{12}$ Pa already sur-

passes the elastic modulus of steel, it represents exceedingly stiff connectors. Consequently, further increasing the connector stiffness would not only dramatically inflate costs but also progressively deviate from practical engineering scenarios.

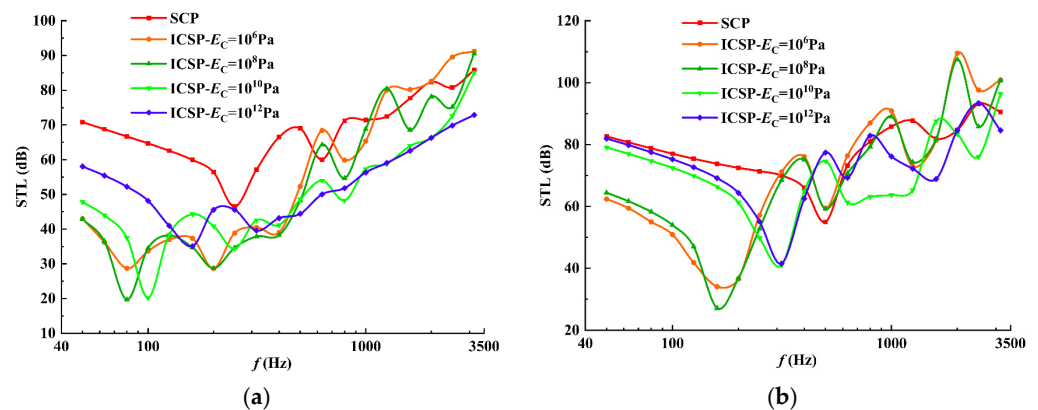


Figure 7. Comparison of STL with different connector stiffnesses. (a) SS boundary condition; (b) CC boundary condition.

Quantifying the results from Figure 7, the R_w values for the various cases are calculated and presented in Table 4. Under the SS boundary condition, as E_c increases, R_w initially decreases, then increases, and gradually stabilizes. Under the CC boundary condition, a similar trend is observed. This occurs because, as E_c increases, the first sound insulation dip for $E_c = 10^8$ Pa drops significantly; meanwhile, for the high-stiffness connectors, the first sound insulation dip exhibits a pronounced rightward shift along with a larger STL. Based on the rating mechanism of R_w , sound insulation dips are penalized; consequently, a reduction in R_w occurs at $E_c = 10^8$ Pa.

Table 4. Comparison of R_w .

Type	SS- R_w (C; C_{tr}) (dB)	CC- R_w (C; C_{tr}) (dB)
SCP	67 (−4; −7)	75 (−7; −9)
ICSP- $E_c = 10^6$ Pa	50 (−3; −8)	60 (−6; −11)
ICSP- $E_c = 10^8$ Pa	48 (−2; −6)	59 (−10; −15)
ICSP- $E_c = 10^{10}$ Pa	49 (−3; −10)	62 (−5; −8)
ICSP- $E_c = 10^{12}$ Pa	51 (−1; −4)	67 (−9; −12)

4.2. Boundary Conditions

Keeping the other parameters constant, the results for $E_c = 10^{10}$ Pa are extracted and illustrated in Figure 8 and Table 5. Due to boundary effects, finite-sized structures exhibit pronounced sound insulation dips. Across the entire frequency band, the ICSP demonstrates superior sound insulation performance under the CC boundary condition. As presented in Table 5, under the SS boundary condition, the $R_w + C_{tr}$ value is merely 39 dB, failing to meet the 45 dB requirement stipulated by the latest standard [54]. This discrepancy clearly demonstrates that the CC boundary condition, owing to its higher constraint stiffness, can effectively enhance the comprehensive sound insulation performance of the components.

Overall, the boundary effect is a primary factor influencing the sound insulation performance of the structure, which further explains why the experimental STL and R_w obtained in Section 3.2 are relatively low. In practical engineering applications, strengthening the boundary constraints of the structure serves as an effective approach to attenuating low-frequency sound waves.

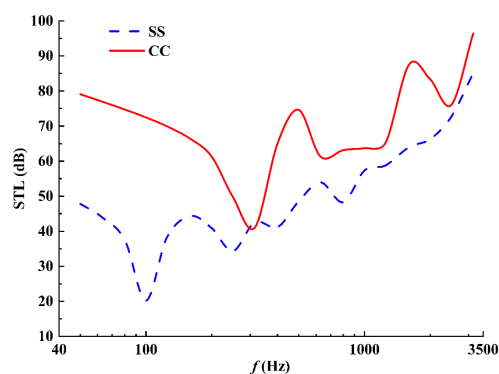


Figure 8. Comparison of STL with different boundary conditions.

Table 5. Comparison of R_w .

Type	R_w (C; C_{tr}) (dB)
SS	49 (−3; −10) = (46; 39)
CC	62 (−5; −8) = (57; 54)

4.3. Thickness of Core Layer

Setting $E_c = 10^{10}$ Pa and keeping the total thickness of the structure constant, this section investigates the influence of different core layer thicknesses on the sound insulation performance. The lower and upper bounds of the core layer thickness are dictated by the requirements of the Chinese Industry Standard JGJ/T 458-2018 [52]. The results are presented in Figure 9 and Table 6.

For the SS boundary condition, the constraints are relatively weak, meaning the overall bending stiffness of the structure relies primarily on its inherent physical properties. As the core layer thickness decreases, the thickness of the face panel increases, and the structural bending stiffness is enhanced. This enhancement causes the resonance dip near 100 Hz to shift to the right, thereby elevating the STL in the low-frequency band (40 Hz–100 Hz). Furthermore, as presented in Table 6, the weighted sound reduction index (R_w) exhibits a steady, monotonically increasing trend (49 dB, 50 dB, and 55 dB), while the spectrum adaptation terms (C and C_{tr}) remain relatively stable. Consequently, the comprehensive sound insulation performance of the structure achieves a linear and consistent improvement as the core becomes thinner.

For the CC boundary condition, the strong constraints on displacement and rotation significantly enhance the global stiffness of the structure. This directly dominates the acoustic response in the low-frequency band, resulting in highly similar STL values across different core layer thickness configurations, which approach the STL of the SCP. In this regime, the STL in the low-to-mid frequency range is primarily governed by the “mass-spring-mass” out-of-phase motion mechanism of the double face panels, and the appearance of a resonance dip is induced by the out-of-phase coupled resonance of the panels. However, unlike the SS boundary condition, the STL curves for varying core thicknesses under the CC boundary condition do not exhibit a simple monotonic trend as the core layer becomes thinner. Particularly in the mid-to-high frequency bands, the curves for the $d = 60$ mm and $d = 80$ mm cases display pronounced intersections and localized peak-and-dip fluctuations. This indicates that the core layer thickness not only alters the areal density and equivalent bending stiffness of the structure, but also triggers a redistribution of the structural modal frequencies, inter-panel coupled vibrations, and local resonance characteristics.

Regarding the weighted sound reduction index (R_w), under the CC boundary condition, the R_w of the ICSPs continues to exhibit a decreasing trend with increasing core layer

thickness; however, the variations in the spectrum adaptation terms are not strictly monotonic. Specifically, the C and C_{tr} values for the $d = 60$ mm case are -9 dB and -11 dB, respectively, which are lower than those for the $d = 80$ mm case (-5 dB and -8 dB). This indicates that, although the R_w at $d = 60$ mm is slightly higher than that at $d = 80$ mm, its STL dips fall within frequency bands to which the spectrum adaptation terms are highly sensitive. Consequently, when practical noise spectrum adaptations are considered, its comprehensive sound insulation performance actually deteriorates. Therefore, the irregular variations in the sound insulation performance of the sandwich panels under the CC boundary condition stem primarily from modal redistribution and resonance frequency shifts induced by thickness variations, rather than a pure mass effect.

In summary, the sound transmission characteristics of the sandwich panels are jointly dictated by the core layer thickness and boundary conditions. Under the SS boundary condition, the sound insulation performance exhibits strong regularity with respect to core layer thickness variations, where the weighted sound reduction index (R_w) demonstrates a monotonically decreasing trend. Conversely, under the CC boundary condition, the rigid constraints on edge displacement and rotation render the structural modes and inter-panel coupled vibrations highly sensitive to thickness variations. This results in pronounced intersections and non-monotonic fluctuations in the STL curves across different thickness configurations within specific frequency bands. Consequently, in the acoustic optimization design of ICSPs, their sound insulation performance cannot be reliably predicted based solely on core layer thickness or areal density. Instead, a comprehensive consideration of boundary conditions, structural modes, inter-panel coupling, and spectrum adaptation terms is indispensable for an accurate acoustic evaluation.

It should be emphasized that the above conclusion is obtained under the assumption that the total thickness of the ICSP remains constant. In this case, reducing the thickness of the core layer will simultaneously increase the thickness, mass, and flexural rigidity of the concrete interlayer, thereby contributing to improved acoustic performance, but may lead to weaker thermal insulation performance of the structure. Therefore, a thinner core layer should not be interpreted as a general optimization strategy for ICSP design. In practical engineering applications, the core thickness should be determined by balancing sound insulation, thermal insulation, structural weight, load-bearing capacity, and construction requirements.

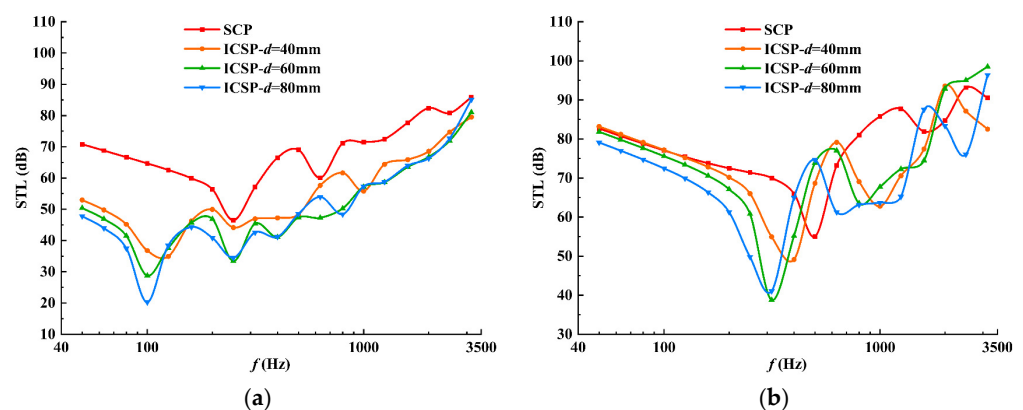


Figure 9. Comparison of STL with different core layer thicknesses. (a) SS boundary condition; (b) CC boundary condition.

Table 6. Comparison of R_w .

Type	SS- R_w (C; C_{tr}) (dB)	CC- R_w (C; C_{tr}) (dB)
SCP	67 (−4; −7)	75 (−7; −9)
ICSP- $d = 40$ mm	55 (−1; −5)	66 (−3; −5)
ICSP- $d = 60$ mm	50 (−2; −6)	64 (−9; −11)
ICSP- $d = 80$ mm	49 (−3; −10)	62 (−5; −8)

5. Discussion

5.1. Comparison with Previous Studies and Limitations

As shown in Table 7, the results show that the airborne sound insulation of finite-sized ICSPs is controlled by the combined effects of concrete wythe mass and stiffness, connector-induced coupling, boundary constraints, and modal characteristics. Unlike conventional lightweight sandwich or double-leaf panels, finite-sized ICSPs contain massive concrete wythes and practical edge restraints, making their acoustic behavior difficult to evaluate using only the mass law or idealized infinite-panel assumptions. The main contribution of this study is therefore the development and validation of a finite-sized analytical framework for predicting the STL and R_w of ICSPs. Nevertheless, the proposed model is still based on Kirchhoff thin-plate theory and equivalent descriptions of the insulation layer and connectors; thus, shear deformation, local three-dimensional connector behavior, frequency-dependent material properties, and imperfect elastic boundary restraints require further investigation. In addition, acoustic optimization should be balanced with thermal insulation, structural weight, and construction feasibility in practical design.

Table 7. Summary comparison between this study and previous works.

Aspect	Comparison with Previous Works
Originality	This study focuses on finite-sized ICSPs, whereas many previous works focused on lightweight sandwich panels, double-leaf panels, or infinite/idealized structures.
Relevance	The model considers concrete wythes, insulation cores, connectors, and boundary constraints, which are directly related to building applications.
Novelty	The effects of connector stiffness, boundary condition, and core layer thickness are systematically incorporated into the STL and R_w prediction of ICSPs.
Advantages	The sound insulation performance of the structure can be predicted by analyzing the model.
Disadvantages	The analytical model is based on Kirchhoff's thin-plate theory, without considering the influence of shear components.
Risks	Not considering the thermal insulation performance comprehensively.
Limitations	Only applicable to SS and CC boundary conditions; unable to handle more complex boundary conditions.

5.2. Engineering Implications

The proposed model can support the acoustic design of ICSPs over the main stages of a construction project. In the design stage, it can be used to preliminarily evaluate the effects of connector stiffness, boundary condition, and core layer thickness on STL and R_w before detailed FE simulations or laboratory tests are conducted. In the component production stage, the results can guide the selection of connector type, connector stiffness, insulation thickness, and concrete wythe thickness. In the construction and installation stage, the findings highlight the importance of edge restraints and joint sealing, since boundary conditions have a significant influence on the sound insulation performance of finite-sized ICSPs. In the operation and maintenance stage, the model can help identify whether insufficient acoustic performance is mainly related to weak boundary constraints,

inappropriate connector stiffness, or unfavorable panel resonance. Therefore, the results provide practical guidance for the acoustic optimization, quality control, and performance evaluation of ICSPs in prefabricated buildings.

6. Conclusions

In this paper, a finite-size analytical model for the sound transmission loss of ICSPs is derived by extending the existing vibro-acoustic formulation and incorporating SS and CC boundary conditions. Subsequently, the analytical model is utilized to conduct a parametric analysis, wherein the sound insulation performance of the ICSPs in a diffuse sound field is evaluated via the weighted sound reduction index (R_w). The principal conclusions are drawn as follows:

6.1. Scientific Findings

- (1) An analytical model for the sound transmission loss of finite-sized ICSPs is established by incorporating the modal functions associated with SS and CC boundary conditions, the elastodynamic interaction forces of the insulation material and connectors, and the acoustic–structure coupling conditions on both sides of the panel.
- (2) The results of the analytical model exhibit agreement with numerical results from a 3D acoustic-structure coupled FE model, successfully capturing the structural responses across both low-frequency global bending and mid-to-high-frequency local resonance regimes. Furthermore, an airborne sound insulation experiment conducted on an actual ICSP specimen verifies the theoretical model trends, particularly when evaluated comprehensively using the R_w and spectrum adaptation terms. This multi-tiered verification demonstrates that the proposed analytical model is applicable for evaluating the sound insulation performance of finite-sized ICSPs.
- (3) The effects of connector stiffness, boundary conditions, and core layer thickness on the sound insulation performance are systematically analyzed. Increasing the connector stiffness can improve the STL in the low-frequency band. However, due to the “acoustic bridging” effect, the sound insulation performance in the mid-to-high frequency bands decreases. Overall, the comprehensive sound insulation performance initially decreases and subsequently increases; once the stiffness becomes sufficiently large, the sound insulation effect tends to stabilize. And stronger boundary constraints yield superior sound insulation performance. Additionally, the influence of the core layer thickness is closely related to the boundary conditions. Under the SS boundary condition, reducing the core layer thickness can gradually improve the sound insulation performance; under the CC boundary condition, thickness variations induce modal redistribution, making the sound insulation performance more sensitive to the inter-panel coupled vibrations, which leads to non-monotonic fluctuations in the overall sound insulation performance. However, regardless of the boundary conditions, it is important to note that reducing the core layer thickness means a reduction in the insulation material alongside an increase in the concrete mass. Therefore, any acoustic improvement achieved through this approach must be carefully weighed against the inevitable degradation in thermal insulation performance and the increase in structural self-weight in practical engineering design.
- (4) Although the sound insulation performance of ICSPs is inferior to that of SCPs, it can significantly surpass the requirements of national standards and codes through optimized design. In particular, under the CC boundary condition, the sound insulation of ICSPs approaches that of SCPs within certain frequency bands. This demonstrates that rational design optimization can enable the sound insulation performance of ICSPs to approach, or even exceed, that of SCPs.

6.2. Engineering Applications

The proposed model can be used as a preliminary acoustic design tool for ICSPs in prefabricated buildings. It can help engineers evaluate the effects of connector stiffness, boundary constraint, and core layer thickness before detailed FE simulations or laboratory tests are conducted.

For practical applications, improving boundary constraints and avoiding excessively stiff acoustic bridging are effective strategies for enhancing the sound insulation performance of finite-sized ICSPs. However, acoustic optimization should be coordinated with thermal insulation, structural safety, component weight, and construction feasibility.

6.3. Future Work

Future work will focus on three aspects. First, the analytical model will be extended by incorporating shear deformation and frequency-dependent material properties to improve its accuracy in the mid- and high-frequency ranges. Second, by optimizing the shape and material of the connectors, a new type of connector will be proposed to reduce the “acoustic bridging” effect and improve the overall sound insulation performance of the structure. Third, the proposed model will be further combined with multi-objective optimization to balance acoustic insulation, thermal performance, structural safety, component weight, and construction feasibility. These extensions will support the integrated acoustic–thermal–structural design and practical implementation of ICSPs in prefabricated buildings.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Nomenclature of the main symbols used in the analytical model.

Symbol	Definition	Symbol	Definition
a, b	Length and width of the ICSP	k_x, k_y, k_z	Acoustic wave number components in the x -, y -, and z -directions
H	Total thickness of the ICSP	k_m, k_n	Modal wave numbers for the SS boundary condition
h_1, h_2	Thicknesses of panel 1 and panel 2	α_m, β_n	Modal wave numbers for CC boundary condition
d	Core thickness (clear spacing between the two concrete panels)	θ, φ	Elevation and azimuthal angles of the incident wave
C	Abbreviation for connectors	$\phi_{SS,mn}$	Modal function under the SS boundary condition

IM	Abbreviation for insulated material	$\phi_{CC,mm}$	Modal function under the CC boundary condition
t_c	Thickness of plate-type connectors	$W_{1,mm}, W_{2,mm}$	Modal amplitudes of panels 1 and 2
L	Spacing between adjacent connectors	Φ_{IM}, Φ_C	Displacement potential function of the insulation material and connectors
x_j	Center position of the j -th connector along the x -axis	λ_{IM}, G_{IM}	Lamé constant and shear modulus of the insulation material
w_1, w_2	Transverse displacements of panel 1 and panel 2	λ_C, G_C	Lamé constant and shear modulus of the connectors
$E_\ell, \nu_\ell, \eta_\ell$	Young's modulus, Poisson's ratio, and loss factor of panel ℓ	I_{mp,x_j}	The integral result of the Heaviside function
D_ℓ	Bending stiffness of panel ℓ	$P_{SS,mm}, P_{CC,mm}$	the projection of the incident sound pressure onto the modal space under the SS and CC boundary conditions
p_1, p_2	Sound pressures on the incident and transmitted sides	$k_1, k_{2,mm}$	The wave number in the z -direction of IM and connectors under the SS boundary condition
$F_{IM,z1}, F_{IM,z2}$	Normal interaction forces exerted by the insulation material on panels 1 and 2	$k_{z,s}$	The wave number in the z -direction of the connectors under the CC boundary condition
$F_{C,z1}, F_{C,z2}$	Normal interaction forces exerted by the connectors on panels 1 and 2	W_i, W_t	Incident and transmitted acoustic powers
$K_{C,t}$	Translational stiffness of discrete connectors	τ	Sound transmission coefficient
m_C	Half mass of a discrete connector	STL	Sound transmission loss
k_0	Acoustic wave number in air	R_w, C, C_{tr}	Weighted sound reduction index and spectrum adaptation terms

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