

Article

Effects of Periodic Materials on Distance Attenuation in Wall–Slab Structures: An Experiment

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Abstract: This research examines the application of periodic materials in wall–slab structures to mitigate impact noise and vibration propagation, a prevalent issue in multifamily housing. Traditional methods, such as floating floors, have proven insufficient in addressing low-frequency impact noises and in facilitating the identification of noise origins, leading to increased resident annoyance. Periodic materials, known for their effectiveness in controlling plane waves in civil engineering, were applied to the intermediate slab of a wall–slab experimental setup. The research involved assessing the attenuation of noise and vibration over distance before and after the application of periodic materials by measuring indoor sound pressure levels and the natural vibration amplitude of the structure’s members upon impact. The results showed that periodic materials not only facilitated distance attenuation but also significantly diminished noise and vibration throughout the structure, without the side effects of vibration amplification seen in prior civil engineering applications. This indicates a practical advancement in using these materials, offering a novel approach to sound insulation and enabling more precise impact source localization. Ultimately, this study contributes to improving urban living by suggesting a method to enhance acoustic comfort in multifamily housing, underlining the importance of further exploration in architectural applications of periodic materials.



Citation: Cho, J.; Song, K.; Kwon, N.; Park, M.; Kim, T.W. Effects of Periodic Materials on Distance Attenuation in Wall–Slab Structures: An Experiment. *Buildings* **2024**, *14*, 694. <https://doi.org/10.3390/buildings14030694>

Academic Editor: Cinzia Buratti

Received: 4 February 2024

Revised: 25 February 2024

Accepted: 29 February 2024

Published: 5 March 2024



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Keywords: periodic materials; impact noise insulation; distance attenuation; wall–slab structure; noise source localization

1. Introduction

Among the various noises generated in urban areas, neighbor noises in multifamily housing become a primary issue as the acoustic requirements in residences rise [1–3]. Notably, floor impact noises (e.g., noises stem from walking, running, and moving furniture) are key detractors of acoustic comfort, with reports indicating that such noises are the main cause of noise complaints in densely populated areas [4,5]. In areas where the city saturation has rapidly progressed, multifamily housing adopting wall–slab systems are popular for their ability to provide more housing units vertically and fewer floor plan irregularities [6]. However, wall–slab system buildings, which are mainly supported by shear walls, are believed to have lower floor impact noise insulation compared to the Rahmen system, which consists of columns and beams, as they allow bending waves generated by floor impacts to transmit through integrated interior walls. The findings of [7,8] show that about half of the noise energy in a room surrounded by concrete plates comes from flanking transmission via walls and slabs not directly impacted by the source support this fact.

Due to the characteristic of having many walls that act as mediums for vibration transmission, the vulnerability to noise in wall–slab buildings includes not only the issue of noise level but also the problem related to the propagation of noise, which makes it difficult to locate the source of the noise. For residents of multifamily housing, relieving acoustic annoyance through dialogue with noise-producing residents is challenging when the noise source remains unidentified [9]. The consistent social demand to identify the noise source in areas heavily supplied with wall–slab multifamily housing implies a need for attention to the propagation of floor impacts [10,11].

Indeed, if the vibration induced by the impacts from daily activities can be sufficiently isolated, the vulnerability of wall–slab structures to the propagation of floor impacts might not be significantly highlighted. The floating floor system is a common vibration isolation method used for sound insulation against floor impacts [12,13]. It features a resilient layer placed between the walking surface and the structural slab, which plays a significant role in dampening vibrations [4]. However, recent studies indicate that the floating floor approach encounters limitations in attenuating floor impact noises below 100 Hz, such as heavy impacts from footsteps or children running and jumping, which is crucial in residential noise annoyance control [14,15].

Therefore, exploring alternative methods to reduce the propagation of vibration over distance is key to enhancing residential acoustic comfort. One promising option is the use of periodic materials, a type of metamaterial designed to block or reduce wave propagation and vibration based on periodic theory [16,17]. The materials which have periodic structure with an elastic modulus and mass density modulated show great potential in suppressing vibrations in civil structures and isolating seismic vibrations [18–20]. However, their application in residential buildings has seen limited research, largely due to the structural modifications required in their implementation [6,21]. In the study exploring the application of periodic materials in residential buildings [21], the methodology was confined to affixing fabricated specimens to existing building slabs and assessing their effectiveness in reducing impact noise and vibrations. Therefore, studies focusing on their attenuation efficiency over distance are even scarcer, pointing to an area needing further exploration.

The primary objective of this research is to enhance understanding of the application effects of innovative periodic materials in wall–slab structures, particularly focusing on distance attenuation. This research adopts an experimental approach, retrofitting periodic materials onto existing structures to evaluate improvements in vibration and noise insulation. Such a method allows for an intuitive assessment of the improvements brought by periodic materials and their compatibility with current construction practices.

The first phase of this research explores rebar construction methods in wall–slab structures. After examining structural design guidelines, this research identifies conditions under which periodic materials can be effectively applied. An experimental structure meeting these criteria is then selected for in-depth examination of its natural vibration and noise insulation characteristics. The natural vibration frequencies are investigated using the frequency response function. Also, attention in this research is given to the attenuation of heavy impacts, typically generating noise and vibrations below 100 Hz. To simulate such impacts, rubber ball excitations, as recommended by the International Organization for Standardization, are employed to replicate noises similar to those caused by barefoot walking or children jumping.

Subsequently, this research progresses to the installation of periodic materials within the experimental structure and reassessing its vibrational characteristics and noise insulation performance. The final stage of the study compares the findings before and after applying periodic materials. This comparison not only focuses on distance attenuations and difference reversals but also includes a juxtaposition with a typical wall–slab multifamily housing scenario. Furthermore, the discussion extends to examining the potential role of periodic materials in localizing the source of impact noises.

2. Literature Review

2.1. Distance Attenuation of Vibration in Wall–Slab Structure

The issue of vibration propagation in wall–slab multifamily housing, which significantly affects acoustic comfort and complicates identifying impact-generating units, has not been as extensively explored as needed. Study [7] noted that in wall–slab buildings with floating floors, approximately a 50.7% to 66.0% portion of sound originates from the ceiling when heavy impacts excite the slab above. The reverse finding that about half of the noise originated from vibrations in members other than the ceiling indicates that the vibrations induced by floor impacts are not sufficiently isolated.

In a structure composed of two combined boxes, the propagation of in-plane waves due to excitation slows down as it passes through the junction where two plates intersect. This phenomenon, known as junction attenuation, is defined as the difference in wave velocity between two adjacent plates [8,22]. This effect has been empirically proven by [23,24], and aligns well with observations in concrete student accommodations where unit boxes are arranged along one side of a corridor [25]. However, in more complex wall–slab multifamily housing, the attenuation effect diminishes or becomes less perceptible with increasing distance from the impact source [9].

There is a referenceable argument that can be linked to the weakened junction attenuation observed in wall–slab structures. Study [26] claims that in situ measurements often include unintended flanking transmission from higher-order paths, which contrasts with the first-order paths considered in isolated junctions. This finding suggests that in complex structures with multiple cellular units, the prevalence of multiple flanking paths significantly influences noise and vibration transmission. In contrast to the clear directionality of environmental vibrations, where the path from the source to the structure is straightforward, wall–slab structures present a more complicated scenario. In these structures, junction attenuation occurs due to the vertical intersection of transmission mediums, and the presence of multiple flanking paths further complicates the transmission of vibrations. As a result, the anticipated distinct distance attenuation of vibrations in wall–slab structures is obscured, posing challenges in identifying ambiguous impact sources and effectively managing noise and vibration control.

2.2. Noise and Vibration Control Methods

For controlling floor impact noises in multifamily housing, floating floor structures have been widely used [27,28]. Floating floors, which comprise rigid walking surfaces decoupled from the surrounding structure by resilient layers, have a high potential for reducing disturbances due to impact noises in dwellings [4,29]. Thanks to the efforts of many researchers [30–32], it has been sufficiently proven that the sound insulation performance of the floating floor improves with a higher density of the walking surface, lower dynamic stiffness of the resilient layer, and suppression of the system's natural vibration at lower frequencies. In particular, floating floors have become widely used due to their effectiveness in insulating the noise induced by hard and light impacts such as high heels footsteps.

However, these improvements have been observed to be effective primarily in a frequency range above 100 Hz, but less so for lower frequency noises below 100 Hz [14,33]. The issue is that these low-frequency noises are often generated by heavy impacts, such as barefoot footsteps or children running and are a major cause of noise annoyance in multifamily residences, especially in cultures where activities are typically conducted barefoot [32]. It has even been reported that the installation of floating floors can sometimes amplify these low-frequency sounds [6,21].

Therefore, to address these challenges, efforts have been directed towards altering floor plan configurations [14] and exploring alternative types of structures [6,15] and floating floors [4]. One innovative approach in this exploration is the use of periodic materials, which are emerging as a viable option for absorbing in-plane waves. Periodic materials, also termed banded materials or phononic crystals, are composite materials characterized

by a geometrically repeated layout [17,19,34]. Their design, which involves modulation of elastic modulus and mass density, is tailored to either obstruct wave propagation or reduce vibrations. The Bragg scattering approach employs unit cells, each with a central scatter, aligned in a consistent grid pattern. This configuration triggers Bragg resonance, a phenomenon that occurs when the arrangement leads to interference between incoming and reflected waves [16]. Such interference effectively creates frequency-specific attenuation zones, where wave transmission is disrupted, depending on the spacing and intrinsic properties of the material used.

To control environmental vibrations caused by earthquakes, train movements, and machinery operations, passive vibration control techniques such as trench walls and pile barriers are commonly used in civil engineering [35]. Among these, pile barriers, which install piles in a periodic layout, employ the Bragg scattering approach. Ref. [36] conducted research on the attenuation of plane waves passing through multiple rows of concrete piles in single-phase soil. This study verified the attenuation of plane waves under harmonic vibrations of constant frequency, demonstrating that an increased number of rows in a periodic arrangement leads to more effective vibration attenuation. Ref. [37] presented results focusing on the distance attenuation effect, which was not the primary focus of [36]. It was observed that the vibration amplitude decreases with increasing distance behind three rows of periodic piles, reducing the vibration magnitude to as low as 0.33 compared to states without installation.

With advancements in precision manufacturing technologies, such as 3D printing, research on complex shape design, including locally resonant materials, has progressed, allowing for more intricate control of wave motion [38]. Locally resonant material features unit cells that house individual resonators, each able to oscillate independently of the structure. These resonators absorb energy from waves that match their resonant frequencies, effectively reducing wave propagation [38,39]. Ref. [21] developed a type of locally resonant material and applied these fabricated specimens onto existing building slabs, testing their efficiency in mitigating impact noise and vibrations. Despite the established properties of periodic materials, their application in multifamily housing has not only been infrequently attempted, but also the improvement effects of replacing entire slab with periodic materials, beyond just attaching them to existing members, have not been empirically confirmed. Table 1 summarizes the major studies regarding the noise and vibration control method mentioned above. As confirmed in Table 1, there exists a significant research gap regarding the potential of periodic materials in wall–slab structural environments. This gap underscores the necessity for thorough research that extends beyond assessing material effectiveness in confined spaces to also include a focus on the broader implications of vibration propagation and distance attenuation.

Table 1. Studies on noise and vibration control methods.

Ref.	Research Contents	Control Method	Excitation Source	Controlling Subjects
[37]	Periodic pile structure for reducing ground vibration through theoretical modeling and parametric study, including the contour of the amplitude attenuation ratio	- Periodic materials (B^{-1})	Harmonic plane waves	- Distance attenuation of vibrations
[27]	Correlation between dynamic stiffness in resilient materials of floating floor and heavyweight impact sound reduction level	- Floating floors	Bang machine	- Sound level (R^{-3})

Table 1. Cont.

Ref.	Research Contents	Control Method	Excitation Source	Controlling Subjects
[33]	Low-frequency impact sound transmission in residential floors, with a focus on floor and room acoustic properties	- Floating floors - Junction states	Impact hammer	- Structural modes (F ⁴) - Acoustic modes (R)
[16]	Vibration attenuation properties of periodic rubber concrete panels, parameter investigations of Bragg scattering and Local resonant periodic panels	- Periodic materials (B and L ²)	Harmonic plane waves	- Frequency attenuation zones
[36]	Wave propagation attenuation in fluid-saturated soils using periodic pile barriers, with a study on the system's physical and geometric parameters	- Periodic materials (B)	Harmonic plane waves	- Frequency attenuation zones
[6]	Impact of the types of reinforced concrete structures on low-frequency heavy impact sound in residential buildings with floating floors	- Structural types - Gross floor area	Bang machine	- Structural modes (F) - Acoustic modes (R)
[14]	Influence of plan configurations on the low-frequency vibroacoustic behavior of floating floors, focusing on structural–acoustic modal coupling and its impact on sound insulation	- Plan shape	Rubber ball	- Vibration level (F) - Sound level (R)
[4]	Performance of heavy-impact sound insulation in floating floors with principal component regression for various floor types	- Floating floors	Rubber ball	- Sound level (R)
[21]	Low-frequency impact sound and vibration reduction of locally resonant periodic materials applied to floating floors in buildings	- Periodic materials (L)	Rubber ball	- Vibration level (F) - Sound level (R)

Note: ¹ Bragg scattering approach, ² Local resonant approach, ³ Room beneath the impacted floor, ⁴ Floor impacted.

3. Experimental Design

3.1. Experimental Structure and Periodic Material Applications

To observe the attenuation of vibrations in accordance with distance, the experimental environment required a wall–slab structure with at least two adjacent rooms. Therefore, a two-story experimental structure composed of concrete in a wall–slab configuration is prepared.

The experiment is structured as follows: (1) Construct the experimental structure in its baseline state. (2) Measure the noise and vibration responses of the structure in this baseline state. (3) Apply periodic material to the structure, transitioning it to the treated state. (4) Measure the changed noise and vibration responses of the structure in its treated state. Figure 1 illustrates the sequential steps of constructing the experimental structure in both the baseline and treated states, and the application of periodic material. Table 2 provides the specification of these stages.

The configuration of the experimental structure shown in Figure 1a takes into consideration the characteristics of the unit rooms in typical Korean wall–slab multifamily housing and the standard slab thickness [40]. This structure consists of two rooms adjoined vertically, each with a floor area of 3000 × 4000 mm and a height of 3000 mm, sharing a 210 mm slab as both the floor for the upper room and the ceiling for the lower room.

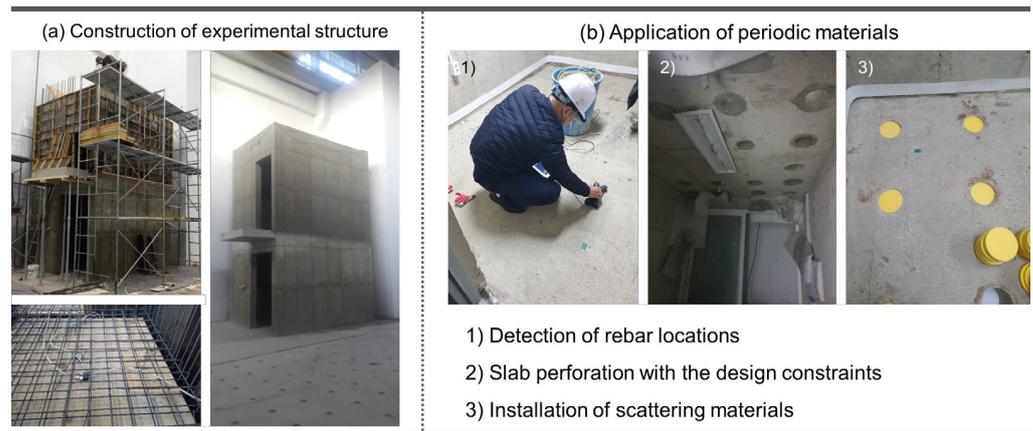


Figure 1. Construction process of experimental environment.

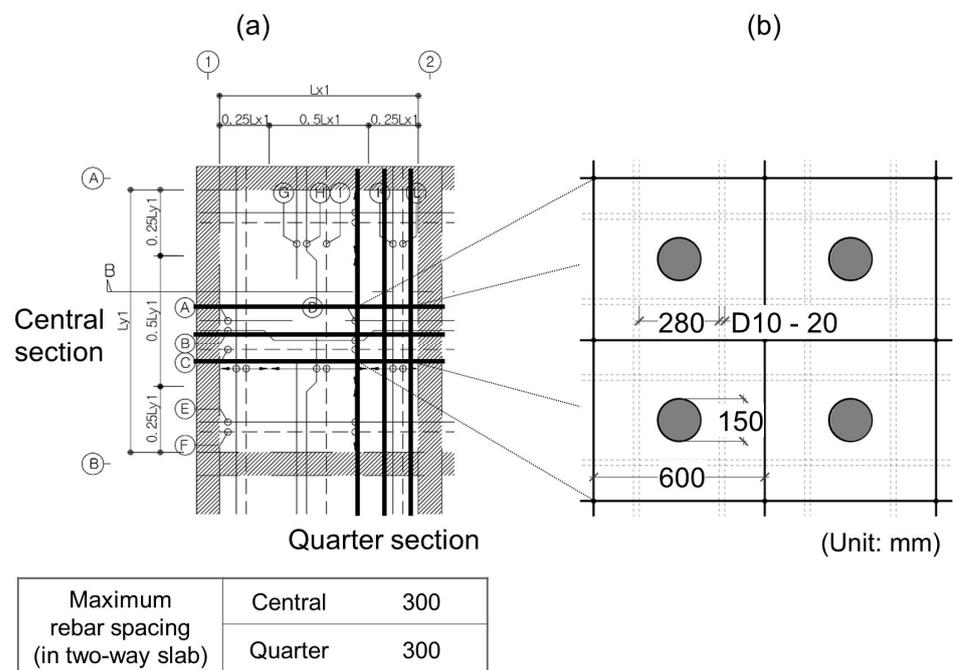


Figure 2. (a) Rebar spacing constraints of experimental structure (top view), and (b) planned unit cell configuration based on the constraints.

Table 2. Detailed specification of experimental environment.

Classification	Detailed Specification	
Construction of the experimental structure (Figure 1a)	- Two-story wall–slab structure	
	- Total size	3.0(x) × 4.0(y) × 6.9(h)m
	- Density (ρ)	2.450 kg/m ³
	- Elastic modulus (E)	2.5×10^{10} N/m ²
Application of periodic materials (Figures 1b and 2)	- Unit cell size	600 × 600 mm
	- Installed scattering materials	
	- Layout (intermediate slab)	4 × 6 EA (Ø150 mm)
	- Density (ρ)	200 kg/m ³
	- Dynamic modulus (s')	40 MN/m ³

The in-plane wave control characteristics of the Bragg-scattering-type periodic materials consisting of repetitive unit cells have been theoretically addressed and validated in controlled experimental environments. A unit cell is comprised of a combination of two or more materials with distinct properties, such as elastic modulus and density. When the unit cell consists of two types of materials, the primary material is referred to as the matrix, and the material within it is called scattering material [18]. The geometry of a unit cell can be designed in either symmetric or non-symmetric configurations. However, symmetric configurations are preferred for more effective control of in-plane waves [16]. Also, from a perspective of the arrangement of unit cells, [36,41] suggest using a minimum of four-unit cells in one dimension to achieve a significant wave-blocking effect.

Based on these findings, this research operates under the assumption that Bragg-scattering-type periodic materials are effective in attenuating in-plane waves. The primary focus here is on the improvement effects observed when the entire slab is replaced with a structure that incorporates these periodic materials. Thus, the treatments of this experimental design are devised with an emphasis on construction constraints, integrating insights from precedent studies on geometric and material properties [16,18,36,41].

To integrate scattering material into the existing structure, it is necessary to perforate the concrete plate. However, perforating the walls from within the structure posed significant challenges due to safety concerns with temporary works and the difficulty of manually lifting boring equipment in cramped spaces. As a result, the installation of periodic materials in the experimental structure was confined to the slab. This limitation to the slab not only addresses safety and logistical concerns but also simplifies the process, making it easier to assess the improvement effects of the periodic material.

Current structural design standards for concrete slabs [42], which the experimental structure follows, require reinforcing bars in openings corresponding to the cut area of slabs. However, if main rebars are not cut and the cutting length is less than 300 mm, additional reinforcement is deemed unnecessary. Consequently, when installing scattering material, openings exceeding 300 mm in length reduce the cost-effectiveness of applying periodic materials.

The experimental structure's slab, with a length ratio of long to short sides of 1.3 (3000 mm to 4000 mm), falls under the category of a two-way slab, where the load is distributed in both directions. Therefore, the uniform spacing between rebar at the quarter sections and the central section of the slab allows for the seamless application of a symmetric unit cell pattern without the need for cutting the rebar, as shown in Figure 2a.

For the experimental structure's slab, rebars with diameters ranging from 10 to 20 mm were used, spaced at intervals of less than 300 mm. To accommodate construction errors, the scattering material was sized at 150 mm in diameter. Considering the rebar spacing constraints of this experimental structure and the requirement for arranging more than four-unit cells in one direction, as illustrated in Figure 2b, unit cells with dimensions of 600 × 600 mm, where one scattering material is placed per two rebar grids, are planned to be positioned in a 4 × 6 array. Consequently, as shown in Table 2, concrete with an elastic modulus of 2.5×10^{10} N/m² and a density of 2450 kg/m³ forms the matrix, while polyurethane with a dynamic modulus of 40 MN/m³ and a density of 200 kg/m³ is used as the scattering material, shaped into cylinders matching the slab thickness (i.e., 210 mm).

To install scattering material in the pre-constructed experimental structure, slab perforation is necessary. Due to practical constraints, reinforcing the rebars within the slab is not feasible. Therefore, rebar locations are identified using a detector to avoid cutting them during perforation. The middle floor slab is then perforated at predetermined points for scattering material installation, as outlined in the unit cell arrangement plan. Scattering materials are inserted into these holes to match the slab's thickness, following the process of Figure 1b.

3.2. Data Collection and Analysis

The experimental design, as outlined in Table 2, encompasses a comprehensive investigation of sound and vibration responses, conducted in two distinct phases. Initially, the experimental structure undergoes a baseline assessment to gauge its sound and vibration responses prior to the application of periodic materials. The measurements of this phase establish a reference point for subsequent comparisons. Subsequently, upon the integration of periodic materials, a second set of measurements is carried out employing identical methodologies. This ensures consistency and reliability in the comparative analysis.

A pivotal aspect of this research is the evaluation of distance attenuation, specifically analyzing how the noise and vibration responses vary at different proximities to the excitation source. To achieve a comprehensive understanding, measurements are taken in rooms located on both the first and second floors, while the roof slab is subjected to repeated impacts. This approach aims to provide insights into the efficacy of the periodic materials in modifying the propagation of sound and vibrations within the structure, thereby contributing significantly to the field of noise and vibration control in architectural environments.

Figure 3 illustrates a schematic of the experimental structure's cross-section, depicting the vertical arrangement of exciters and sensors for sound and vibration response data collection. Also, Table 3 summarizes the detailed methods for data collection and analyses. The sound response data collection process is conducted in accordance with the measurement procedures for impact sound insulation set by the International Organization for Standardization [40]. This involves generating impacts on the roof slab using a rubber ball, while simultaneously capturing sound pressure levels (*SPL*) with microphones located in rooms on both the first and second floors. The impact generation by the rubber ball is executed at five points across the roof slab, with the doors of the experimental structure closed. These points include a central impact location, complemented by four additional points, each situated 0.7 m from the edges of the slab. In a similar vein of precision, microphones are placed in the receiving rooms at four specific spots. Each microphone is positioned 0.7 m away from the walls and at a height of 1 m, a placement designed to avoid any aberrant measurements that might occur near the edges of the rooms. The measured fast time-weighted maximum *SPL*, $L_{i,Fmax}$, typically ranges from 50 to 630 Hz. The measurements, k , obtained from each microphone through a 1/3 octave band filter were then averaged using Equation (1):

$$L_{i,Fmax} = 10 \lg \frac{1}{n} \sum_{k=1}^n 10^{L_{Fmax,k}/10} \text{ (dB)} \quad (1)$$

The analysis also incorporated single numerical rating values, denoted as $L'_{i,Fmax,AW}$ [41]. These values represent a transformation of the *SPL* obtained from each 1/3 octave band into a singular, comprehensive figure, facilitating a more streamlined and informative comparison.

The collection of vibration response data commences with excitations generated by an impulse hammer. Similar to sound response, the excitation occurs on the roof slab, with the acceleration levels being measured on the surrounding members of the rooms on both the first and second floors. As depicted in the right cross-section of Figure 3, the measurement of acceleration levels takes place at four points in each room: the center of the ceiling, the floor, and both side walls. Each sensor at the measurement points is labeled for identification, as denoted in Figure 3. The acceleration (k), measured in m/s^2 , is expressed in decibel units (L) using a reference value of 10^{-5} m/s^2 through the following conversion:

$$L = 20 \cdot \lg \left(\frac{k}{10^{-5}} \right) \text{ (dB)} \quad (2)$$

The collection of vibration responses is conducted using a signal analyzer capable of simultaneous acquisition of excitation and measurement signals. The analyzer's built-in

transfer function feature facilitates the computation of the frequency response function (FRF). This allows for the determination of the system's eigenfrequencies between the excitation and measurement points. The analysis utilizes the average acceleration level's eigenfrequencies, derived from ten excitations at each measurement point, as the data for vibration response.

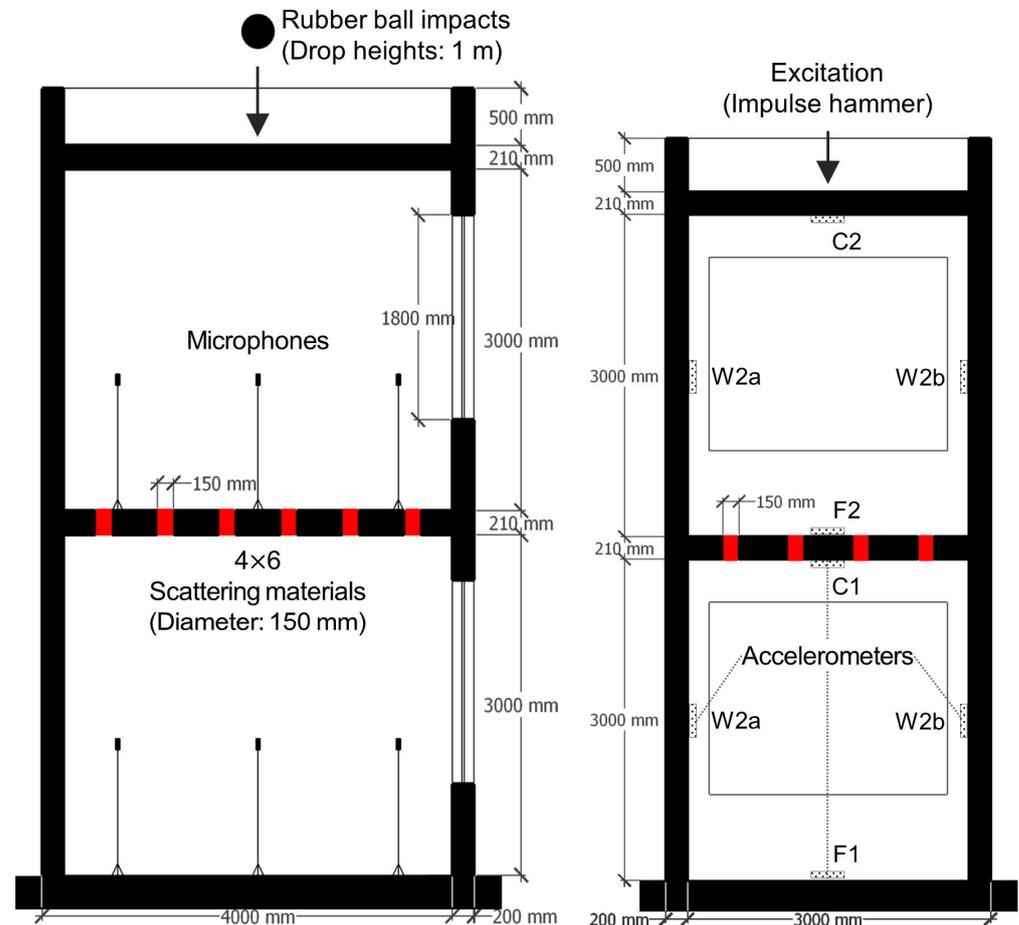


Figure 3. Vertical arrangement of exciters and sensors in experimental structure for data collection.

Table 3. Description of data collection and analysis methods.

Measurement Classification	Detailed Description		
Sound responses	-	Impact source	Rubber ball [43]
	-	Measuring sensors	Microphones
	-	Measured values	Sound pressure levels (dB)
	-	Analysis methods	Averaged FFT (1/3 octave band), $L'_{i,Fmax,AW}$ [44]
Vibration responses	-	Impact source	Impulse hammer
	-	Measuring sensors	Accelerometers
	-	Measured values	Acceleration levels (dB)
	-	Analysis methods	Averaged FFT + Transfer FRF, OA [7]

Analogous to the $L_{i,Fmax,AW}$ value in sound response analysis, the Overall Amplitudes (OA), is employed, which represents the power sum of the total magnitude of a system's vibration encompassing all contributing frequencies and modes. This approach of singular numerical representation of vibration response, also employed in [7], facilitates a more straightforward and informative comparison.

4. Experimental Results

4.1. Changes in Distance Attenuation of Sound Responses

The analysis of the experimental results of periodic material applications commences by assessing the changes in sound responses of the experimental structure. Figure 4 elucidates the modifications in *SPL* within rooms on the first and second floors induced by rubber ball impacts on the roof slab. Measurements are visualized through contrasting lines, with the lighter gray indicating the results prior to the implementation of periodic materials and the darker lines delineating the post-application results. Figure 4 provides a detailed representation of the average $L_{i,Fmax}$ for each 1/3 octave band in the rooms on both floors, while also explicitly illustrating the attenuation of sound with distance.

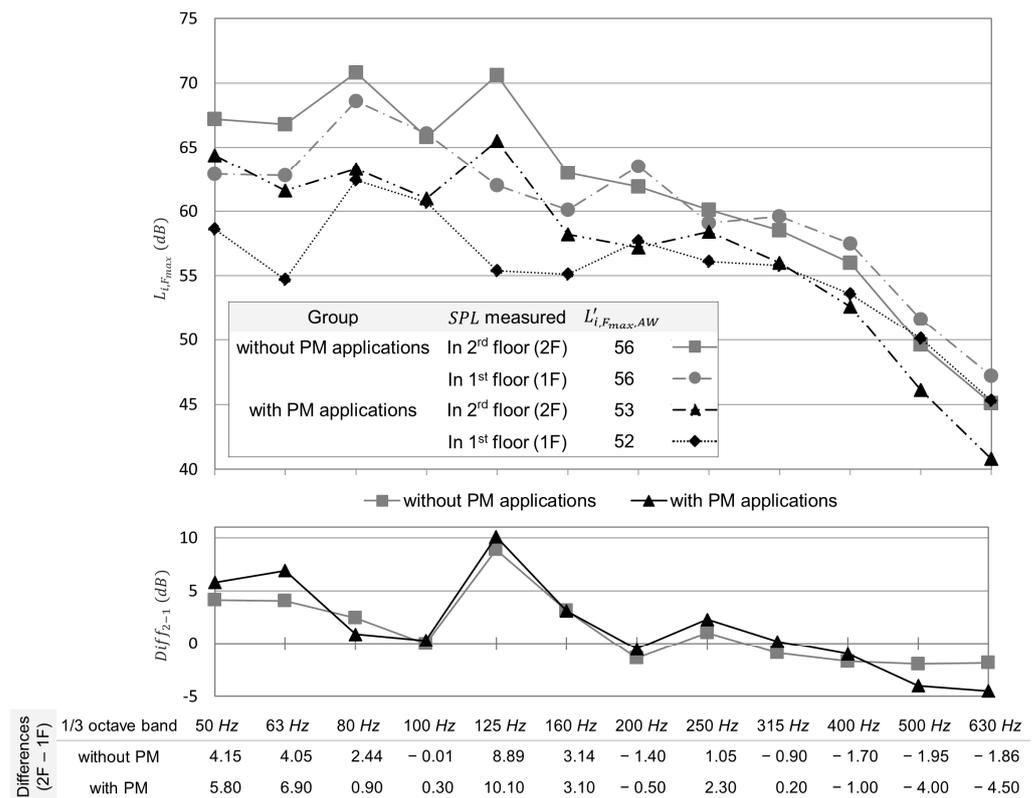


Figure 4. Noise response changes according to the periodic material (PM) application.

The upper portion of the graph presents the individual *SPL* measurements for each one-third octave band, providing a detailed frequency response profile. The post-application results exhibit a general trend of reduction in *SPL*. This detailed frequency breakdown allows for a nuanced understanding of the periodic materials' damping properties and their frequency-specific effectiveness. In addition to showing the average *SPL* measurements, the lower portion of the figure displays the difference in *SPL* between the two rooms on the second and first floors across the frequency bands ($Diff_{F2-1}$), both with and without the application of periodic materials. The table below the graph quantitatively summarizes these differences, further underscoring the enhanced sound attenuation achieved through the application of periodic materials. The post-application disparity in *SPL* between the second and first floors becomes pronounced in the octave bands of lower frequencies, notably in the 50, 63, 100, 125, 200, 250, 315, and 400 Hz ranges. This suggests that the periodic materials' application has a considerable influence on the transmission of lower-frequency sounds, which are often challenging to mitigate in building environments.

Based on the $L'_{i,Fmax,AW}$, before the application of periodic materials, the $L'_{i,Fmax,AW}$ was uniformly 56 dBA in the rooms on both the second and the first floors. This result indicates a lack of distinct distance attenuation of low-frequency impacts. Post-application, how-

ever, the $L'_{i,Fmax,AW}$ in the second floor room decreases to 53 dBA, while the first floor room registers a further reduction, reaching 52 dBA. Considering the pre-application $L'_{i,Fmax,AW}$ value (56 dBA) as 1 for comparison, the relative value becomes 0.95 on the second floor with an $L'_{i,Fmax,AW}$ of 53 dBA, and 0.93 on the first floor with an $L'_{i,Fmax,AW}$ of 52 dBA. This 5% reduction in the second floor room clearly demonstrates the improvement in impact noise insulation due to the periodic materials, while the greater reduction of 7% in the first floor room also indicates effectiveness in terms of distance attenuation.

4.2. Changes in Distance Attenuation of Vibration Responses

Next, the changes in vibration responses, which act as a medium for the transmission of impact noise, are followed. Figure 5 represents the experimental results analyzing the effects of applied periodic materials on the natural vibrations of the experimental structure. The figure is arranged with a cross-section of the experimental structure in the center, flanked by a total of six graphs. The cross-section of the experimental structure is marked with the locations of the installed scattering materials and each vibration measuring point. The central black arrow indicates the point of impact force application.

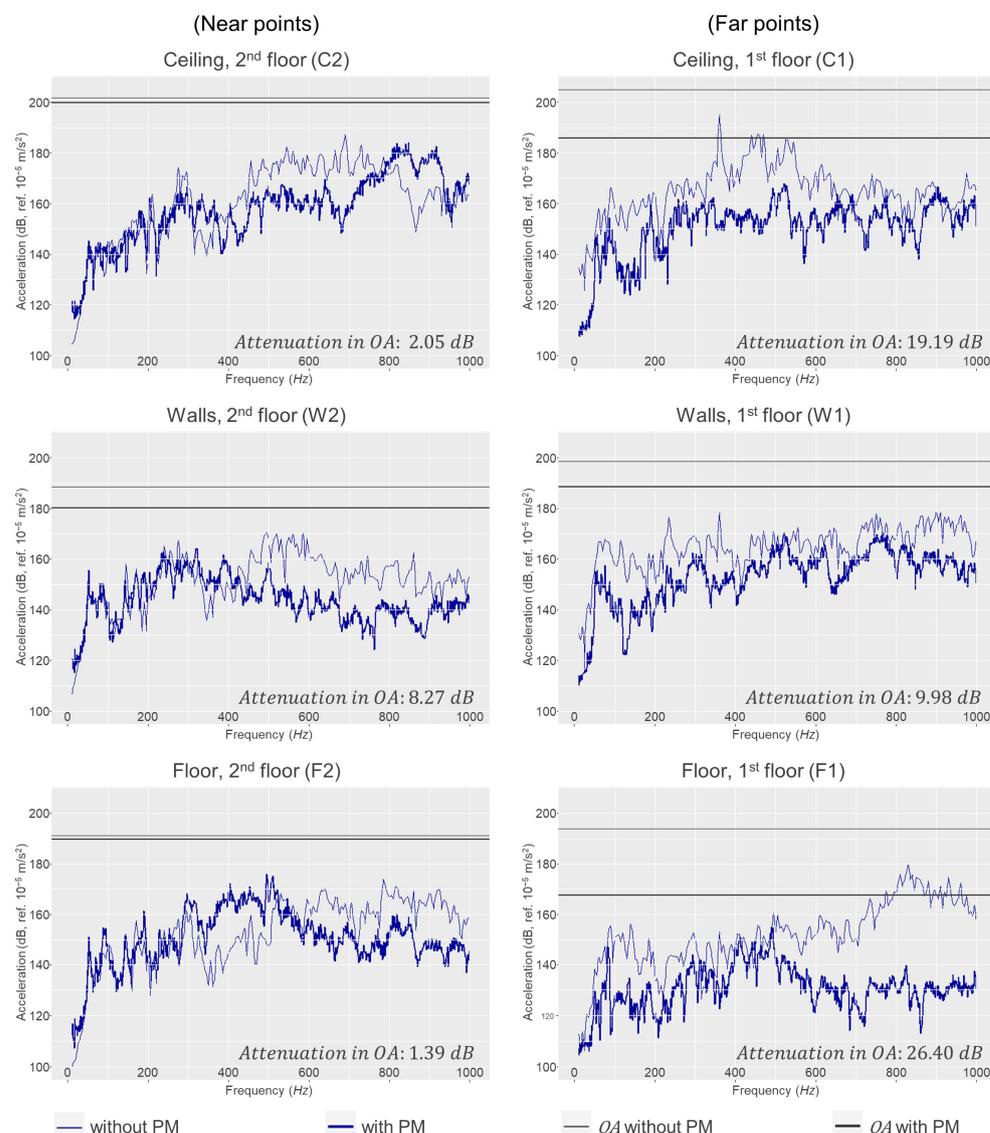


Figure 5. Vibration response changes according to the periodic material (PM) application.

The graphs present the average eigenfrequency response from 10 to 1000 Hz derived through the FRF between the impulse hammer excitation and each measurement point. The

graphs are organized in a vertical sequence with different parts of the building represented in each. The top graph shows the vibration response of the ceiling, the middle graph depicts the walls, and the bottom graph illustrates the floor's response. To understand the location of these responses, see the sides of Figure 5: the left side of each graph shows the responses on the second floor—these are the points that are closer to the excitation point. On the right side, you will see the responses on the first floor, which are the points that are further away from the excitation point. The vibration response of the walls is expressed as the average of the values measured at two points. In each graph, the lighter lines represent the vibration response before the application of periodic materials, and the darker lines after their application. At the bottom of each graph, the *OA* difference in vibration response before and after the application of periodic materials is denoted. Before the application of periodic materials, the experimental structure showed greater vibration responses in all components of the first floor compared to the second floor. This suggests that the members of the first floor are more vulnerable to the roof slab excitation of the experimental structure. As can be seen through a comparison of *OA* (light black lines), the vibrations of the ceiling, walls, and floor of the second floor were relatively lower, which is believed to be due to the smaller scale of the experimental structure compared to actual multifamily residences.

Periodic materials were applied only to the intermediate slab. Nevertheless, a reduction in vibration response was observed throughout the structure, with an average reduction of about 11.21 dB based on the averaged *OA*. The vibration response on the second floor mainly decreased in the area above 200 Hz, and the vibration rebound on the first floor decreased uniformly across all areas. Particularly noteworthy is the vibration response of the walls (W2) on the second floor. If one considers the in-plane waves propagating along the structure, despite there being no section with applied periodic materials between the excitation point and the two points W2a and W2b, a significant reduction of 8.27 dB was observed. This suggests that the distance attenuation effects resulting from the application of periodic materials in buildings cannot be simply interpreted.

After the application of periodic materials, the phenomenon of larger vibration responses at points farther from the excitation than those closer was improved in the experimental structure. Specifically, lower vibration responses were observed in the ceiling and floor of the first floor compared to the second floor, indicating that the effects of periodic materials contributed to the reduction in vibration propagation throughout the structure. These results demonstrate that periodic materials are highly effective in controlling vibration propagation.

Let us delve deeper into the effectiveness of periodic material applications in terms of distance attenuation. Table 4 illustrates the distance attenuation changes in *OA* resulting from the application of periodic materials. This table distinguishes the difference between pre- and post-application of periodic materials, displaying the *OA* at each vibration response measurement point. For each structural member group, it contrasts the differences between points that are nearer and further from excitation. By presenting this data, the table also compares the changes in distance attenuation for each member at specified measurement points, both before and after the application of periodic materials.

In the column 'OA without periodic material applications', attenuation values for the ceiling, walls, and floors are shown at points near (2F, A) and far (1F, B), with the difference between these two values presented as (A–B). The 'OA with periodic material applications' column presents data in the same manner, allowing for a comparison of the effects of periodic material applications at each measurement point.

When comparing before and after the application of periodic materials, it is evident that the difference in vibration attenuation between near and far points has increased for the ceiling, walls, and floors. This suggests that periodic materials effectively reduce the propagation of vibration energy and that this effect increases with distance.

Table 4. Distance attenuation changes in OA according to the periodic material applications.

Measured Point	OA without Periodic Material Applications			OA with Periodic Material Applications		
	Near Point (2F, A)	Far Point (1F, B)	Distance Attenuation (A–B)	Near Point (2F, A)	Far Point (1F, B)	Distance Attenuation (A–B)
Ceiling	(C2) 201.80	(C1) 204.89	−3.09	(C2) 199.75 (0.99) *	(C1) 185.70 (0.91) *	14.05
Wall	(W2) 188.39	(W1) 198.51	−10.12	(W2) 180.12 (0.96) *	(W1) 188.53 (0.95) *	−8.41
Floor	(F2) 191.11	(F1) 193.96	−2.85	(F2) 189.72 (0.99) *	(F1) 167.56 (0.86) *	22.16
Average	193.77	199.12	−5.35	189.86 (0.98) *	180.60 (0.91) *	9.26

Note: the '**' marked values are relative values compared with respective values in 'OA without periodic material applications'.

For example, for the ceiling, before the application of periodic materials, the near point shows 201.80 dB and the far point 204.89 dB in OA vibration response. This shows a difference of −3.09 dB, with a larger vibration response at the far point. After the application of periodic materials, the near point showed 199.75 dB and the far point 185.70 dB in attenuation, with the difference increasing significantly to 14.05 dB. A similar pattern is observed in walls and floors, confirming that the effect of periodic materials on vibration attenuation is consistent throughout the structure. In Table 4, it is confirmed that the average attenuation difference changed from −5.35 dB to 9.26 dB. In other words, the difference in vibration response between points near to and far from the excitation point shifted from negative to positive, indicating that the experimental structure transformed into one where lower vibration responses are seen at further distances. When comparing to the pre-application OA values, members on the second floor showed an average vibration response decrease of about 2%, while members on the first floor exhibited a reduction of approximately 9%. In other words, after the application of periodic materials, the reduction in vibration response was more pronounced at points further from the excitation source.

The results described in Sections 4.1 and 4.2 indicate that before the application of periodic materials, the experimental structure did not exhibit distance attenuation characteristics for impact noise and vibration. After the application, the environment transformed to clearly show distance attenuation for both impact noise and vibration. In terms of vibration, the change from negative to positive in the difference between points near to and far from the excitation point confirms a clear change in distance attenuation. However, the improvements in distance attenuation for impact noise were relatively less pronounced, suggesting that it is more challenging to achieve as clear an effect on noise distance attenuation as on vibration. Despite this, the application of periodic materials still brought about consistent improvements in distance attenuation across the entire structure for both impact noise and vibration aspects. These results imply that the use of periodic materials can play a significant role in the development of strategies for the management and control of impact noise within buildings.

5. Discussions

This study examines the impact noise and vibration response of structures undergoing change through the application of periodic materials in wall–slab structures, from the perspective of distance attenuation. The attenuation effect of plane wave propagation through periodic materials is well known through applications in civil engineering, such as pile barriers [20,36,37]. Although there has been research on the application of periodic materials in wall–slab structures [21], the focus has often been on the magnitude of impact noise, resulting in limited consideration of the propagation of in-plane waves related to the localization of impact source where multiple plates are combined.

The research by [37] on the feasibility of using periodic materials in the form of pile barriers as an earthquake wave mitigation measure shows results related to distance attenuation. According to this research, the magnitude of vibrations decreases by approximately 15%, 40%, and 75% with the addition of one, two, and three rows of pile barriers, respectively, compared to before the application of periodic materials. Also, the slope of the decrease with distance increases. However, compared to before the application, this distance attenuation effect is observed only after the plane wave passes through the section of the periodic material arrangement. Near the center of the section in which periodic material is applied, the vibration response is rather increased by approximately 40–50%, as the section of periodic materials absorbs the vibrational energy of the plane wave.

In contrast, in the experimental structure of this research, the average vibration reduction in all measurement points was 9%, with the largest decrease observed at point F1 by about 14%, compared to before the application of periodic materials. However, the results also show suppressed amplification of vibration response in members where periodic materials were applied (C1, F2).

The most significant difference between the propagation of environmental vibrations commonly addressed in civil engineering and vibration propagation in architectural structures such as wall–slab configurations lies in the complexity of the transmission paths. As noted by [26], in wall–slab structures, there are multiple flanking paths through which in-plane waves can travel between the same impact and observation points, rather than just a single path. The most influential is the shortest first-order path connecting the two points, but the impact of lower-order paths can also be significant.

The observation results of the noise and vibration response of the experimental structure before the application of periodic materials align well with this explanation. In the experimental structure without periodic materials, the distance attenuation of noise and vibration responses is not observed. Rather, vibration responses are more pronounced at observation points farther from the excitation point. This fact can be interpreted as being due to the overlapping of vibrational energy caused by the influence of multiple flanking paths in wall–slab structures.

The change in average vibration response at points W2a and W2b before and after the application of periodic materials also highlights the characteristic of wall–slab structures having numerous flanking paths. In this research, periodic materials were applied only to the intermediate slab of the experimental structure. Therefore, there are no sections with applied periodic materials on the shortest path from the excitation points to these two wall observation points. It seems unlikely that the point directly below the excitation point, C0, would be significantly affected by the periodic materials. Nevertheless, a reduction in the *OA* at C0 (2.05 dB) and W2 (8.27 dB) was observed, with a more significant decrease at W2. This indicates that even if the application of periodic materials does not affect the first-order path, the effect of in-plane wave attenuation by periodic materials in a wall–slab structure can be more pronounced due to the presence of numerous flanking paths.

From the perspective of the excitation location, the application of periodic materials not only reduced the vibration response in the section in front of the application but also suppressed vibration amplification in the slab where periodic materials were applied. This led to a more noticeable decrease in vibration response further away from the excitation location, and the experimental structure was able to achieve distance attenuation characteristics in both noise and vibration aspects.

Furthermore, the application of periodic materials to the intermediate slab resulted in improved sound insulation against heavy impacts for the room on the second floor, reducing $L_{i,Fmax,AW}$ from 56 dB to 53 dB. Considering that floating floors—extensively studied for sound insulation—show limited performance against low-frequency, heavy impacts, alternative solutions were constantly explored [4,27]. These solutions involved changes in structural type [6], plan configuration [14], and junction conditions [33], with the incorporation of periodic materials [21] being one of them. Therefore, while the focus of this research was on distance attenuation, confirming heavy-impact sound insulation

improvements in the room beneath the impacted floor is notably significant. This finding greatly contributes to enhancing acoustic comfort in wall–slab residential buildings.

In summary, architectural structures such as wall–slab configurations, which involve a complex combination of multiple plates, tend to observe the phenomenon of reversed distance attenuation characteristics due to the numerous flanking paths in vibration transmission. When periodic materials are applied to wall–slab structures, compared to the straightforward transmission direction of plane waves with periodic materials in the form of pile barriers in soil, the presence of numerous flanking paths brings about several differences: First, it is relatively challenging to achieve a significant distance attenuation effect in terms of vibration transmission. Second, however, side effects such as amplification of the applied area due to vibrational energy absorption are mitigated. Third, the application to specific sections can still achieve an overall reduction in structural vibration, which also positively affects the insulation of impact noises.

However, it is difficult to claim that periodic materials could entirely substitute conventional approaches such as floating floors. The transition of the surface material from high-density to low-density in our experiment might adversely affect airborne noise insulation. Our focus was on low-frequency wave attenuation from heavy impacts, so we did not extensively discuss tapping machine impact results in Sections 3 and 4. The single numerical rating values, $L'_{n, AW}$, resulting from tapping machine impacts are benchmarks for assessing noise insulation against light and hard impacts. The $L'_{n, AW}$ values, measured similarly to rubber ball impact sound responses, showed no significant difference pre- and post-application of periodic materials (70 dBA on the second floor and 71 dBA on the first floor). The lack of noticeable effects on higher frequency impacts indirectly suggests a vulnerability in the airborne noise insulation capability of this method. Nonetheless, the noise insulation against light impacts could be managed with floating floors or modifications to the flooring material. Therefore, integrating periodic materials with existing soundproofing strategies could better secure acoustic comfort in multifamily housings.

As mentioned in the introduction, the localization of impact sources in multi-dwelling residences is a research area of significant social demand [10,11]. The approach of identifying impact sources through the sensing of structural vibrations offers a non-intrusive method, which is not only beneficial for improving acoustic comfort but is also promising in the study of human behavior recognition [45]. However, the practical application of such localization techniques is limited to short-range sensing at the individual plate level, not extending beyond the junctions between structural members [46,47]. As observed in the vibration response of the experimental structure before the application of periodic materials, the wall–slab structure does not readily exhibit the distance attenuation effect of vibrations. Consequently, estimating the distance to the excitation location based solely on the magnitude of the vibration response presents significant challenges. Therefore, by applying periodic materials to enhance the discernibility of vibration response differences due to distance changes in a wall–slab structure, it can contribute to overcoming the limitations of short-range sensing in impact source localization. This approach can aid in achieving the same objectives with fewer sensors, offering a practical solution to the challenges highlighted earlier.

6. Conclusions

This research applied periodic materials, promising in controlling in-plane waves and previously used mainly in civil engineering for environmental vibration control. This research applied periodic materials to the intermediate slab of a wall–slab experimental setup. The experiment involved delivering impacts to the roof slab of a two-story experimental structure and measuring the indoor sound pressure levels and overall amplitude of natural vibration of each member before and after the application of periodic materials. The experimental structure, before the application of periodic materials, was a structure where distance attenuation of impact vibration was not observed, with members further from the impact location exhibiting an average vibration response 5.4 dB higher than those

closer, based on OA. However, compared to the pre-application, after applying periodic materials, impact noise and vibration decreased by 5% and 2%, respectively, in points closer to the impact location, and by 7% and 9% in farther points. These findings indicate not only the emergence of distance attenuation characteristics but also a reduction in impact noise and vibration responses across all rooms and members. This is a notable result, as unlike applications in civil engineering, vibration amplification was suppressed even in the sections where periodic materials were applied.

In the experimental setup of this research, the application of periodic materials was executed by perforating the existing structure. The consideration of potential side effects on airborne noise transmission due to perforation was, however, limited in this study. Moreover, this research did not perform a sensitivity analysis of various parameters, which could be explored using analytical models. Therefore, further research is necessary before practical application, specifically on application zones, arrangement methods, and material properties. Future studies should also evaluate integrating this method with conventional approaches, like floating floors, to mitigate any potential side effects.

This research contributes to the potential application of promising in-plane wave control materials in architecture. It was confirmed that periodic materials can suppress side effects such as vibration amplification in sections where they are applied in wall–slab structures and enhance distance attenuation characteristics. Should the proposed future research be undertaken, our findings could facilitate the development of impact source localization techniques. Such advancements could enhance acoustic satisfaction and mitigate neighbor noise conflicts, contributing to more sustainable urban residential environments.

Author Contributions: Conceptualization, J.C.; data curation, K.S.; formal analysis, N.K.; funding acquisition, T.W.K.; methodology, N.K.; project administration, M.P.; supervision, M.P.; visualization, K.S.; writing—original draft, J.C.; writing—review and editing, T.W.K. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by Post-Doctor LAB employment support Program (INU SURE LAB Program) (2023) in the Incheon National University.

Data Availability Statement: Some or all data, models, or code generated or used during the study are available from the corresponding author by request.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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