Fundamental Natural Frequency and Floor Impact Sound Insulation Performance of CLT Slabs Based on Wood Species and Panel Connections: An Experimental Study

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The effects of wood species and panel connections on the vibration and heavy-weight impact sound insulation performance of cross-laminated timber (CLT) slabs were investigated. CLT panels (5-ply, 150 mm thick, 1 m wide, and 4.2 m long) made of larch (*Larix kaempferi*) and pine (*Pinus densiflora*) were manufactured with 30 mm thick laminae, considering three types of joints. Three CLT panels of the same species and joint type were connected using spline joints, butt joints, or half-lap joints to form 3 m wide and 4.2 m long slabs for testing. The floor impact sound insulation performance of the CLT slabs was measured according to KS F ISO 10140-3, using the standard heavy-weight impact source, a rubber ball. Additionally, four accelerometers were installed at 400 mm intervals beneath the CLT slabs to analyze the deflections and natural frequencies of the slabs. The results of the experiment indicated that there were no significant differences depending on the wood species and the CLT panel joints. These findings suggest that wood species and joint methods can be flexibly applied in the design of CLT slabs.

DOI: 10.15376/biores.20.1.100-120

Keywords: Cross-laminated timber (CLT); Vibration; Floor impact sound; Stiffness; Panel joints

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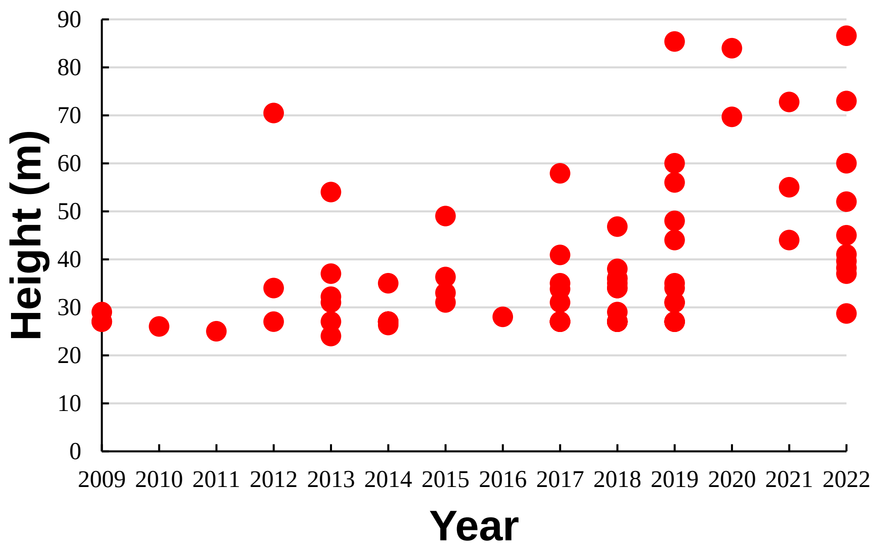
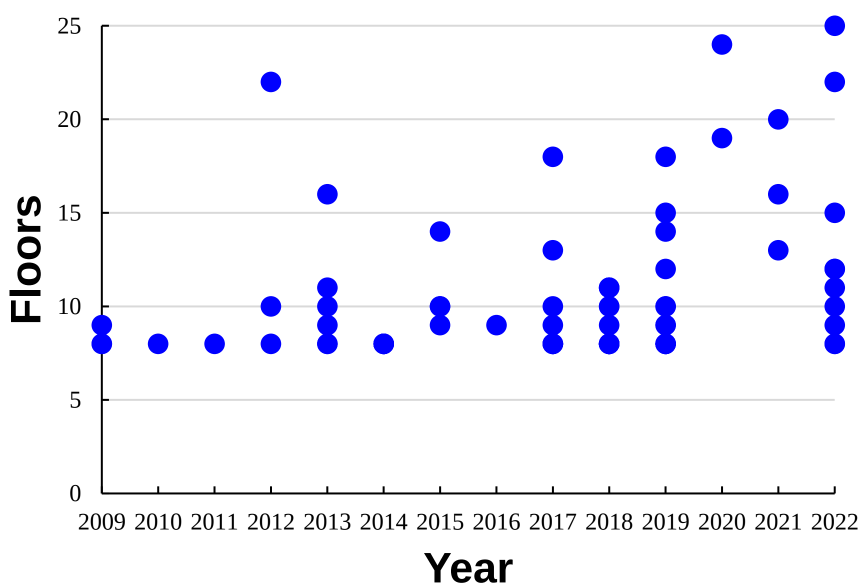
INTRODUCTION

Timber buildings are becoming taller, with an increasing number of floors (CTBUH 2023). Figure 1 shows a global overview of mass timber buildings, either completed or under construction, specifically those that are eight stories or taller. There is a noticeable trend towards constructing taller and more multi-story buildings, indicating a growing preference for structures exceeding eight stories. The development of cross-laminated timber (CLT) has significantly contributed to the increasing height and number of floors in timber buildings (Duan *et al*. 2022; Younis and Dodoo 2022; Bhandari *et al*. 2023). CLT is an engineered wood product that consists of layers of lumber boards stacked and glued together in alternating directions (Balasbaneh and Sher 2021; Santos *et al*. 2021; Ayanleye *et al*. 2022). This crosswise layering enhances the material's strength, stability, and structural performance (Brandner *et al*. 2016; Siddika *et al*. 2021; Shulman and Loss 2023).

Korean national standards for the quality of CLT have been developed to produce and use CLT from domestically sourced wood (KS F 2081 2021; Oh *et al*. 2023; Yang *et* *al*. 2023, 2021). The structural performance of Korean CLT made from local wood species has been evaluated (Pang and Jeong 2019, 2018; Pang *et al*. 2021), along with the shrinkage and expansion characteristics in response to moisture content (Pang and Jeong 2020). Research also led to the development of hybrid CLT using plywood (Choi *et al*. 2015, 2018; Pang *et al*. 2019), and hybrid slabs combining CLT and concrete (Oh *et al*. 2023; Pang *et al*. 2022; Quang Mai *et al*. 2018), with their structural characteristics thoroughly evaluated. These studies primarily have focused on structural safety. However, the vibration and noise between floors cause significant anxiety and discomfort for users (Jeon 2001; Jeon *et al*. 2009; Jo and Jeon 2019). Research on the vibration and noise characteristics of CLT slabs is essential for high-quality residential timber buildings.



a) Height of timber building



b) Number of floors in a timber building

Fig. 1. The rise of tall timber buildings (CTBUH 2023)

The issue of inter-floor noise in high-rise apartments is a common concern in densely populated urban areas, not unique to Korea (Gibson *et al*. 2022; Kang *et al*. 2023). This issue often arises from factors such as footsteps, moving furniture, loud music, or other activities that generate sound and vibrations, which can easily travel through a building's structure. Korea enforces the world's strictest inter-floor noise standards. To construct an apartment with more than 30 units in Korea, the impact sound must meet the standard of 49 dB or less (Ha *et al*. 2023). These stringent building codes and regulations pose challenges to the expansion of tall timber buildings.

CLT panels are manufactured by laminating solid wood, thereby inheriting the characteristics of the chosen wood species. Additionally, the dimensions of CLT panels are limited by the size of pressing machinery and practical considerations related to transportation. When used as slabs or walls in buildings, CLT panels should be assembled on-site to function as integral components of slabs or walls. This study aimed to investigate whether wood species selection and panel connection methods impact the vibration and noise characteristics of CLT slabs. Furthermore, the correlation between the vibration performance and noise performance of CLT was analyzed, and an attempt was made to estimate noise performance based on the vibration performance of CLT.

MATERIALS AND METHODS

Specimens

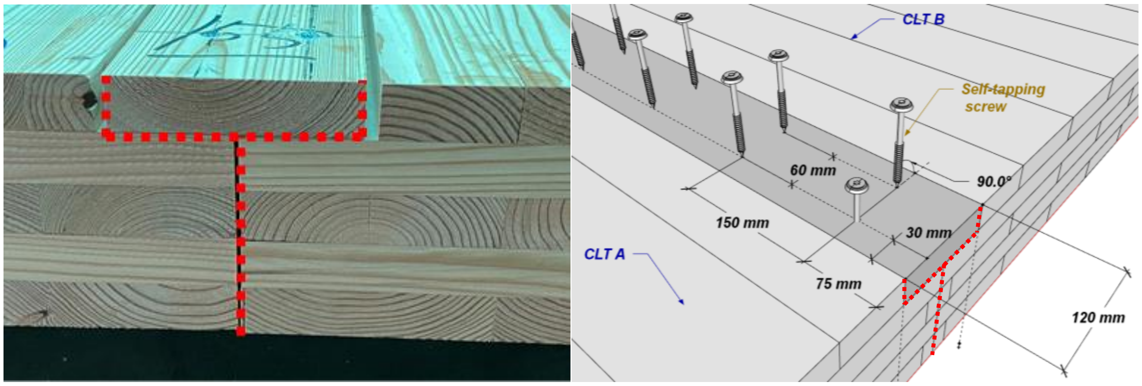
Eight types of test specimens were prepared with different wood species, thickness, and CLT panel joints (Table 1). The specimen ID format indicates the wood species with the first letter, the joint type with the second letter, and the CLT thickness with the number, which comes third. The test specimens with CLT panel thicknesses of 300 mm and 450 mm were classified as "mixed" because they designed stacking 150 mm thick CLT panels with different types of CLT panel joints.

The CLT panels were made with two species, larch (*Larix kaempferi*) and pine (*Pinus densiflora*), respectively. The dimensions of each lamina were 30 mm in thickness, 130 mm in width, and 4,200 mm in length. The laminas were graded according to KS F 3020 standard using a machine grader (MGFE-251, IIDA Kogyo, Komaki, Japan).

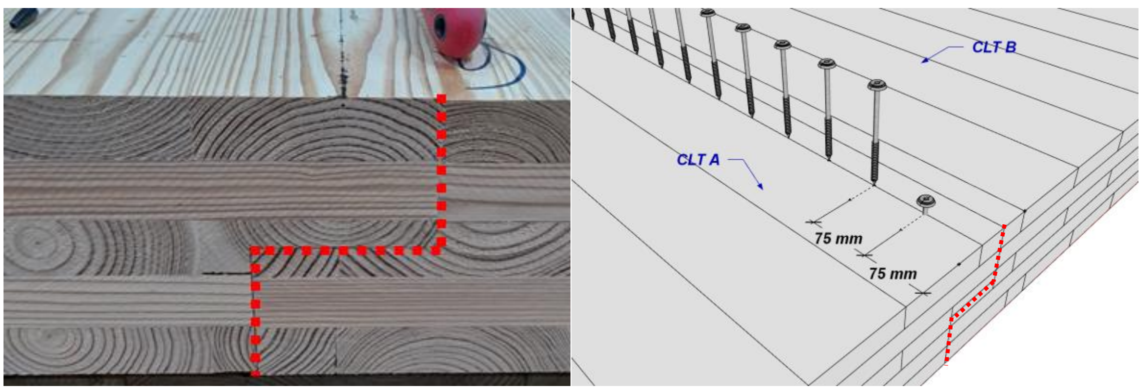
Table 1. CLT Specimens and Experimental Results

No.	Specimen ID	Species	Joint type	CLT thickness (mm)
1	L-S-150	Larch *(Larix kaempferi)*	Spline	150
2	L-H-150		Half-lap	150
3	L-B-150		Butt	150
4	L-M-300		Mix	300
5	L-M-450		Mix	450
6	P-S-150	Pine *(Pinus densiflora)*	Spline	150
7	P-H-150		Half-lap	150
8	P-B-150		Butt	150

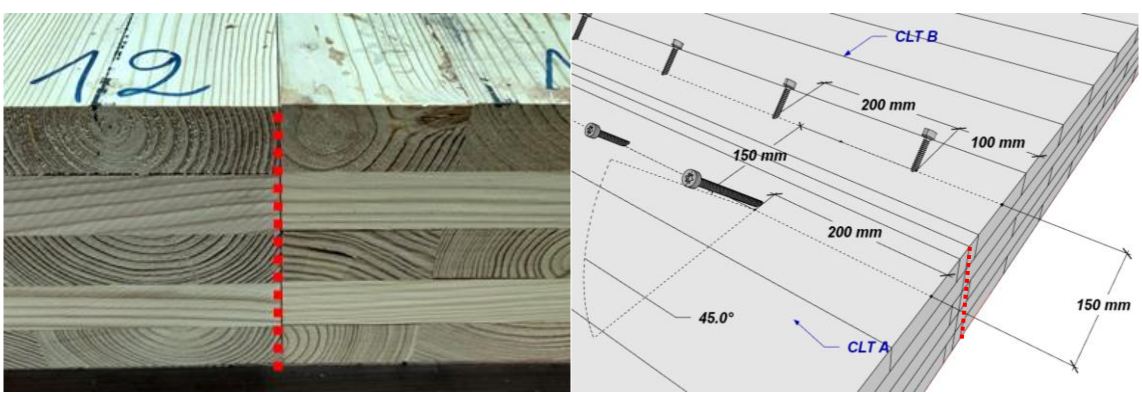
The graded laminas were laminated into five layers to achieve CLT grades, C-E10-E8 (Larch CLT) and C-E8-E6 (Pine CLT), as specified in KS F 2081 standard. In the CLT grade nomenclature, the first letter signifies CLT, the second letter denotes the grade of the outermost layer, and the third letter denotes the grade of the inner layer. The grade of lamina used in both outer layers of the CLT is identical, and similarly, the grade of lamina used in the three inner layers is also the same.



a) Spline



b) half-lap



c) butt

Fig. 2. Joint types used to connect the CLT panels

The adhesive used to glue laminas was Phenol - Resorcinol - Formaldehyde (PRF). A quantity of 200 g/m^2 was applied for each layer. The press pressure was set at 1 MPa, followed by a 20-hour pressing period and an additional week for curing. The mean moisture content of the CLT was 12 ± 2%, and the specific gravity of the produced CLT panels were 0.587 for larch CLT and 0.476 for pine CLT. The overall dimensions of the CLT panels were 150 mm in thickness, 1000 mm in width, and 4,200 mm in length.

The CLT panels were connected using spline joints, half-lap joints, or butt joints to form 3000 mm in wide and 4200 mm in length for tests. Figure 2 shows the three joint types, all of which utilize self-tapping screws. For the spline joints, Ø 6 mm × 80 mm screws (HBS model, Rothoblass) were used. For the half-lap joints, Ø 6 mm ×130 mm screws (HBS model, Rothoblass) were used. For the butt joints, Ø 7 mm × 180 mm screws (VGZ model, Rothoblass) were installed at a 45° angle.

Experimental Tests

The vibration characteristics and impact sound insulation performance of the CLT specimens were evaluated following the floor impact sound laboratory measurement methods outlined in KS F ISO 10140-3 (2021). Figure 3 illustrates the setup of a CLT specimen and the designated locations for the impact source. The tests were conducted at an internationally certified testing agency, Fire Insurers Laboratories of Korea, specializing in assessing floor impact sound insulation performance.

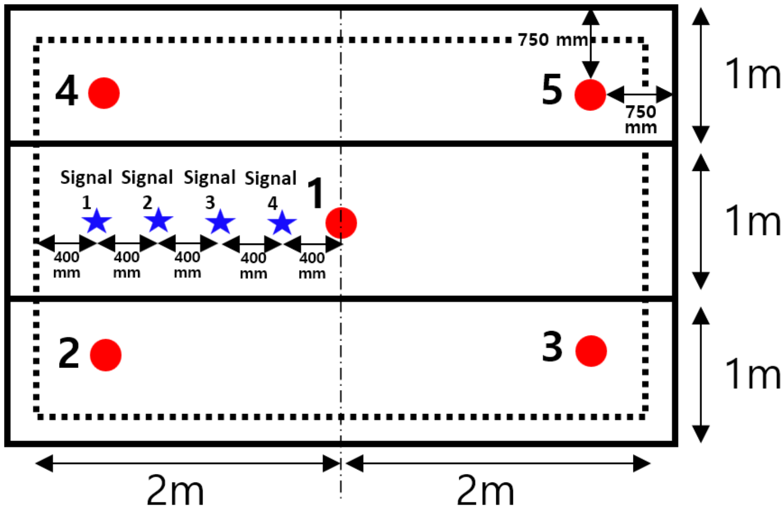
Figure 3 shows the internal laboratory environment and experimental setup. A standard heavy-weight impact source, a rubber ball (Rion, YI-01), was dropped from a height of 1 m at five points (Fig. 3 (b)). These positions included the center of the slab and four corners positioned 750 mm away from the borders of the slab (Fig. 3 (c)). Each drop of the rubber ball was repeated nine times at each specified position.

To analyze the deflection and natural frequency of the CLT slab during impact testing, four accelerometers (B&K, type 4527) were installed beneath the CLT slab at 400 mm intervals, as illustrated in Fig. 3 (c) and Fig. 4 (a).

a) Installation of CLT specimen

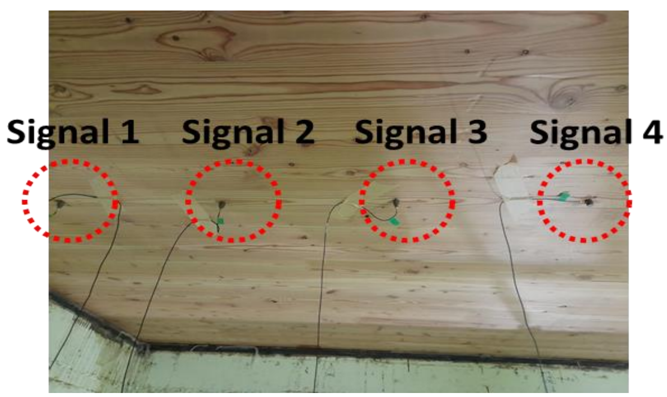
b) Application of standard heavy-weight impact source (rubber ball)

Fig. 3(a & b). Installation of CLT specimen and locations for impact source hitting



c) Position of impact source hitting (red circle) and accelerometer installation (blue star)

Fig. 3 (c). Installation of CLT specimen and locations for impact source hitting



a) Accelerometers

b) Microphones

Fig. 4. Installation of accelerometers and microphones

For measuring the floor impact sound insulation performance of the CLT slabs, five microphones (B&K, type4189) were installed at a height of 1.2 m within the sound receiving room (Fig. 4 (b)).

Analysis Method for Vibration and Acoustic Behavior of CLT Slabs

The displacement and natural frequency of CLT slabs were obtained from the recorded acceleration response spectrum. Figure 5 outlines the process and method used to analyze the acceleration spectrum. The displacement of CLT slabs was computed by performing double integration of the acceleration spectrum over the time axis. The natural frequency of the CLT slab was derived by transforming the time domain of the displacement response to the frequency domain using the Fast Fourier Transform (FFT) (He *et al*. 2023; Xie *et al*. 2020).

The floor impact sound insulation performance of CLT slabs was evaluated using a single-number quantity base on the KS F ISO 717-2 standard (KS F ISO 717-2 2020). The sound pressure level, recorded using the microphone, was divided into the 1/3 octave band based on the frequency. The evaluation frequency for the floor impact sound was 50 to 630 Hz. The single-number quantity for the heavy-weight floor impact sound ($L_{\mathrm{i,\,Fmax}}$) was calculated using Eq. (1),

$$L_{\mathrm{i,\,Fmax}} = 10\log\left(\frac{1}{m}\sum_{j=1}^{m} 10^{(L_{i,Fmax,j})/10}\right) \qquad (1)$$

where m is the number of impact source locations and $L_{i,Fmax,j}$ is the maximum floor impact sound level for impact source location j.

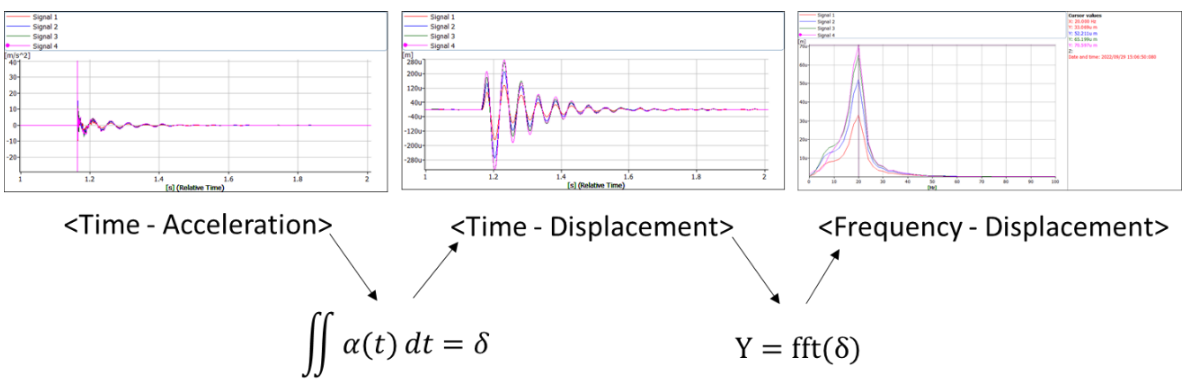


Fig. 5. Derivation of displacement and natural frequency of CLT slab from acceleration data

Stiffness of CLT Slabs by Impact Load

The three types of stiffness related to the behavior of the slab, bending stiffness (*EI)*, dynamic stiffness, and impact stiffness, were determined. Bending stiffness represents the structural member's resistance to deformation under bending. It is determined by the material's elastic modulus (*E*) and the geometric properties of the member, specifically the moment of inertia (*I*). The *EI* value was derived by Eq. (2), and more information can be found in the CLT handbook (FP Innovations 2014).

$$EI = \sum_{i=1}^{n} E_i \cdot b_i \cdot \frac{h_i^3}{12} + \sum_{i=1}^{n} E_i \cdot A_i \cdot z_i^2 \qquad (2)$$

In Eq. 2, EI is the effective bending stiffness of CLT (N·mm^2), E_i is the modulus of elasticity of i^{th} layer (MPa), b_i is the width of i^{th} layer (mm), h_i is the thickness of i^{th}

layer (mm), A_i is the cross-section area of i^{th} layer (mm^2), and z_i is the distance between the center point of i^{th} layer and the neutral axis (mm)

Dynamic stiffness is associated with the vibration of the slab and indicates how the slab behaves at specific frequencies. Dynamic stiffness was determined using the mass of the slab and the vibration frequency measured by accelerometers. Equation (3) describes the relationship between vibration frequency, stiffness, and mass under the assumption that the structure undergoes simple harmonic motion. Based on Eq. (3), Eq. (4) was derived to calculate the dynamic stiffness.

$$f = \frac{1}{2\pi}\sqrt{\frac{k_{dynamic}}{m}} \quad (3)$$

$$k_{dynamic} = (2\pi f)^2 \cdot \mathrm{m} \quad (4)$$

where f is the natural frequency measured by acceleration response spectrum (Hz), $k_{dynamic}$ is the dynamic stiffness of CLT slab (N/m), and m is the mass of CLT slab (kg).

The impact stiffness is related to the deflection of the slab due to out-of-plane loads. The impact stiffness of the test slab was calculated by dividing the applied loads by the resulting deformation, as described in Eq. (5). The load acting on the slab comprises the impact force generated by the test ball, the self-weight of the slab, and the weight of the experimenter. The impact load was generated using a hollow silicone rubber ball with a diameter of 185 mm and a thickness of 30 mm. The ball, weighing 2.5 ± 0.2 kg, was dropped from a height of 1 meter, producing an impact load of approximately 1,500 N (Ha *et al*. 2023; Hyo-Jin Lee *et al*. 2023; KS F ISO 10140-3 2021; Yazbec *et al*. 2022),

$$k_{impact} = (W_{impact} + W_{CLT} + W_{experimenter})/\delta_{max} \quad (5)$$

where k_{impact} is the impact stiffness of CLT slab (N/m), W_{impact} is the impact load by the rubber ball (1,500 N), W_{CLT} is the self-weight of CLT panel (N), $W_{experimenter}$ is the weight of the experimenter (N), and δ_{max} is the maximum deflection of CLT slab (mm)

The maximum deflection of the slab was simulated using finite element method (FEM), since it is difficult to experimentally measure the deflection shape and deflection at all points of the slab. The FEM was performed using Midas NFX software (Midas IT 2024), and the input parameters, material properties, are presented in Table 2. The properties of the laminas were assumed to be those of an orthotropic material.

In Table 2, the elasticity for each grade was set to the median value of that grade according to KS F 3020. The elasticity in the transverse direction was defined as 1/30 of the longitudinal elasticity, based on the CLT handbook (FP Innovations 2014). The shear modulus in the longitudinal direction was set to 1/16 of the longitudinal elasticity, and the shear modulus in the transverse direction was set to 1/10 of the longitudinal shear modulus.

Poisson's ratios were applied based on values from the Wood Handbook (Forest Products Laboratory - USDA 2021). In Poisson's ratio notation, the first subscript denotes the stress direction, and the second denotes the lateral deformation direction. For stress applied in the longitudinal direction, deformation in the radial direction is very small, and thus, no specific value for μ_{RL} is provided. Therefore, simulations varied μ_{RL} between 0.01 and 0.1.

The predicted deflection values were then compared with experimental displacement measurements obtained using accelerometers. The actual deflection of the CLT slab was calculated by double integrating the acceleration spectrum (Fig. 5).

Table 2. Material Properties for Finite Element Analysis

Material		Density (kg/m^3)	Elasticity* (MPa)	Shear modulus** (MPa)	Poisson's ratio***
Larch	E10	587	10500 (E_L) 350 (E_T)	656.25 (G_L) 65.625 (G_T)	0.276 (μ_{LT}) 0.352 (μ_{TR}) 0.01 – 0.1 (μ_{RL})
	E8		8500 (E_L) 283.34 (E_T)	531.25 (G_L) 53.125 (G_T)	
Pine	E8	476	8500 (E_L) 283.34 (E_T)	531.25 (G_L) 53.125 (G_T)	0.315 (μ_{LT}) 0.308 (μ_{TR}) 0.01 – 0.1 (μ_{RL})
	E6		6500 (E_L) 216.67 (E_T)	406.25 (G_L) 40.625 (G_T)	

*E_L: elasticity for longitudinal direction, E_T: elasticity for transverse direction to longitudinal direction
**G_L: shear modulus for longitudinal direction, G_T: shear modulus for transverse direction to longitudinal direction
***μ_{LT}: Poisson's ratio for tangential deformation due to longitudinal stress, μ_{TR}: the Poisson's ratio for radial deformation due to tangential stress, μ_{RL}: Poisson's ratio for longitudinal deformation due to radial stress

RESULTS AND DISCUSSION

Effects of Wood Species and Panel Connections on Vibration Characteristics

The vibration characteristics of a floor are mainly determined by its natural frequency, which significantly affects its impact sound insulation performance. In this study, impact sound insulation was evaluated according to the KS F ISO 10140-3 standard by measuring responses at five specified impact locations. The effects of wood species and panel connection configurations on the vibration behavior of CLT slabs were systematically analyzed based on these measurements, providing insights into how material and structural factors influence acoustic performance.

Figure 6 shows the impact-induced vibration response spectrum of CLT slabs obtained using the FFT. Each graph for an impact location presents 36 frequency spectra (4 accelerometers × 9 repetitions). The amplitude in the vibration frequency spectrum varied across different experiments and accelerometer positions. However, the dominant frequency, which exhibited the largest amplitude, remained consistent regardless of the accelerometer position and the number of repetitions. This phenomenon was observed in all graphs in Fig. 6, irrespective of the impact locations and wood species.

A slab can exhibit multiple natural frequencies, each corresponding to a different vibration mode, such as bending or twisting. The first mode typically appears at the lowest frequency, with higher modes occurring at successively higher frequencies. In the frequency spectrum, peaks indicate these natural frequencies, each associated with a specific vibration mode. Therefore, the dominant peak in Fig. 6, which had the highest amplitude, can be considered the primary natural frequency that best characterizes the slab's overall dynamic behavior.

The amplitude of a graph in Fig. 6 refers to the displacement of the CLT specimens at a specific frequency. The frequency with the highest amplitude corresponds to the natural frequency that has the greatest influence on the deflection of the slab. The effect of the dominant frequency on displacement was greatest when the impact occurred in the center for all test specimens. When the impact occurred at the four corners, the effect of the dominant frequency on displacement was similar. This indicates that the largest displacement occurred when the impact took place in the center, and the difference was not significant when the impact occurred at the corners.

Table 3 presents the test results based on wood species, CLT panel joint type, and the thickness of the CLT specimens. The natural frequency of the test specimens ranged from 20 Hz to 22 Hz, exceeding the minimum natural frequency requirement of 8 Hz specified in BS EN 1995-1-1 (Kang *et al*. 2023) and 9 Hz specified in the CLT Handbook (FP Innovations 2014). Specifically, the natural frequencies of L-M-450 and P-B-150 specimens were 22 Hz, while all other specimens exhibited a natural frequency of 20 Hz. Therefore, there was little difference in natural frequency due to variations in wood species and CLT panel joints.

The vibration performance of CLT is influenced by the boundary conditions, as well as the grade and size of the panel (Breneman *et al*. 2021; Huang *et al*. 2020). In this study, the size of the test specimens and the test conditions in the laboratory were consistent. Therefore, the results indicate that the boundary conditions likely governed the natural frequency of the CLT specimens, rather than the wood species (density) of the CLT panels and the structural performance of the CLT panel joints.

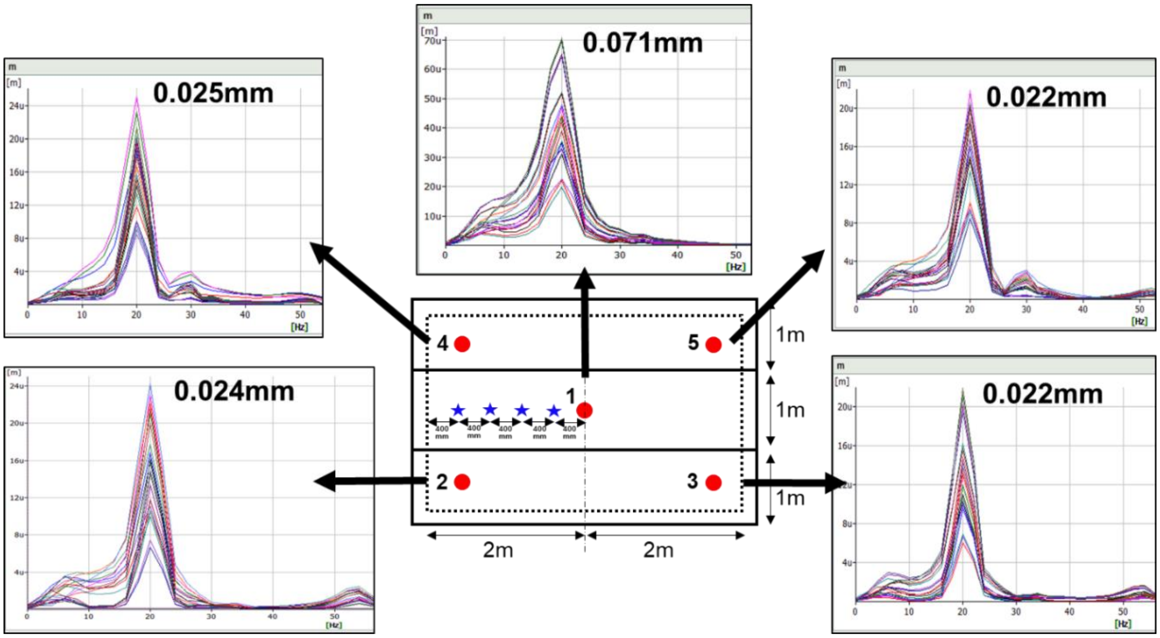
Table 3. Experimental Results

No.	Specimen ID	Fundamental natural frequency (Hz)	Mass (kg)	Bending stiffness (kN·m^2)	Dynamic stiffness (N/m)	Impact stiffness (N/m)	Single-number quantity *
1	L-S-150	20	945	6707.8	14922.8	28815.1	69
2	L-H-150	20	945				70
3	L-B-150	20	945				71
4	L-M-300	20	1890	13415.6	29845.7	147831.8	63
5	L-M-450	22	2835	20123.4	54169.9	341176.5	59
6	P-S-150	20	850.5	5367.6	13430.6	21140.2	72
7	P-H-150	20	850.5				71
8	P-B-150	22	850.5		16251.0		72

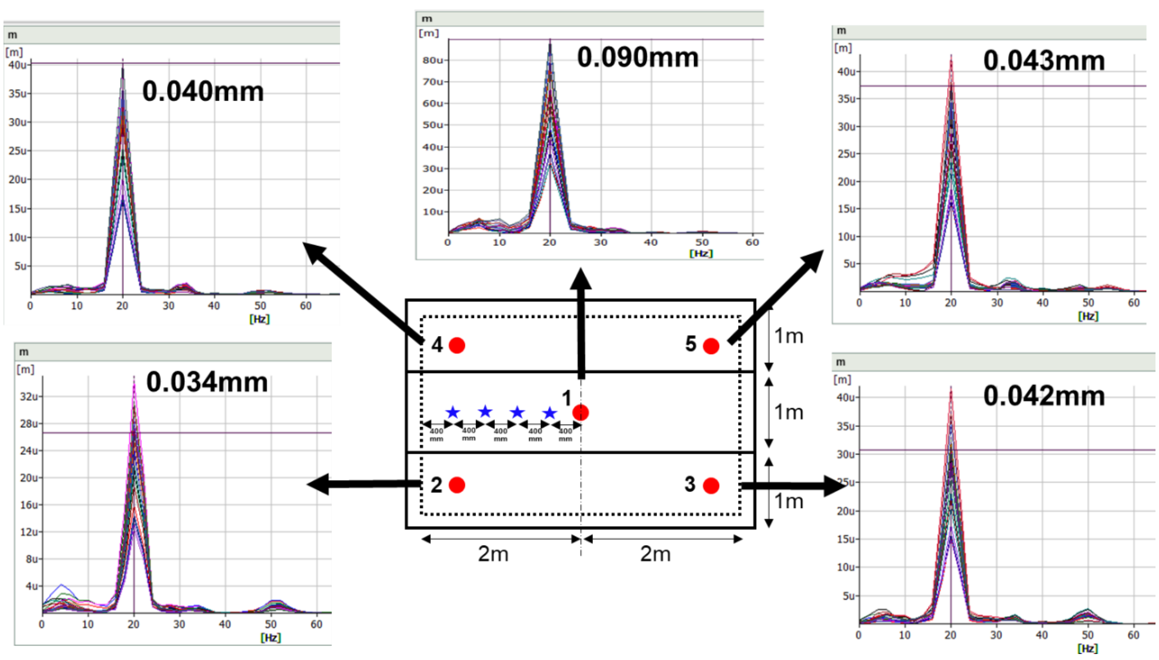
*From Ha *et al*. 2023.

Relationship between CLT Slab Stiffness and Floor Impact Sound Insulation Performance

In this study, the three types of stiffness related to the behavior of the slab, namely the bending stiffness (*EI)*, impact stiffness, and dynamic stiffness, were determined. Bending stiffness represents the structural member's resistance to deformation under bending. It is determined by the material's elastic modulus (E) and the geometric properties of the member, specifically the moment of inertia (I). The EI value was derived by Eq. (2), and more information can be found in the CLT handbook (FP Innovations 2014).

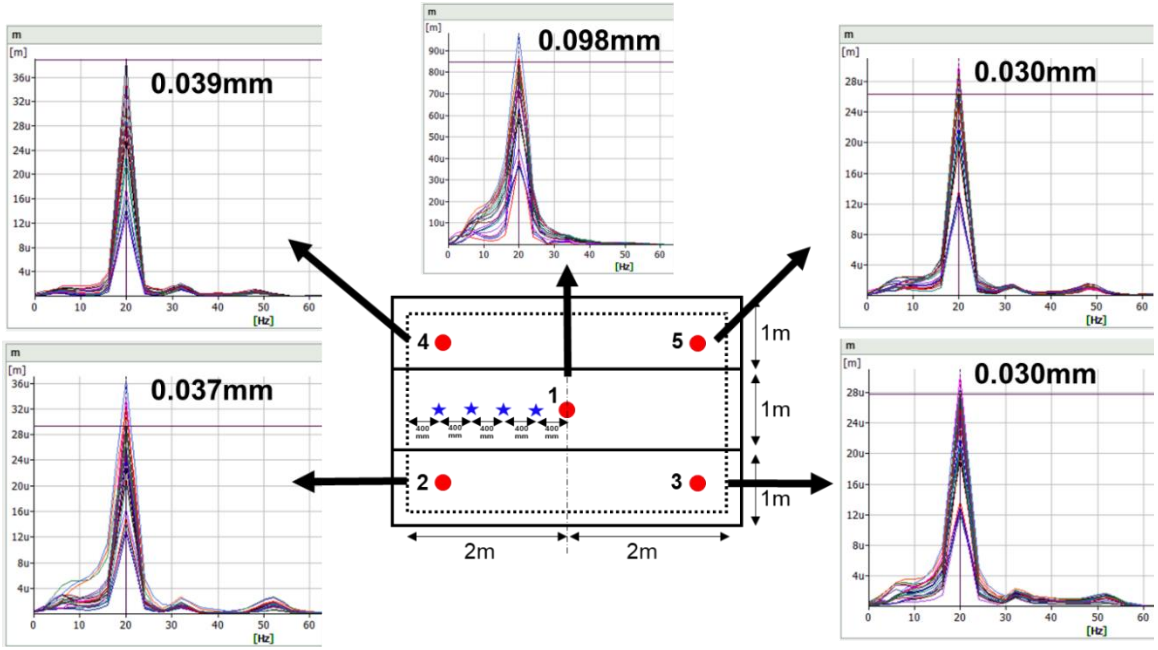


a) L-S-150

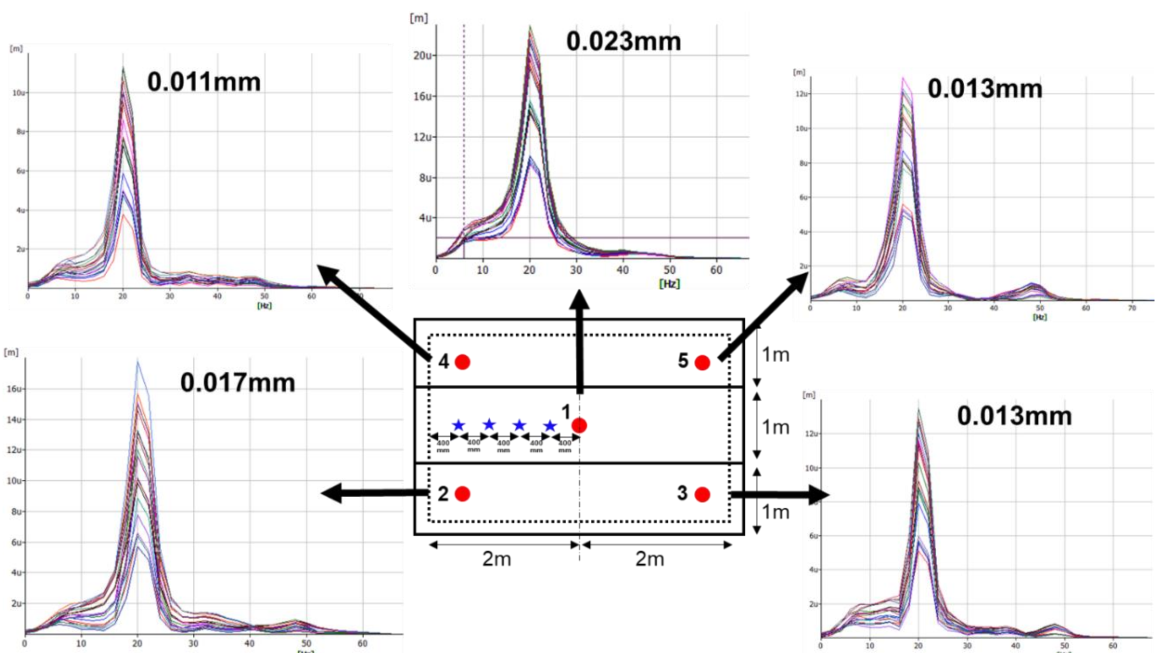


b) L-H-15

Fig. 6 (a & b). Impact-induced vibration response spectrum at each impact location

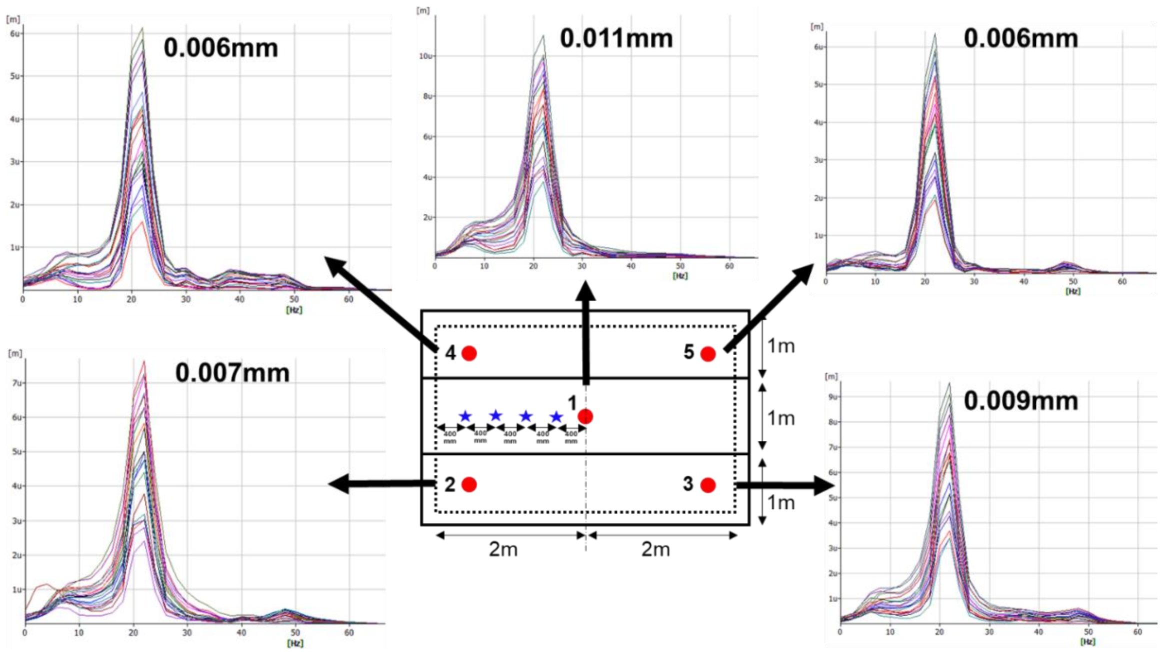


c) L-B-150

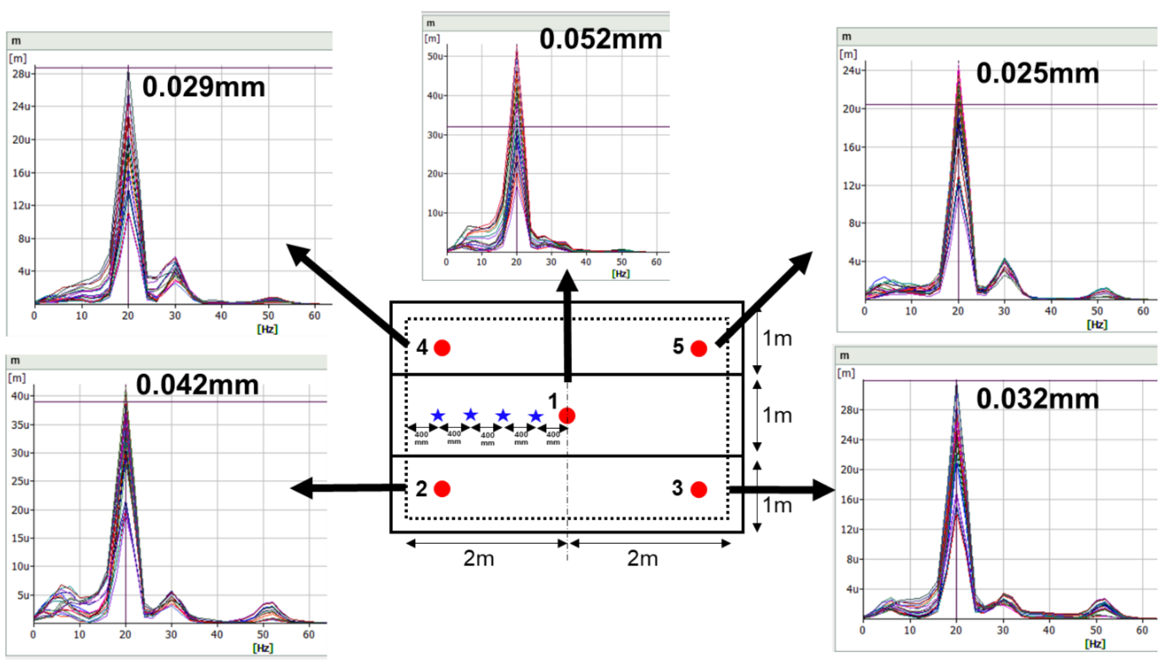


d) L-M-300

Fig. 6 (c & d). Impact-induced vibration response spectrum at each impact location



e) L-M-450



f) P-S-150

Fig. 6 (e & f). Impact-induced vibration response spectrum at each impact location

Figure 7 illustrates the correlation between bending stiffness and floor impact sound insulation performance of CLT slabs. Equation (6) represents an empirical formula developed to estimate the single-number quantity for CLT floors based on their bending stiffness,

$$L_{i,\,Fmax} = -0.0009\,EI + 76.087 \quad (6)$$

where $L_{i,\,Fmax}$ is the single-number quantity for heavy-weight impact sound insulation performance (dB), and EI is the bending stiffness of CLT slab (N·mm^2).

The single-number quantity of CLT slabs listed in Table 3 was calculated using Eq. (1), as reported by Ha *et al.* (2023). They analyzed the effect of species and CLT panel joints on the floor impact sound insulation performance of CLT slabs. The single-number quantity represents the floor impact sound performance. The lower the single-number quantity value the better the floor impact sound performance. They revealed that the single-number quantity for the same CLT slabs ranged from 59 dB to 72 dB.

When the stiffness of the CLT slab was high, the single-number quantity was low and the floor impact sound insulation performance was better. Similar trends are observed in reinforced concrete slabs, where higher rigidity typically results in better floor sound insulation performance (Arenas and Sepulveda 2022; Lee *et al.* 2023). Therefore, increasing the stiffness of CLT slabs is expected to enhance their impact sound insulation performance.

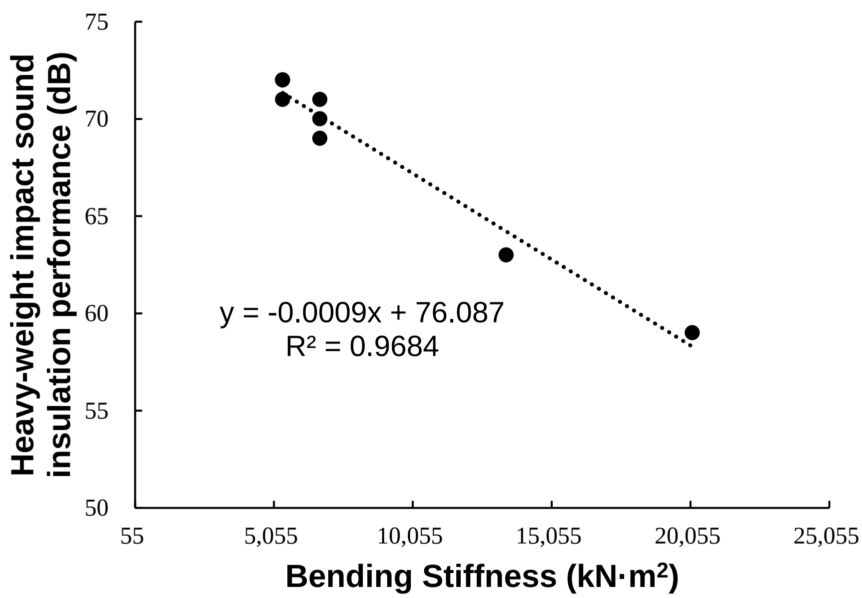


Fig. 7. Relationship between bending stiffness of CLT slab and impact sound insulation performance

Figure 8 illustrates the relationship between the dynamic and impact stiffness of the CLT slab and the heavy-weight impact sound insulation performance (dB) of CLT slabs. Both stiffness values are expressed in the same unit, kN/m. The sound insulation performance exhibited a linear relationship with dynamic stiffness and a quadratic relationship with impact stiffness. The linear trend indicates that higher dynamic stiffness is required to achieve better sound insulation performance (lower dB). These results imply that both dynamic stiffness and impact stiffness must increase to improve sound insulation performance, but with different rates and characteristics of increase.

While the lowest natural frequencies of the CLT slabs exhibited similarities, variations in dynamic stiffness were observed due to differences in the density and thickness of the respective wood species. Since the dynamic stiffness increases in proportion to the weight (Eq. 4), the dynamic stiffness satisfying the sound insulation performance of CLT slabs can be achieved by adjusting the weight. On the other hand, the impact stiffness is related to the structural system and suggests that the stiffness must increase more significantly to achieve similar sound insulation performance levels. This difference in behavior is important for designing CLT slabs to optimize inter-floor noise.

A lower sound insulation performance value indicates better insulation, and the impact stiffness is related to the structural system of the building. In other words, the results of this study suggest that a structural system with significantly high stiffness is required to achieve sound insulation performance above a certain threshold. The impact stiffness was derived by Eq. (5), and the deflection of the slab was simulated using FEM to predict the slab stiffness for different layer configurations of the slab and the load combinations, the self-weight of the slab, the force applied by the impact ball, or the weight of the experimenter.

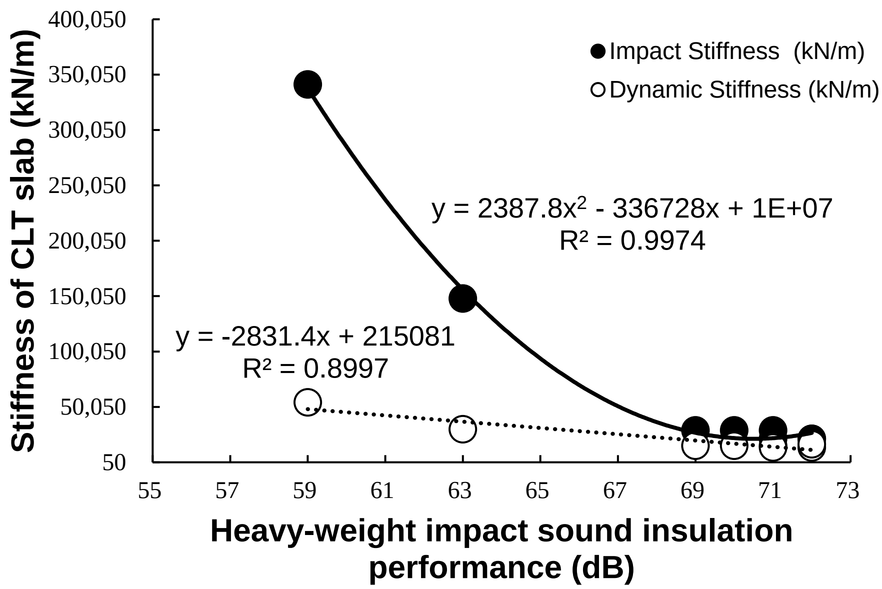
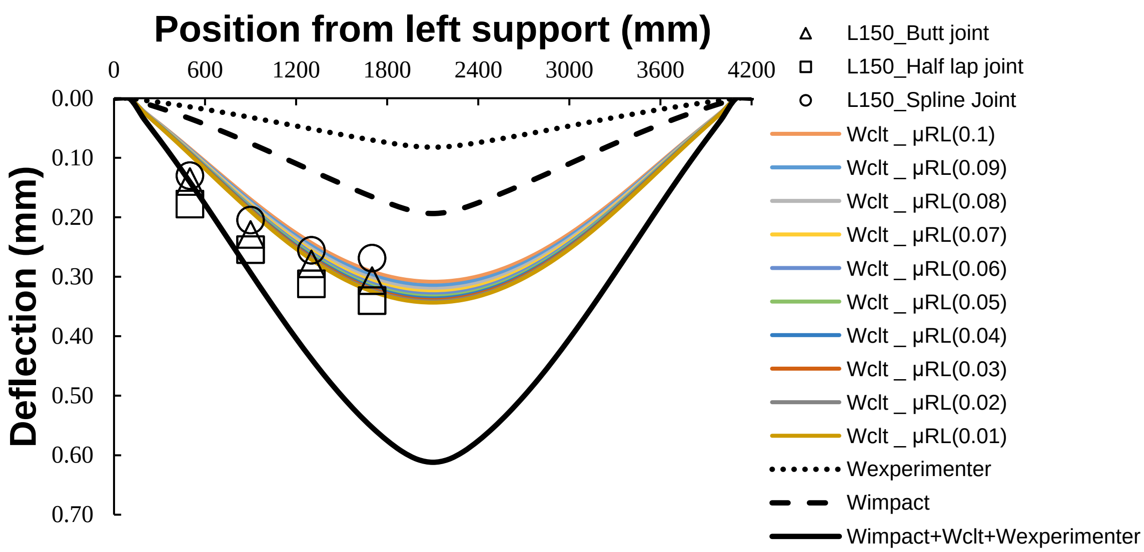
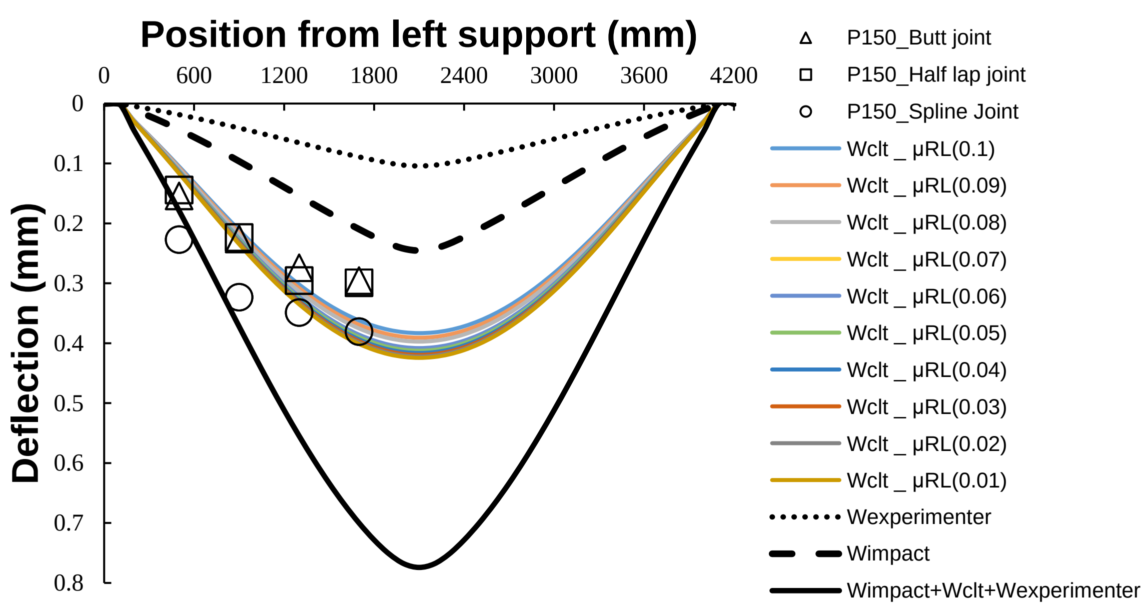


Fig. 8. Relationship between dynamic and impact stiffness of CLT slab and heavy-weight impact sound insulation performance

Figure 9 shows the deflection results of the CLT slab by FEM, showing the deflection profile along the length of the slab from the left support (0 mm) to the right support (4200 mm). In the graph, butt joints (△), half-lap joints (□), and spline joints (○) are experimental measurements, and the lines are FEM simulation results. The curve marked as Wclt_μRL(n) shows the simulated deflection according to Poisson's ratio (range 0.01~0.10) for longitudinal deformation due to radial stress. The higher the Poisson's ratio, the lower the deflection, which increases the resistance of the structure. The dotted line ($W_{\text{experimenter}}$) shows the deflection under the experimenter's load, and the dashed line (W_{impact}) shows the deflection due to the rubber ball. The black solid curve shows the deflection under all applied loads. The simulated deflection under the combined load ($W_{\text{impact}} + W_{\text{clt}} + W_{\text{experimenter}}$) was similar to the sum of the deflections due to each load, which shows that the principle of superposition can be applied.



a) Larch CLT



b) Pine CLT

Fig. 9. Predicted and measured deflection of CLT slabs

Figure 10 shows the deflection of the CLT slab measured over time. After the rubber ball was dropped on the CLT slab (the first peak), the center of the CLT slab vibrated up and down, and the vibration decreased over time due to the damping effect. The second (negative direction) and third peaks were measured to be larger than the first peak, which is the displacement when the rubber ball was dropped on the CLT slab. The slab deflects downward as the rubber ball impacts the slab. At this time, a repulsive force is generated due to the elastic recovery of the CLT. This recovery demonstrates that the material returns to its original shape after deformation, reflecting the inherent elasticity of the structure. This repulsive force pushes the slab upward, causing a displacement in the negative direction. Then, the weight of the CLT accelerates downward again, causing a larger displacement than the first peak.

After the experimenter stood on the CLT slab holding the ball, the initial deflection was set to 0 mm, and the subsequent deflection of the specimen was measured. The weight of the CLT slab was transferred to the concrete frame supporting the specimen. Therefore, the deflection under the combined load, as shown in Fig. 9, exceeded the deflection measured in the experiment. Among the simulation results, the simulation using only the weight of the CLT slab provided the closest match to the actual deflection. Therefore, the dynamic stiffness was calculated based on this simulation result.

As future research, the damping effect on the vibration and sound insulation properties of CLT slabs, long-term durability, modeling and simulation techniques, and hybrid effects with steel or concrete materials will be investigated. Such research will help expand the application of CLT slabs as a sustainable building material.

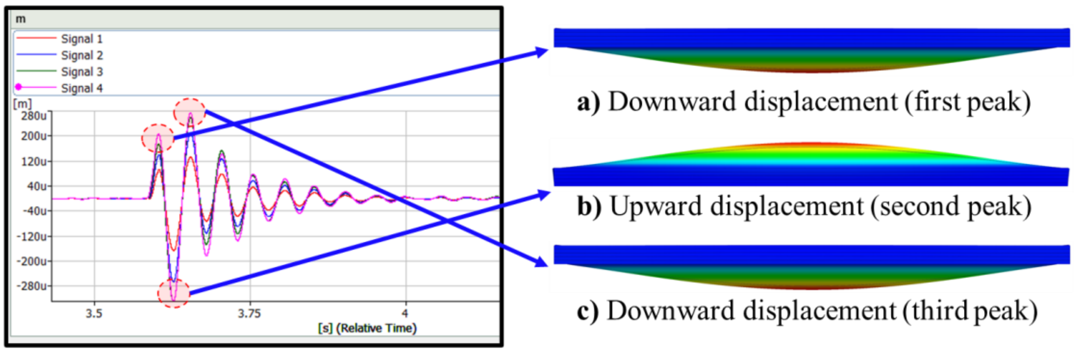


Fig. 10. Time-history deflection and deformation of slabs upon impact

CONCLUSIONS

In this study, the vibration characteristics and the floor sound insulation performance of CLT slabs were investigated based on variations in wood species and CLT panel joints. Concurrent measurements of vibrations and a single-number quantity of CLT slabs were conducted to analyze the relationship between stiffness and impact sound insulation performance.

1. The results of this study show that the wood species and panel joint types did not significantly impact the vibration characteristics and heavy-weight impact sound insulation performance of CLT slabs. These results suggest that wood species and joint methods can be flexibly applied in the design of CLT slabs, providing important information for the expansion and optimization of CLT use in the construction field.
2. The three types of stiffness in CLT slabs—bending stiffness, dynamic stiffness, and impact stiffness—were derived, and their effects on acoustic performance were analyzed. The improvement in sound insulation performance resulting from increased stiffness was quantified. These findings are expected to contribute to the development of technologies for mitigating inter-floor noise transmission in CLT slab applications.
3. The single-number quantities representing the sound insulation performance of the CLT slabs ranged from 59 dB to 72 dB. Higher bending stiffness in the CLT slabs correlated with improved floor impact sound insulation performance. An empirical formula was derived to estimate the single-number quantity based on the bending stiffness of CLT.

4. The lowest natural frequency range of the CLT slabs was consistently between 20Hz and 22 Hz, showing no significant variance based on wood species or CLT panel joint type. However, the dynamic stiffness of the CLT slabs, influenced by wood density and CLT thickness, exhibited noticeable variations among different wood species and panel configurations.

ACKNOWLEDGEMENTS

This research was supported by a Research Project (FP0200-2022-01-2024) through the National Institute of Forest Science (NIFoS), Korea.

Competing Interests

The authors declare they have no competing interest.

Authors' Contributions

Sung-Jun Pang analyzed the test results and drafted the manuscript. Hyo-Jin Lee and Yeon-Su Ha designed the experimental test procedures and analyzed the acoustic performance. Chul-Ki Kim provided the mechanical properties of CLT. Ho-Jeong Cho revised the manuscript, including figures and tables. Sang-Joon Lee managed the research project and approved the final manuscript.

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Article submitted: July 9, 2024; Peer review completed: August 1, 2024; Revised version received: October 17, 2024; Accepted: October 19, 2024; Published: November 8, 2024.
DOI: 10.15376/biores.20.1.100-120