

Article

An Experimental Comparison of Airborne Sound Insulation between Dovetail Massive Wooden Board and Cross-Laminated Timber Elements

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Abstract: Adhesives and metallic fasteners play a pivotal role in the domain of engineered wood products (EWPs). Nevertheless, owing to their origins in petroleum, adhesives can pose environmental hazards, whereas metal fasteners can complicate end-of-life disposal and reusability. Nonetheless, a resolution emerges in the form of dovetail massive wooden board elements (DMWBEs), characterized by their pure wood composition and absence of adhesive metal connections. The existing literature pertaining to DMWBEs has predominantly focused on inadequate structural analysis and model testing of connection specifics rather than appraising the efficacy of a structural member, such as a floor slab. This article presents a comparative analysis between a DMWBE and a correspondingly sized cross-laminated timber (CLT) panel, focusing on their respective airborne sound insulation capabilities. Experimental samples of model scale with dimensions of 200 mm thickness, 1160 mm width, and 1190 mm length were employed for both CLT and DMWBE. The evaluation of airborne sound insulation performance was conducted in accordance with ISO 10140-2 standards. The findings underscored the superior performance of DMWBE ($R_w = 43$ dB) in contrast to CLT ($R_w = 40$ dB) concerning airborne sound insulation efficacy. Additionally, the damping of the panel increased due to the different composition of the DMWBE, as evidenced by a higher measured total loss factor (TLF) compared with CLT.

Keywords: dovetail massive wooden board element (DMWBE); cross-laminated timber (CLT); airborne sound insulation; total loss factor (TLF)



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1. Introduction

Currently, engineered wood products (EWPs) are becoming more common in the construction sector, especially for demanding purposes [1–3]. Among the different EWPs, cross-laminated timber (CLT) is notably preferred. CLT, a prefabricated engineered wood material with multiple layers of boards bonded using adhesive and pressure, has a distinctive status [4]. The construction of CLT structures, whether prefabricated or performed on-site, significantly trims down construction schedules, making it a preferred choice for architects and structural engineers [5]. Notably, CLT finds extensive use in the construction of tall timber buildings [6], evident in buildings like the 84 m, 24-story HoHo in Vienna (2020) and the 48 m, 14-story Lighthouse Joensuu in Joensuu (2019).

Effective sound insulation performance constitutes a significant criterion for expanding the commercial utility of building components [7] and plays an important role in the acoustical conditions of buildings. Therefore, the airborne (and impact) sound insulation of CLT and other EWPs is of importance. Requirements for sound insulation between spaces are given by national regulations, but the target values and descriptors differ strongly between countries [8]. For example, the range of comparable regulatory requirements for airborne sound insulation between European countries is about 7 dB [8]. In Finland, the requirement for airborne sound insulation between apartment rooms is given as a

minimum allowed weighted standardized level difference $D_{nT,w}$, which is 55 dB. To meet this target level, CLT panels are frequently used in double walls of apartment buildings [9] since the weighted sound reduction index (R_w) of a bare CLT panel is modest, namely between 30 and 45 dB, depending on the plate thickness and composition [10].

In the context of advancing construction industry standards, adhesives and metal fasteners have become the most common connectors in EWPs, supplanting traditional wood-to-wood assemblies in modern timber constructions. This underscores the significance of adhesive bonding, as adhesives have a pivotal role in EWPs, contributing notably to wood preservation, structural robustness, lightweight attributes, and the mitigation of dimensional changes arising from ambient humidity fluctuations. Nevertheless, the utilization of adhesives prompts concerns pertaining to sustainability, recyclability, and broader environmental repercussions due to hazardous emissions (e.g., VOC emissions and formaldehyde) throughout their lifecycle [11]. Furthermore, despite ongoing strides in this research domain, significant inquiries persist concerning ecologically viable bio-based adhesive alternatives. Notably, metal fasteners, along with adhesives, hold paramount importance for EWPs; however, they introduce challenges concerning end-of-life disposal, reusability, and the recyclability of these materials [12].

Nonetheless, an opportunity persists for a resolution involving solid and untainted wood, rooted in an ancient traditional bonding technique devoid of adhesives and metal connectors—dovetail massive wooden board elements (DMWBEs). While the existing literature extensively explores the technical aspects of EWPs through various construction approaches, there remains a scarcity of investigations focused on DMWBEs. The literature on ‘DMWBE’ predominantly revolves around structural analyses and model examinations of jointing intricacies rather than encompassing an evaluation of the performance of a structural module, such as a floor slab (e.g., [13,14]). This deficiency hampers a comprehensive comprehension of DMWBEs’ potential within multistory building erection, particularly concerning their ecological impact and recyclability. As a part of this comprehension, the sound insulation performance of DMWBEs should also be studied since the changes in the mechanical properties of the EWPs caused by differing fabrication techniques are likely to influence the sound insulation of the product. This occurs since the main properties affecting the sound insulation of plate-like structures are the mass per unit area (m'), dimensions and boundary conditions, stiffness properties (namely elastic moduli in different directions), and total loss factor (TLF) [15,16].

The present study revolves around the performance of DMWBEs (depicted in Figure 1a) composed of wooden lamellae interconnected through one of the earliest joining methodologies (illustrated in Figure 1b). This fabrication technique presents an alternative to traditional CLTs by eliminating the release of harmful substances from adhesives [17]. Given the novelty of this approach, comprehensive information pertaining to its technical and structural performance remains limited, warranting further research into specific domains such as dimensional and structural stability [18]. As part of the DoMWOB project (Dovetailed Massive Wood Board Elements for Multi-Story Buildings) (refer to Acknowledgment), endeavors encompassing sound insulation were undertaken. These efforts aimed to advance the development of DMWBEs for multistory structures on a global scale, serving as a substitute for conventional EWPs [19].

Even though airborne sound insulation of EWPs can efficiently be improved with different types of building board linings or constructing them as a double structure [9], the performance of bare EWPs is also of importance. While existing research shows how changes in the CLT panels affect their sound insulation [10], an open question is how different fabrication techniques of ostensibly similar EWPs, namely DMWBEs and CLT, affect the airborne sound insulation of the product.

The primary objective of this research was to conduct a comprehensive airborne sound insulation performance evaluation by directly comparing a DMWBE with a similarly sized CLT panel. The dimensions of both materials under examination were standardized, with each having a thickness of 200 mm, a width of 1160 mm, and a length of 1190 mm. To

achieve this objective, experimental samples were meticulously prepared and utilized for conducting the performance assessments. These assessments were carried out in strict accordance with the guidelines and specifications laid out in the ISO 10140-2 standards.

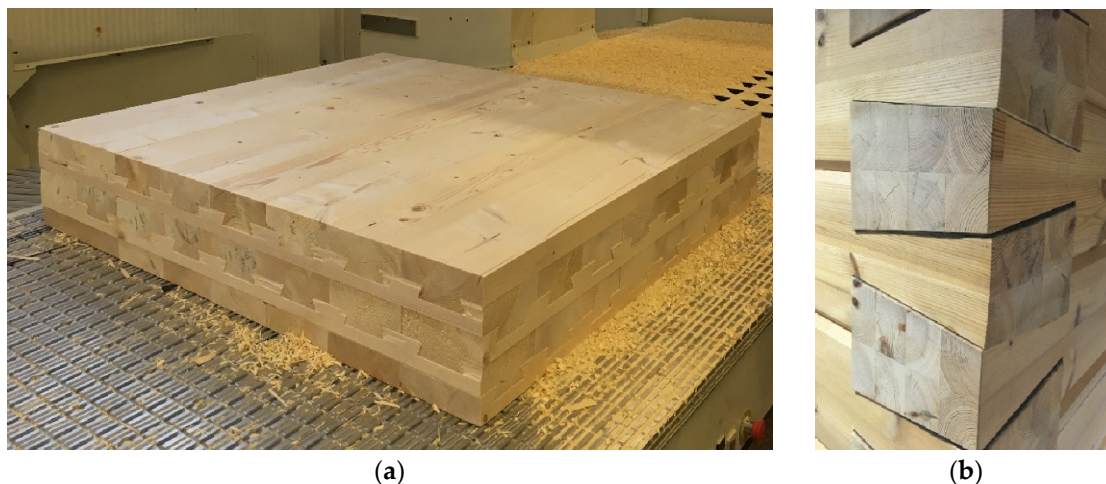


Figure 1. Dovetail concept (a) DMWBE; (b) dovetail wall connection (photos by authors).

The significance of this research extends to the domain of EWPs by introducing an innovative and environmentally sustainable alternative in the form of DMWBEs. DMWBEs represent a substantial advancement in the field due to their ability to offer improved sound insulation and fire performance [20,21] while simultaneously reducing the overall environmental impact associated with traditional building materials. This is primarily achieved through the unique attributes of DMWBEs, such as their composition of pure wood, completely devoid of adhesives or metal connections, which are known to have negative environmental implications.

Furthermore, this study not only underscores the immediate advantages of DMWBEs but also serves to broaden our knowledge and awareness of their potential applications. In particular, it sheds light on the promising utility of DMWBEs in areas where sound insulation is crucial. By recognizing the structure's sound-insulating properties, the research opens doors for its incorporation into architectural and construction projects where acoustical performance is paramount, thus diversifying the practical applications of DMWBEs within the industry. This expanded understanding of DMWBEs' capabilities positions them as a viable and sustainable choice in the ever-evolving landscape of engineered wood products, addressing both performance and environmental considerations.

The novelty of this research lies in its pioneering approach to addressing critical environmental and functional concerns associated with EWPs. Specifically, it introduces a groundbreaking solution in the form of a DMWBE, which stands out due to its unique attributes:

1. **Pure wood composition:** Unlike conventional EWPs that heavily rely on adhesives derived from petroleum, the DMWBE features a composition of pure wood. This characteristic is a groundbreaking departure from the traditional use of adhesives, reducing the environmental hazards associated with petroleum-based materials.
2. **Absence of adhesive and metal connections:** The DMWBE sets itself apart by entirely eliminating the need for adhesive and metal connections. This innovation not only contributes to improved environmental sustainability but also simplifies end-of-life disposal and enhances reusability, addressing a key challenge in the industry.
3. **Performance evaluation:** The research introduces a rigorous comparative analysis, which, to the best of our knowledge, has not been extensively explored in the existing literature. It examines the performance of the DMWBE in terms of airborne sound insulation, a critical property in building parts. The use of standardized ISO 10140-2 testing protocols ensures the reliability and repeatability of the results.

In summary, the research introduces a DMWBE as a sustainable and high-performance alternative in the field of EWPs, addressing environmental concerns, simplifying material disposal, and significantly enhancing acoustic properties. These innovative features make DMWBEs a noteworthy contribution to the field, offering potential solutions to long-standing challenges associated with traditional engineered wood products.

2. Materials and Methods

This section delineates the airborne sound insulation measurements performed on DMWBE and CLT panels at Turku University of Applied Sciences, Acoustics Laboratory (Turku, Finland). The measurements carried out by the accredited laboratory were performed according to ISO 10140-2 [22] to determine the sound reduction index R within the frequency range 50–5000 Hz. The weighted sound reduction index R_w and the spectrum adaptation terms C_i were calculated in accordance with the standard ISO 717-1 [23]. Additionally, TLFs of the installed specimens were determined according to the standard ISO 10848-1 [24].

2.1. Test Specimens

The test specimens for DMWBE and the CLT panels were constructed from Norway Spruce timber boards with a strength classification of C24 PS. Both DMWBE and CLT panels exhibited dimensions of 200 mm in thickness, 1160 mm in width, and 1190 mm in length (depicted in Figure 2).



Figure 2. Test specimens: DMWBE (**upper**) and CLT (**lower**) (photo by authors).

2.1.1. Dovetail Test Specimen

DMWBEs were produced (depicted in Figure 3) at Lapland Vocational College, located in Finland [25]. A 5-axis CNC machine integrated with the NUM operating system and compatible SOLIDWORKS computer application was employed to create the test specimen. The CNC postprocessing approach was employed, establishing an integrated framework that streamlined the various stages of finishing, tool path optimization, and G-code simulation for the fabrication procedure. The moisture content of the dovetail boards ranged from 10% to 12% during their manufacture. However, the production process encountered challenges primarily attributed to the absence of a mass production line, resulting in a relatively extended production time, as well as the necessity for diverse types of tools like blades and the need to manage dust during fabrication.

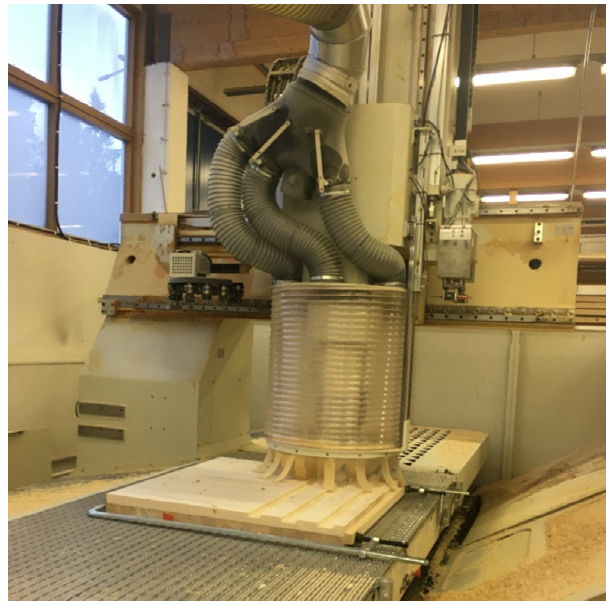


Figure 3. The fabrication of DMWBEs (photo by authors).

It is important to highlight that our calculations indicate a potential reduction in wastage by up to twenty-five percent if we utilize the rectangular pieces removed during panel production as sill or plinth. Furthermore, since the remaining waste in the form of sawdust will be repurposed for thermal insulation, we anticipate a further decrease in waste levels, making them more environmentally and economically acceptable. Consequently, the management of waste plays a pivotal role in ensuring the economic viability of panel manufacturing and will be closely managed during the mass production phase.

The DMWBE panel was originally fabricated with dimensions of 200 mm in thickness, 1015 mm in width, and 1450 mm in length, as indicated in Figure 4. It was later trimmed to its ultimate measurements of 200 mm in thickness, 1160 mm in width, and 1190 mm in length, as seen in Figure 2.

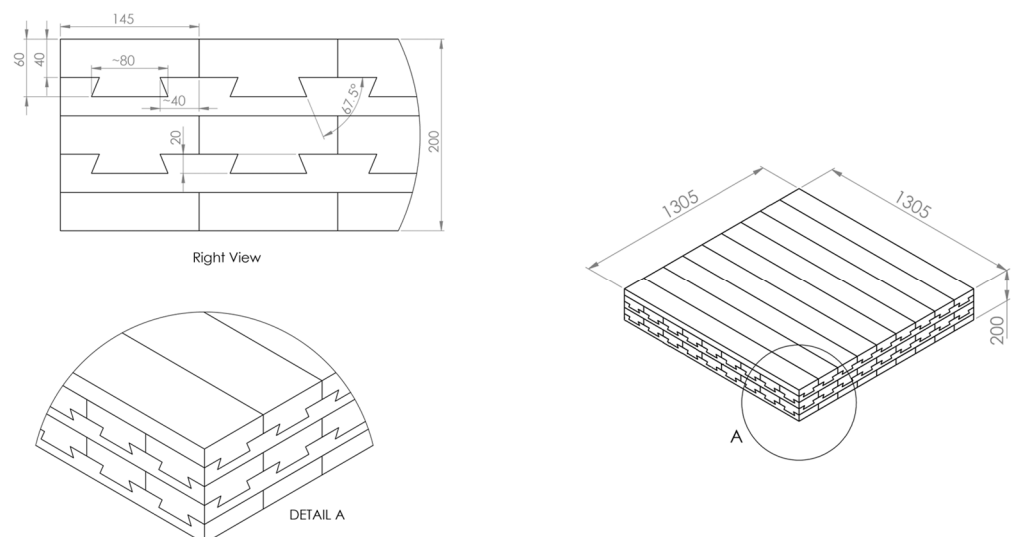


Figure 4. DMWBE test sample production drawings (all dimensions are in millimeters) (drawings by authors).

2.1.2. CLT Test Specimen

The CLT panel, designed for comparison with DMWBE, was manufactured at CLT Plant Oy located in Kauhajoki, Finland. The individual lamellae were measured to have

dimensions of 145 mm by 40 mm. In constructing the CLT panel, M1 class polyurethane adhesive obtained from Kiilto Oy (Tampere, Finland) was employed [26]. The adhesive was applied to all surfaces between the lamellae.

2.2. Mounting of Test Specimens

The height of the laboratory test opening (in total, 2100 mm) was effectively decreased by 890 mm through the addition of three concrete blocks, each possessing a thickness of 250 mm, thus adjusting the height to 1210 mm (as depicted in Figure 5). A layer of polyethylene foam (5 mm) was interposed between the concrete blocks. Consequently, the width and height of the modified opening were 1210 and 1210 mm, respectively. The test specimens and the concrete blocks were affixed within the remaining test opening. To fill the gaps between the frame of the test opening and the construction, mineral wool was introduced. This entire assembly was then enclosed on both sides using 20×20 mm wooden laths and acryl mastic for sealing.



Figure 5. Mounting of test specimens: (a) CLT; (b) DMWBE (photos by authors).

2.3. Measurement Arrangements

2.3.1. Sound Insulation Measurements

The sound in the source room was produced using five loudspeakers and uncorrelated pink noise generators for each speaker (Behringer Ultra curve DEQ 2496, Willich, Germany). The speaker signals were amplified with three terminal amplifiers (QSC RMX 850, 850, 2450, Costa Mesa, CA, USA). Sound pressure levels in the source and receiving rooms were measured using condenser microphones and preamplifiers (Brüel & Kjær 4165 and Brüel & Kjær 2669, Nærum, Denmark) and rotating microphone booms (Brüel & Kjær 3923, Nærum, Denmark) with 1 m radii of rotation. The sound pressure level measurements in the rooms were made simultaneously with an average time of 64 s. The microphones and measurement channels were calibrated prior to the measurements with a sound level calibrator (Brüel & Kjær 4231, Nærum, Denmark). A pink noise test signal used in the reverberation time measurements of the receiving room was produced with a real-time analyzer and amplified with a terminal amplifier (QSC 900 W Costa Mesa, CA, USA). The measurements were carried out with two loudspeaker positions and three receiver positions. The reverberation time was determined in accordance with the standard ISO 3382-2 [27]. The analysis was made with a two-channel real-time analyzer (Norsonic Nor121, Tranby, Norway).

2.3.2. Measurements of TLF

TLF was determined using the impulse excitation method outlined in the standard ISO 10848-1 [24,28] within the frequency range 100–5000 Hz. The measured TLF comprises the internal, coupling, and radiation losses of the structure. Since the specimens were of similar size and shape, and they were installed equivalently, it is likely that differences in the TLFs are mostly due to differences in the internal losses of the panels.

2.3.3. Other Measurements

Sound reduction indices can depend on laboratory conditions such as temperature and relative humidity [22], and thus, these environmental factors were considered when determining the sound reduction indices in the specific measurement situations. Temperature and relative humidity of the source and receiving rooms were measured using an environmental measurement device (Thermo Recorder TR-73U, Waltham, MA, USA). The specimens were weighed with a weighing machine (Vetek TI-500 SL, Väddö, Sweden), and the dimensions of the specimens were measured with a roll meter (Stanley Fat Max, New Britain, CT, USA). The laboratory dimensions and conditions in the measurements have been presented in Table 1. The mass per unit areas (m') of DMWBE and CLT panels were 84 and 85 kg/m², respectively, and the measured areas of the test elements were 1.5 m². It is important to highlight that the laboratory conditions for the sound insulation measurements were intentionally kept consistent for both specimens. This careful control of environmental factors was undertaken to guarantee the comparability and reliability of the measurement results between the two specimens.

Table 1. Laboratory conditions and dimensions.

Room temperature	21.8 °C
Relative humidity	43%
Source room volume	201 m ³
Receiving room volume	71 m ³

3. Results and Discussion

3.1. Airborne Sound Insulation and Loss Factor

Measurement results for sound reduction indices R and TLFs of both DMWBE and CLT specimens are illustrated in Figure 6. The single-number quantities describing the

airborne sound insulation of the specimens are presented in Table 2. According to the results, the sound reduction index R of DMWBE exceeds the results for the CLT panel in a large frequency range except at the low frequencies and at a few frequency bands between 250 and 500 Hz, where the results nearly match each other. These differences can be seen in the fact that the weighted sound reduction index R_w of DMWBE was 3 dB better than CLT. This difference was greater than the standard uncertainty for reproducibility of the R_w , 1.2 dB [29]. The TLF of DMWBE was major in comparison with the CLT above 100 Hz. This is one reason explaining the better airborne sound insulation of DMWBE.

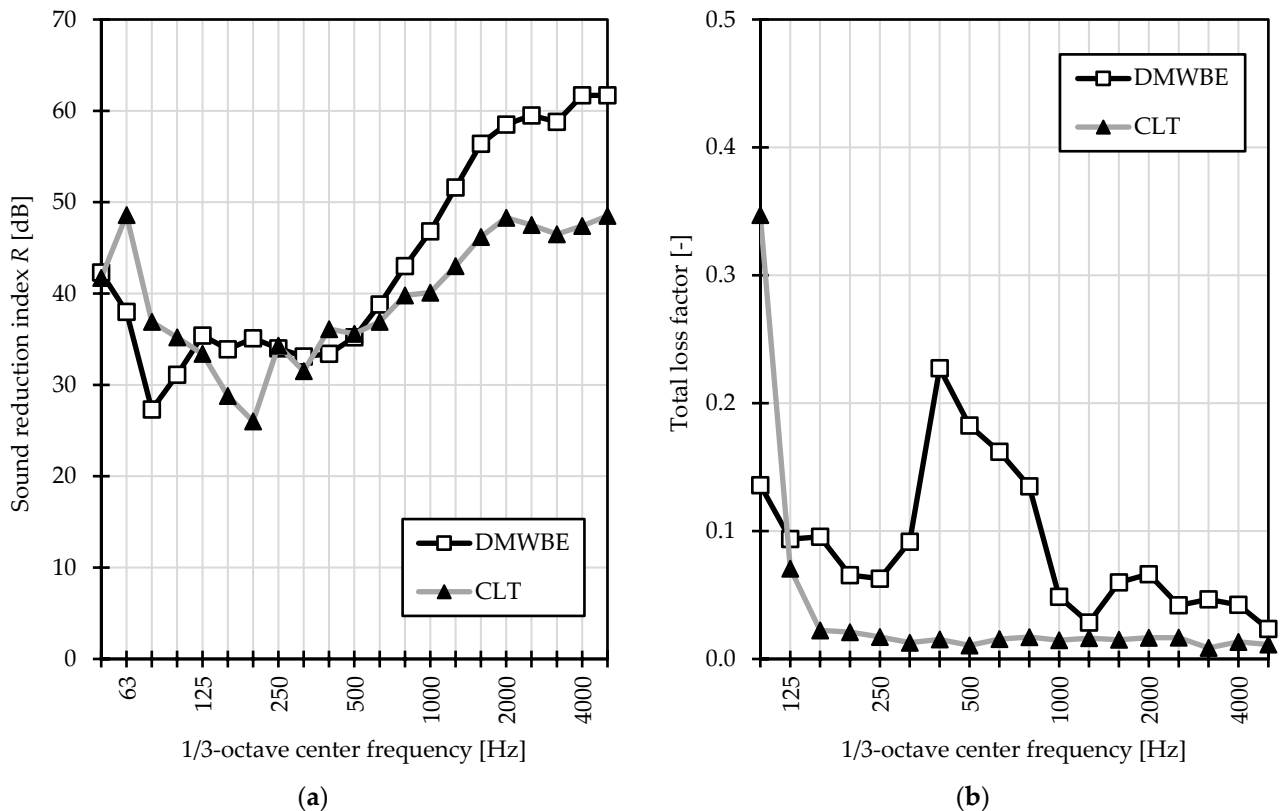


Figure 6. Measured sound reduction indices and loss factors of the 200 mm thick DMWBE ($m' = 84 \text{ kg/m}^2$) and CLT ($m' = 85 \text{ kg/m}^2$) specimens. The panels were installed similar to the laboratory opening, and their areas were $1.210 \times 1.210 \text{ m}^2$: (a) sound reduction index; (b) TLF.

Table 2. Single-number quantities for airborne sound insulation according to ISO 717-1 for both DMWBE and CLT specimens.

Single-Number Quantity	DMWBE	CLT
R_w	43 dB	40 dB
$R_w + C$	42 dB	39 dB
$R_w + C_{tr}$	39 dB	37 dB
$R_w + C_{100-5000}$	43 dB	40 dB
$R_w + C_{50-3150}$	42 dB	39 dB
$R_w + C_{50-5000}$	43 dB	40 dB
$R_w + C_{tr,100-5000}$	39 dB	37 dB
$R_w + C_{tr,50-3150}$	39 dB	37 dB
$R_w + C_{50-5000}$	39 dB	37 dB

Although the mass per unit areas, specimen sizes (both thickness and areas), installations (i.e., boundary conditions), and raw materials used to produce the studied DMWBE and CLT panels were practically equivalent, the differently fabricated specimens resulted

in differing sound insulation performance. This occurred due to discrepancies in the composition of the structures, leading to differences in the mechanical and damping properties between the panels. These, again, were affected by the different timber lamella profiles and their connection methods.

Different fabrication techniques led to discrepancies between the equivalent elastic moduli of the specimens [30]. This affected the bending stiffness and coincidence frequencies f_c of the structures (i.e., where the wavelength in air equals the wavelength of the bending wave of the panel). The coincidence frequencies f_c can be seen as a dip in the sound reduction index curve. According to the results (see Figure 6a), the higher f_c of the CLT panel occurred around 200 Hz, whereas, for DMWBE, the higher f_c was probably between 250 and 400 Hz due to the lower bending stiffness of the panel. These issues explain some of the differences between the sound reduction indices of the DMWBE and CLT panels in the low- and mid-frequency range below 500 Hz but also at higher frequencies due to the shift of the resonant part of the sound reduction indices [16].

It is evident that the absence of adhesives in DMWBE increased the damping of the panel as the measured TLF was major in comparison with the CLT (see Figure 6b). This probably occurred due to the increased internal losses of the DMWBE panel due to the remaining small air gaps between the individual boards of the panel and because of the internal frictional contacts consequently formed. However, TLF affects the sound insulation of the panels mainly above the coincidence frequency [31,32]. This is another probable reason why the sound reduction index R achieved greater values for DMWBE than CLT above 500 Hz.

Overall, to compare the sound insulation performance of the studied DMWBE and CLT panels, two important scientific factors must be highlighted:

1. Structural composition: While the mass per unit area, specimen sizes, installation conditions, and raw materials used for both DMWBE and CLT panels were quite similar, the crucial distinction lies in the composition of the panel structures. This composition directly impacts the mechanical and damping properties of the panels.
2. Timber lamella profiles and connection methods: The different fabrication techniques used in the DMWBE and CLT panels resulted in variations in the elastic moduli of the specimens. This affected the bending stiffness, sound insulation, and coincidence frequencies (f_c) of the panels. Moreover, the absence of adhesives in DMWBE played a significant role in enhancing the damping of the panel, leading to superior sound reduction indices at least above 500 Hz.

In practical terms, these scientific factors demonstrate that the structural composition, connection methods, and damping characteristics of DMWBE differ from those of CLT, leading to superior sound insulation performance. This clarifies why DMWBE outperforms CLT in terms of sound insulation in this study.

3.2. Limitations and Need for Further Research

The test campaign's limitations could include the following: (1) The study utilized experimental samples at a model scale characterized by precise dimensions (thickness of 200 mm, width of 1160 mm, and length of 1190 mm). The constrained size and scale of the samples might not accurately mirror real-world construction behavior, potentially impacting the applicability of the results. (2) The samples were constrained to specific dimensions and composition. Introducing variations in sample properties such as thickness, width, and length could offer a more comprehensive understanding of how these variables affect the effectiveness of airborne sound insulation. (3) A broader test campaign involving diverse environmental conditions and usage scenarios (e.g., varying temperature fluctuations or humidity levels) would enhance the robustness of the assessment.

Several pivotal technical performance assessments for DMWBEs have been conducted, representing a significant aspect of this study. The investigations encompassed multifaceted evaluations to gauge the behavior and capabilities of DMWBEs. The scientific literature documenting these evaluations has been published, addressing critical domains such as

fire performance [30]. These studies have provided valuable insights into the fire resistance characteristics and airflow permeability of DMWBEs. Moreover, ongoing research is dedicated to enhancing the structural bending performance of DMWBEs, specifically focusing on evaluating their potential as a floor slab element. This ongoing work aims to thoroughly assess and ascertain the structural suitability of DMWBEs in the context of floor slab applications, ensuring robustness and reliability in their performance under various loading conditions.

3.3. Practical Implementations of the Research

The research holds significant relevance for practical implementation in the following ways:

- (a) Environmental sustainability: By introducing DMWBEs with their pure wood composition and the absence of adhesives or metal connections, the research aligns with the increasing global emphasis on sustainable and eco-friendly construction materials. This makes DMWBEs a practical choice for environmentally conscious construction projects.
- (b) Improved sound insulation: The research highlights the superior sound insulation properties of DMWBEs. This is particularly relevant for applications where noise control is crucial, such as residential buildings, offices, and public spaces. The practical implication is that DMWBEs can be effectively used to create quieter and more comfortable indoor environments.
- (c) Simplified end-of-life disposal and reusability: DMWBEs' design simplifies the disposal and reusability of construction materials. This practical aspect can significantly reduce the environmental impact of construction projects and contribute to more sustainable building practices.
- (d) Versatility in construction: Understanding the enhanced performance of DMWBEs in terms of sound insulation expands their potential applications. Practical implementations can include using DMWBEs in walls, ceilings, or floors to enhance acoustic performance and create better living and working spaces.
- (e) Reduced material complexity: The elimination of adhesives and metal connections simplifies the manufacturing process and may lead to cost savings in production. This practical advantage can make DMWBEs an economically viable choice for construction projects.

In conclusion, the research offers practical solutions to the construction industry by introducing a sustainable and high-performance alternative in DMWBEs. Their benefits in terms of environmental sustainability, acoustic performance, and ease of use make them a practical choice for a wide range of construction applications, contributing to more eco-friendly and efficient building practices.

4. Conclusions

In this study, a comprehensive experimental comparative analysis was conducted between DMWBE and CLT boards with similar dimensions (200 mm in thickness, 1160 mm in width, and 1190 mm in length). The primary objective was to assess their respective abilities to provide insulation against airborne sound, following the criteria outlined in the ISO 10140-2 standard. The findings demonstrated a notable advantage of DMWBE over CLT in terms of sound insulation. DMWBE exhibited a superior insulation performance with a weighted sound reduction index R_w of 43 dB, whereas CLT achieved a rating of 40 dB, underscoring the enhanced effectiveness of DMWBEs in mitigating airborne sound transmission. The difference implies, for example, a reduced need for sound insulation linings if DMWBEs are used within sound insulative structures.

The notable aspects contributing to this enhanced performance are as follows:

- (1) Absence of adhesives and enhanced damping: One of the key factors contributing to the superior sound insulation performance of DMWBEs is the absence of adhesives in their composition. As known, adhesives in traditional construction materials can

introduce stiffness and reduce internal losses in structures, leading to less effective sound insulation. In contrast, DMWBEs' pure wood composition lacks these adhesives, allowing for increased internal losses within the panel. This enhanced damping is likely due to the presence of small air gaps between individual boards comprising the DMWBE panel. These gaps create opportunities for panel vibration to be dissipated within the structure, thus improving its sound insulation properties. However, the small air gaps between the boards themselves can also contribute to the sound insulation of the DMWBE panel.

- (2) Structural and acoustic implications: The elevated structural damping in the DMWBE is of particular significance in its sound insulation performance. When sound waves pass through the panel, the increased damping within the DMWBE leads to a greater sound transmission loss of the structure. These structural and acoustic implications underline the effectiveness of DMWBEs as a sound-insulating material.

At present, the utilization of DMWBEs in commercial and structural applications is minimal. However, recent research, exemplified by the DoMWOB project (Dovetailed Massive Wood Board Elements for Multi-Story Buildings), as mentioned in Funding, has shed light on the promising potential of the 'innovative dovetail concept'. This concept draws inspiration from one of the oldest joining techniques and holds promise for expanded applications.

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

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