SOUND TRANSMISSION LOSS OF CROSS-LAMINATED TIMBER WALLS: COMPARISON BETWEEN MEASUREMENTS CARRIED OUT IN TRANSMISSION SUITES AND POINT MOBILITY MEASUREMENTS

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The transition from concrete-based to wood-based construction is drawing more attention to the use of cross-laminated timber elements, especially in the building sector. In this context, there is a need to assess the transmission loss performances of such elements already during the research and development phase, when making several tests in sound transmission suites would be overly expensive and time-consuming. The flexural behavior of a composite structure can be determined by point mobility tests. From this kind of measurements, it is possible to estimate the loss factor of the partition and its bending stiffness which, in turn, can be used to determine its sound transmission loss once some basic physical properties are known. In this paper, the sound transmission of cross-laminated timber partitions is obtained with this method. Results are validated by means of measurements in sound transmission suites.

Keywords: cross-laminated timber, bending stiffness, wave propagation approach, coincidence frequency, sound transmission loss)

1. Introduction

The building sector is constantly looking for innovative and sustainable solutions. In areas with abundant wood resource, making wooden buildings is becoming a popular option. The problems connected to the choice of this materials are known, ranging from noise and vibration transmission [1] to limited high-temperature resistance and flammability [2, 3] and the risk of mold formation in the space between walls. On the other hand, wooden solutions are more and more exploited because they are suitable even to multi-story buildings, they can be conveniently assembled starting from pre-fabricated elements and they greatly contribute to create a warm, cozy environment.

In this context, cross-laminated timber (CLT) solutions are acquiring growing market shares. With this solution, floors and walls are realized with wood layers which are glued together with 90°-crossed lamination directions. Thanks to the alternate longitudinal-transversal gluing technique, the natural movements of the materials are reduced and the structure acquires enhanced dimensional stability.

CLT was born in the 1990s as the natural evolution of laminated timber (glulam) beams, and not only is it more sustainable and often cheaper and faster-to-install than traditional concrete/steel structures [4], but it is also more stable and more versatile than other wood construction technologies such as glulam or solid wood. In terms of thermal comfort, CLT structures ensure thermal insulation both in winter and in summer, and they contribute to regulate the room humidity level. Finally, although CLT in itself has a brittle behavior, it can be part of highly ductile structures by means of mechanical joints.

The acoustic performances of CLT are of great interest [5] because reliable sound insulation data are essential for the correct design of the building structures. The material can come in a great number of orthotropic variants because of its relatively simple construction technology. This, in a way, could confuse the designer, who must choose the most appropriate solution among several available orthotropic configurations which strongly influence the acoustic performances of the structure. In order to meet the requirements, the addition of mineral wool or fiberboard layers may also be necessary

The aim of this work is to characterize the acoustic performances of a typical plain CLT wall, using both measurements in sound transmission suites and measurements of point mobility. The latter technique can be particularly interesting for the estimation of the sound transmission loss of already-mounted partitions, thus eliminating the problem of the coupling between the panel and the acoustic modes of the test rooms, which could affect the measurement results [6].

2. Theoretical background

The sound insulation of a partition is described by the sound transmission loss, STL, expressed in decibels. The measurement of the STL is standardized in ISO 10140-2, where a procedure based on the measurement of time- and space-average of the sound pressure level in two rooms separated by the partition under test is given. The sound transmission loss for diffuse sound field is a function of the sound transmission coefficient for diffuse incidence, τ_d:

$$STL = -10 \log_{10} \tau_d = -10 \log_{10} \left(2 \int_0^{\varphi_{lim}} \tau(\varphi) \cos(\varphi) \sin(\varphi) \, d\varphi \right) \tag{1}$$

where $\tau(\varphi)$ is the sound transmission coefficient and φ_{lim} is the limit integration angle corresponding, in theory, to $\pi/2$. However, it is known that the STL values obtained with $\varphi_{lim} = \pi/2$ is underestimated, thus φ_{lim} is generally limited between 78°and 85°[7]. The incidence-angle-dependent sound transmission coefficient $\tau(\varphi)$ for a thin homogeneous plate can be written as:

$$\tau(\varphi) = \left\{ \left[1 + \frac{\mu\omega}{2\rho c} \cos(\varphi) \left(\frac{f}{f_c} \right)^2 (\sin(\varphi))^4 \eta_{tot} \right]^2 + \left[\frac{\mu\omega}{2\rho c} \cos(\varphi) \left(\frac{f}{f_c} \right)^2 (\sin(\varphi))^4 - 1 \right]^2 \right\}^{-1} \tag{2}$$

with μ mass per unit area, $\omega = 2\pi f$ angular frequency, c speed of sound in air, ρ air density, and η_{tot} overall loss factor. f_c is the critical frequency, defined as the frequency at which the trace-matching between flexural waves on the panel and waves in air occur:

$$f_c = \frac{c^2}{2\pi} \sqrt{\frac{\mu}{D}} \tag{3}$$

Here, D is the bending stiffness per unit width of the structure, which, for homogeneous structures, is essentially constant over the frequency range of interest. For sandwich structures, the bending stiffness has been found to be a frequency-dependent function D_a [8] according to an equation in the form

$$\frac{A}{f}D_a^{3/2} - \frac{B}{f}D_a^{1/2} + D_a - C = 0 \tag{4}$$

where coefficients A, B and C can be estimated from the geometric, dynamic and mechanical properties of the panel. However, depending on the type, size and mounting conditions of the structure to be tested, the "apparent" bending stiffness D_a can also be determined using either of two experimental test procedures that proved to give consistent results [9, 10, 11]. The first method is based on the measurement of the natural frequencies of suspended beams made of the material to test [12]. This method generally provides good results with limited experimental and computational effort [13]. However, when the panels are massive [14, 15] or already mounted [16], they cannot be brought into sound transmission suites, nor can beams be cut from them. In this case, the apparent bending stiffness can be estimated by point mobility measurements, as in the present work.

In the medium-high frequency range, where the modal density inside a typical frequency band is high, the space- and frequency-average of the real part of the point mobility, measured on a finite panel in several points far from the boundaries, is equal to the real part of the point mobility of an equivalent infinite structure [17]:

$$\mathrm{Re}\left\langle \overline{Y}(\omega) \right\rangle = \mathrm{Re}\left(Y_\infty(\omega)\right) \tag{5}$$

In the low frequency range, where the modal density is usually poor, frequency bands must be extended to include at least 5 modes for Eq. 5 to be still valid. The more numerous and randomly distributed over the panel surface the measurement points are, the better the space-average represents the dynamic properties of the panel. If these conditions are met, the following equation applies:

$$\mathrm{Re}\left\langle \overline{Y} \right\rangle = \frac{1}{8\sqrt{D_a\mu}} \tag{6}$$

and, consequently, the apparent bending stiffness can be found as

$$D_a = \frac{1}{64\mu\left[\mathrm{Re}\left\langle \overline{Y} \right\rangle\right]^2} \tag{7}$$

From the (f_k, D_k) pairs obtained by the point mobility measurements, the least square method is used to fit to determine the coefficients A, B and C in Eq. 4 that best fit the experimental data. Equations 1-3 are then used to obtain the STL of the panel.

3. Specimens and test conditions

The tested partitions are of three types, illustrated in Fig. 1. The characteristics of the layers are detailed in Table 1. The panels, of size 3.6 m $\times$ 2.8 m, have been tested in the sound transmission suites of the University of Padova according to the procedure outlined in ISO 10140-2 standard (Fig. 2). Point mobility measurements have also been carried out on the mounted panels in order to estimate their apparent bending stiffness according to 2. To do so, a PCB Piezotronics impedance hammer Type 086C03 was used to excite the panel, and the vibration velocity was recorded by a PCB Piezotronics accelerometer Type 352C33. The transducers were connected to a multichannel OROS analyzer Type OR36.
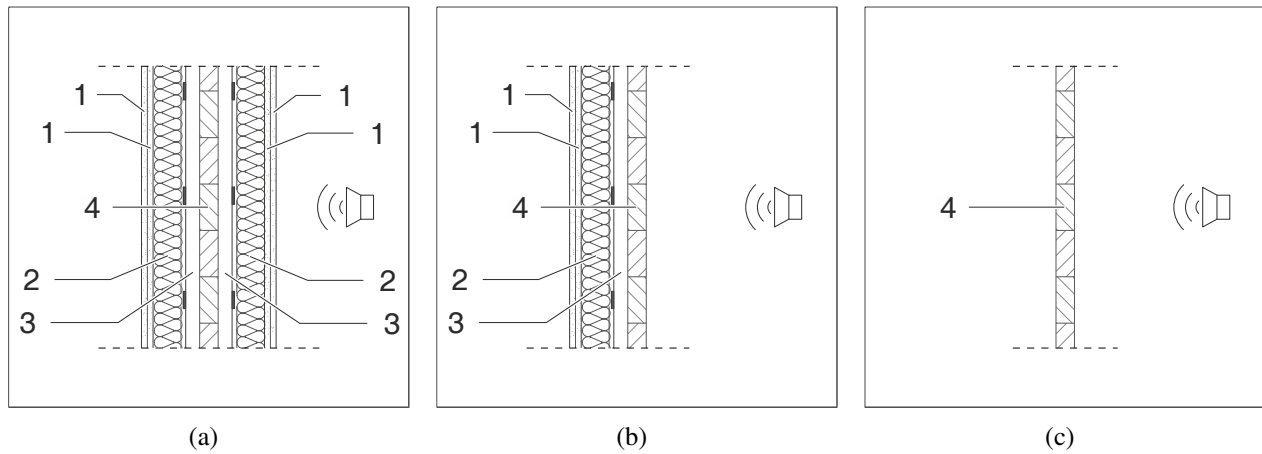
Figure 1: Types of partitions under test.

Table 1: Materials details.

Layer #	Description	Thickness [mm]	Density [kg/m^3]
1	Plasterboard	12.5	686
2	Mineral wool	50	70
3	Air	10	1.2
4	CLT with 3 layers of spruce timber alternately laid at 90° to each other	33 + 33 + 33	470

Figure 2: CLT panel undergoing tests in sound transmission suites.

In order to estimate the STL, it is necessary to determine the total loss factor of the panel (η_{tot} in Eq. 2) when it is mounted in the opening dividing the source room from the receiving room. This parameter can be calculated from the impulse response recorded during point mobility measurements. The structural reverberation time, T_R, is obtained, from which η_{tot} can be derived as $\eta_{tot} = 2.2/(T_R \cdot f_{1/3\text{oct}})$ (Fig. 3).
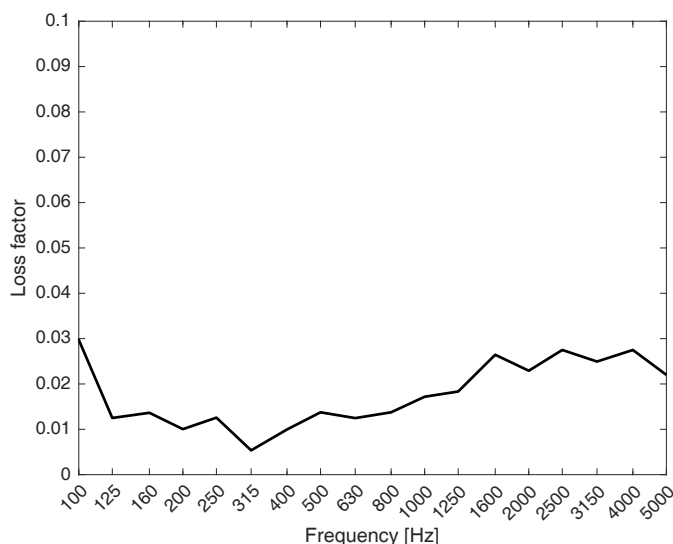
Figure 3: Total loss factor η_{tot} for the three types of tested panels.

4. Results

4.1 Measurements in transmission suites

The results of the measurements performed in sound transmission suites according to ISO 10140-2 standard are summarized in Fig. 4 for all the types of configurations under test. It can be noted that in the plain CLT wall the coincidence zone is centered around 250 Hz. The extension of the coincidence zone indicates that the material has an orthotropic behavior. Above the coincidence, the slope is in agreement with the mass law. The effect of air permeability, due to the presence of microcracks in the CLT panel, can be observed around 4000 Hz, where the STL curve flattens.

As concerns the other two layered configurations, a slight loss of insulation capability can still be noted close to the CLT coincidence zone in the case of configuration #2 (cladding only on the receiving side), while in configuration #3 the coincidence dip moves towards 500 Hz.

These results confirm that the acoustic performances of the plain CLT (weighted sound reduction index R_w = 31 dB) are not enough to meet the basic sound insulation requirements for façades or internal walls. The addition of insulating layers allows to obtain excellent sound insulation performances (R_w = 65 dB for two-side insulation and R_w = 53 dB for one-side insulation).

4.2 Point mobility measurements

The complexity of panels #2 and #3 did not allow to obtain reliable point mobility measurements, thus in the following only the results obtained for structure #1 are shown. Structure #1 can indeed be considered a sandwich panel, since it consists of three layers where the core and the two laminates have different mechanical properties, due to the different orientation of the layers.

Point mobility measurement technique allows to directly take into account the apparent bending stiffness D_a resulting from the combined characteristics of the different wood layers and from the actual boundary conditions. Once the calculated $D_{a,k}$ values are plotted against frequency, the frequency-dependence of the bending stiffness is clearly visible and the function Eq. 4 can be reconstructed by least-square method (Fig. 5). A "static" bending stiffness point has been introduced to improve the curve reconstruction. This value has been calculated as $E \cdot H^3/12$, that is, the bending stiffness per unit width
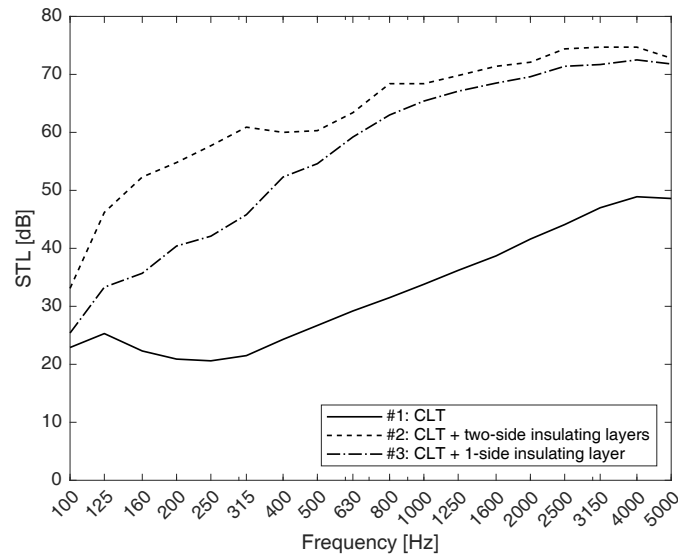
Figure 4: STL measured in sound transmission suites for the three types of tested panels.

of a homogeneous panel having Young's modulus $E = 10$ GPa, based on the technical datasheet provided by the manufacturer, and total thickness $H = 99$ mm.
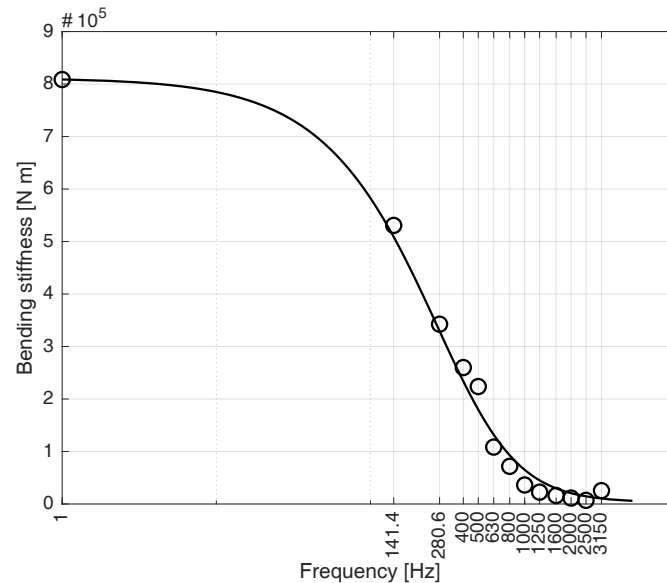

Figure 5: Apparent bending stiffness derived from point mobility measurements on the CLT wall (bullets) and reconstructed by least-square method (solid line).

Substituting the calculated $D_a(f)$ in Eq. 3 and the resulting f_c function in Eq. 2, the STL can be calculated through Eq. 1. The comparison between the STL values obtained from sound transmission suites and point mobility measurements is shown in Fig. 6. It can be observed that the coincidence zone is correctly predicted by the point mobility measurements, and that the estimation of the loss factor allows to obtain very good agreement at and above the critical frequency. The same figure reports the reference curve proposed for bare CLT wall in [18], which overall is a good estimation of the panel's STL even if the predictions based on experimental mobility measurements provide better results for the specific partition under test especially around the critical frequency.
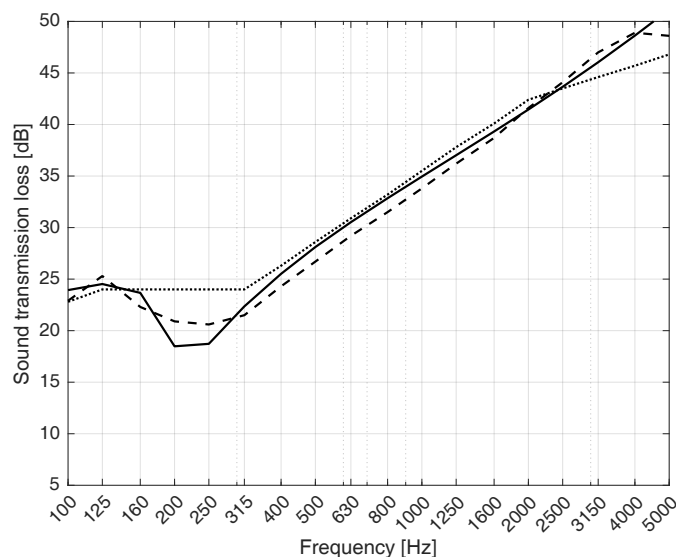
Figure 6: Comparison between STL measured in sound transmission suites (dashed line) and calculated by point mobility measurements (solid line). Dotted line: reference curve for bare CLT proposed in [18].

5. Conclusions

Cross-laminated timber (CLT) walls are increasingly employed in the building sector, thus their acoustic characterization is important to provide the built environment with the necessary comfort. Three configurations of typical CLT walls have been tested in sound transmission suites, showing that the sound insulation performances of the plain CLT wall are poor and the addition of at least one insulating layer is necessary. The application of the point mobility method allowed to identify the sandwich behavior of the CLT structure, highlighted by its frequency-dependent bending stiffness, and to correctly predict its sound transmission loss. However, it was not possible to extract usable mobility data for the two insulated configurations. In the case of complex structures involving CLT, the sound transmission loss can be estimated, for instance, using the transfer matrix method, after calculating the acoustic impedance of the CLT layer from the bending stiffness obtained by point mobility measurements [19].

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