Modelling the Sound Insulation of Mass Timber Floors Using the Finite Transfer Matrix Method

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Abstract

Cross Laminated Timber (CLT) technology has revolutionized the use of timber in construction in just 20 years. However, the development of mid- and high-rise CLT buildings has raised concerns about the sound insulation provided by these structural elements and about the reliability of simulation tools and models which are currently used. The mechanical characteristics of mass timber elements do not allow simplifications such as infinite out-of-plane stiffness, diffuseness of the vibrational field and perfectly elastic behavior upon impact, to mention a few, which are commonly assumed for traditional structures. The availability of modelling/simulation tools (and the relative input data) that provide accurate predictions of airborne and structure-borne sound insulation is therefore a current and relevant topic. This work presents an investigation into the input parameters to use for modelling CLT elements using the Finite Transfer Matrix Method (FTMM). The results of laboratory measurements on two CLT floors are compared to results obtained using two FTMM-based software packages in a three-step procedure. First, measurements were performed on two timber floor solutions. Following this, two operators working with different FTMM-based software packages performed blind simulations, based upon the information shared on the materials' characteristics. Finally, the input data were modified in order to return the best fit to the experimental data. The aim of the work is twofold: (1) to verify the degree of accuracy of the software and (2) following a reverse-engineering process, to retrieve the properties of the materials that need to be modelled through equivalent physical dimensions. The results for the bare CLT floor show that using dynamic E value for the plate modelling returns slightly more accurate results. Conversely, the question of modelling of a complete floor, including a floating floor, deserves greater attention, as modelling the resilient underlay using static values of dynamic stiffness can alter the results to a great extent.

1. Introduction

Cross Laminated Timber is an engineered wood product made of layers of wood planks, which are glued crosswise to form a monolithic element. Its development in recent years has provided the opportunity for timber construction to enter the sector of mid- and high-rise buildings (Albee et al., 2018; Muszynksi et al., 2017). The renewed attention to the characterization of the sound insulation of timber elements stems from this diffusion of multi-unit residential buildings and the consequent need for the fulfilment of the acoustic requirements according to national regulations.

Wood exhibits a strongly anisotropic behaviour but CLT elements are usually modelled as orthotropic plates due to the above-mentioned fabrication process. CLT is furthermore characterized by low structural damping and large out-of-plane bending stiffness in relation to the low density. Several hypotheses that underlie acoustic modelling of traditional building elements, such as concrete slabs or brick walls, are not verified for CLT elements. For example, the infinite out-of-plane stiffness hypothesis does not hold, and therefore the modelling of additional linings and floating floors requires cus-

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tom adaptation terms and reference curves (Di Bella et al., 2016; Schoenwald et al., 2013). Moreover, when evaluating the response to impact excitation, one must consider that no elastic rebound can be assumed on timber elements.
These considerations emphasize the need to control the input data of any simulation tool for modelling CLT elements. In this scenario, the aim of this paper is to identify the optimal input parameters for acoustic modelling of CLT elements through the comparison of experimental measurements to the results of the modelling performed with two TMM-based software packages.

2. Methodology

The study is based on a three-step procedure. First, measurements of the sound insulation of two different CLT-based floor configurations were carried out under controlled laboratory conditions. Second, information concerning the materials used for the tests was provided to two operators, using two different software packages implementing FTMM. This method was preferred to other tools such as Finite Element Method or analytical methods for ease of implementation and for reduced computational time.
The operators performed 'blind' simulations, i.e. without having access to the results of the measurements. The results of the simulations were collected and compared to the measured data. Third, a strategy for the optimization of the modelling was addressed. The optimized input values were used to run additional simulations and compared to (i) the input data chosen and (ii) the different results provided by the two software packages.

2.1 Measurements

The airborne and impact sound insulation measurements were conducted at the Laboratory of Applied Acoustics at the University of Bologna. CLT floors were mounted and tested in the acoustic chambers with suppressed flanking transmission, according to the ISO 10140 standard. For the purpose of this study, the sound insulation relative to two different construction stages are analysed:

A. bare CLT floor;
B. complete structure including: CLT, polyethylene sheet, wet subfloor, resilient interlayer, sand and cement screed.

The availability of measured data at additional intermediate stages provided the opportunity to evaluate the contribution of each layer separately.
The description of the materials is reported in Table 1; for each layer, t is the thickness, ρ is the mass density and s' the dynamic stiffness.

Table 1 – Characteristics of materials shared with the two operators

Material	Floor A	Floor B
CLT	t = 0.16 m ϱ = 420 kg/m^3	t = 0.16 m ϱ = 420 kg/m^3
PE sheet	No	Yes
Subfloor	-	t = 0.12 m ϱ = 500 kg/m^3 *
Resilient underlay	-	t = 0.01 m s' = 12.5 MN/m^3 * ϱ = 80 kg/m^3
Floating floor	-	t = 0.05 m ϱ = 1950 kg/m^3 *

* The dynamic stiffness of the resilient underlay and the density of all cast-in screeds were measured at the Laboratory of Applied Acoustics and Structural Engineering at the University of Bologna.

Additional information was provided on the mechanical characteristics of CLT, such as out-of-plane E and G moduli as declared in the datasheet. The structural loss factor η was estimated from measurements of the structural reverberation time. The information provided was deemed representative of the average data available to practitioners.

2.2 Blind Simulations

The two operators were asked to perform blind simulations of the two floors, based upon the information provided and making assumptions on the missing information. At this stage, relevant differences had already been found in the approaches of the two operators. Table 2 reports a comparison of the choices performed.

Table 2 – Modelling assumptions chosen by the two operators for the blind simulation phase

Element	OP 1	OP 2
CLT	Viscoelastic, isotropic FTMM Static value of E ν = 0.3 η as given	General laminate, 5 layers FTMM Static value of E ν = 0.01 η = 0.01 [3]
Resilient interlayer	E = 0.125 MPa ν = 0.41 [1] η = 0.2 [2]	E = 2300 MPa [4] ν = 0.08 [5] η = 0.49 [6]

[1] G. Neville Greaves, Poisson's ratio over two centuries: challenging hypotheses, Notes Rec R Soc Lond. 2013 Mar 20; 67(1): 37–58

[2] A. Schiavi, Improvement of impact sound insulation: A constitutive model for floating floors, Applied Acoustics Volume 129, 1 January 2018, Pages 64-71

[3,4,5,6] Hard rubber, from the Isotropic Elastic Material Library, Nova software, https://www.mecanum.com/nova?lang=en

The main differences are found for the modelling of the CLT element and the resilient underlay.

OP1 modelled CLT as a viscoelastic, isotropic material; this choice was influenced by previous experience in CLT modelling. Conversely, OP2 modelled CLT as a general laminate composed of 5 layers, having the thickness described in the technical datasheet. Both operators used finite size windowing and attributed to the CLT the static value of E that was provided in the datasheet. The assumption on the value of Poisson's ratio ν was different: OP1 picked the classical value of wood, while OP2 opted for an extremely low value to match the relation between the given E and G moduli, at the expense of a loss in physical meaning. For the structural loss factor η, OP1 picked the actual measured value (slightly dependent on frequency, but realistically approximated to a value of around 0.02), while OP2 picked the proposed fixed value of 0.01 (a hard rubber material was arbitrarily chosen from the existing materials library).

The resilient underlay was also characterized differently. OP1 assumed a Young's modulus of 0.125 MPa, calculated from the value of dynamic stiffness provided, and assumed damping and Poisson's ratio typical of similar materials present in the software library. OP2 also picked a resilient material from an existing library, but the elastic modulus was estimated as 2.3 GPa – indicating that the material is not used for building acoustics applications. It should be noted that the two operators had different backgrounds in acoustics: OP1 mainly works on building acoustics, while OP2 works on aerospace applications.

The results of the simulations performed with these input parameters are presented in Fig. 1.

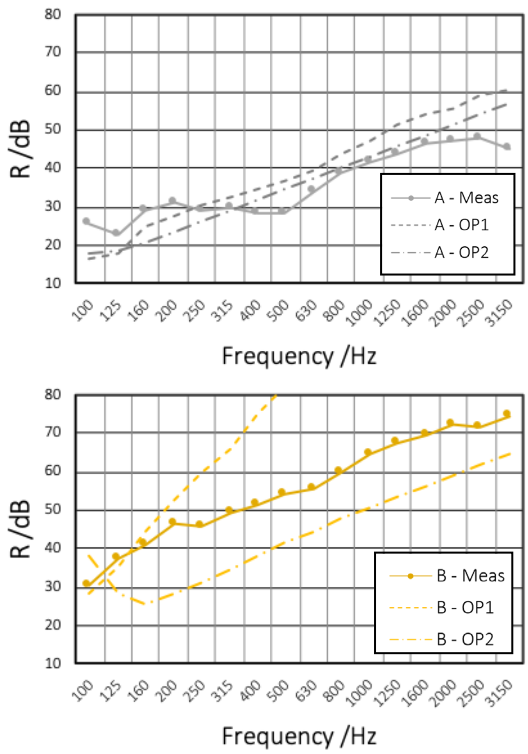

Fig. 1 – Sound reduction index R: measurements vs simulations. Top: configuration A, bare floor. Bottom: configuration B, complete floor. Measurements are represented using markers; the dashed line corresponds to OP1 while the dash-dot line corresponds to OP2

The results of the blind simulations are reported in Fig. 1. For the bare floor (configuration A), the frequency-averaged absolute difference between measurements and simulations is 6.6 dB for OP1 and 4.7 dB for OP2, suggesting that, besides software differences, the modelling of CLT as a lami-

nate provides a better estimate of the transmission coefficient. In case of the complete floor, the absolute difference between measurement and simulation results reach much larger values: 26.0 dB for OP1 and 12.6 dB for OP2.
The differences between simulations performed by the two operators are mostly related to the different input parameters chosen for the resilient underlay. The simulation performed by OP1, which uses values that closely match the actual characteristics of the resilient underlay, leads to a large discrepancy in results of the measurements.

2.3 Optimization Approach

The optimization process followed two approaches: on the one hand, objective optimization based upon mechanical characteristics of the materials and on the other hand, a 'differential' approach that seeks optimization across the available data.

2.3.1 Dynamic Young's modulus for CLT

If one considers CLT as a viscoelastic material, then its mechanical characteristics will be affected by the driving frequency; the higher the frequency of excitation, the more stiff the material will behave. The apparent frequency-dependent Young's modulus E can be calculated from Kirchhoff's theory of wave propagation in thin plates, starting from the dispersion relations (Santoni et al., 2017):

$$E(f) = \frac{12\rho c_b^4(f)(1-\nu^2)}{h^2\omega^2} \quad [Pa] \tag{1}$$

Where ρ is mass density, c_b is the bending waves velocity, ν is Poisson's ratio, h is the thickness of the considered slab and ω is the angular frequency.
The bending waves velocity of the CLT plate under test had been previously measured on the two main symmetry directions and averaged to compensate for the orthotropy of the plate. In this application, these previous results were used to calculate the dynamic E modulus.
The thin plate hypothesis underlying Kirchhoff's theory implies a relevant simplification in the estimate of E. This happens because, starting from a cut-off frequency, the dispersion curves are affected by the predominance of shear waves, and this effect is not considered for thin plates. Therefore, the E modulus is forced to compensate for this ill-posed model of wave propagation, assuming values that, at high frequencies, might not be physically meaningful (Rindel, 1994).

2.3.2 Dynamic Young's modulus for the resilient underlay

The resilient underlay can be modelled using frequency-dependent values. The measurement procedure for dynamic stiffness, reported in the standard EN 29052-1, determines the measurand at the resonance frequency of a system consisting of a 200 kg/m² plate resting on a resilient layer, which lies on an inertial base. When the measurements are conducted using an electrodynamic shaker, the force injected by the shaker is measured with an impedance head and tests are repeated for different input amplitudes, the final values being read as an extrapolation of the measured data at null frequency. Approximately speaking, the dynamic stiffness expressed as a single number only describes the behavior of the material at the resonant frequency of the above-described system. For the results presented in this paper, it will be noted that simulations carried out using a single number match reasonably well to the results of the measurements at very low frequencies, i.e. where the behavior of the resilient material is well described by the testing methodology described above.
The dynamic values used thereinafter were retrieved using a simplified scheme, in which the difference between the measurement on the bare floor and on the complete floor is attributed to the frequency-dependent mechanical properties of the resilient interlayer (Caniato et al., 2019). The input data for all other materials are assumed according to the values provided.
The standard EN ISO 12354-2:2017 provides a simplified equation to estimate the reduction of the impact sound pressure level ΔL of floating floors made of sand/cement, compared with a bare structure:

$$\Delta L = 30 log\frac{f}{f_0} \ [dB] \tag{2}$$

where f (Hz) are the one-third octave band centre frequencies and f_0 (Hz) is the resonance frequency of the spring-mass system describing the floating floor:

$$f_0 = 160\sqrt{\frac{s'}{m'}} \quad [Hz] \tag{3}$$

Where s' represents the dynamic stiffness of the resilient interlayer, expressed in MN/m³, and m' the mass per unit area of the floating floor, in kg/m².

Since the sound insulation improvement ΔL was measured (as the difference between configuration A and B, see Section 2.2), it is possible to deduce the frequency-dependent value of s′ from Equations 2 and 3. It is important to notice that the obtained value is not merely representative of the behavior of the resilient underlay, but also accounts for the global response of the floating floor.

3. Results and Discussion

The dynamic values of the elastic modulus of CLT and of the resilient interlayer were used as new inputs for the FTMM software and the updated outputs were compared to measurement results. Since the measured loss factor was almost constant in frequency, a constant value of 0.02 was considered and a Poisson's ratio of 0.3 was assumed.

The results of the previous and optimized simulation for the bare floor are presented in Fig. 2, together with the experimental results.

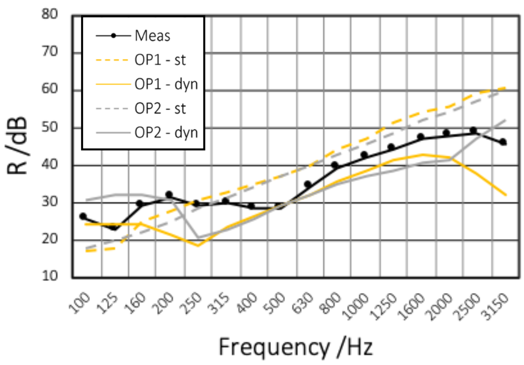

Fig. 2 – Measurements vs optimized simulations of the bare CLT floor (OP1). Measurements are represented with a continuous black line with markers, simulations with static values are represented in grey while dynamic values are presented in yellow

The results show a substantial improvement in the fit of the measured data in the frequency range above the critical frequency. For OP1, the frequency-averaged absolute error decreases from 6.6 to 5.2 dB. The difference is not relevant *per se*, but it is clear from Fig. 2 that the metric chosen is strongly affected by the behaviour of sound insulation at specific frequencies.

For the complete floor, the combinations proposed are the following:

- static E_{CLT} and static E_{RES}
- static E_{CLT} and dynamic E_{RES}
- dynamic E_{CLT} and static E_{RES}
- dynamic E_{CLT} and dynamic E_{RES}

The results presented by OP1 are presented in Fig. 3.

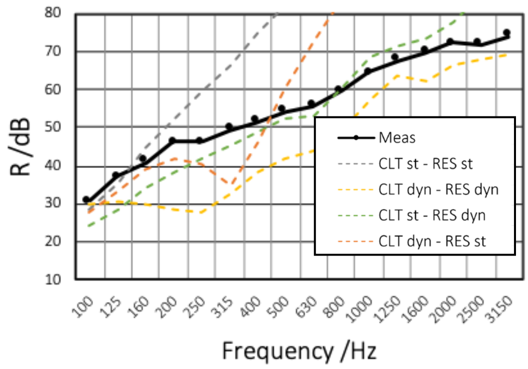

Fig. 3 – Measurement vs optimized simulations of the complete floor (OP1). Measurements are represented with a continuous black line with markers, while combinations of static/dynamic values of E for the CLT and the resilient interlayer are represented as colored dashed lines

The results that emerge from this analysis show that the most accurate analysis is achieved through modelling the CLT floor using a single static value of Young's modulus for the CLT part and dynamic values of E for the resilient interlayer. This emphasizes the need for further research on the characterization of these materials.

It should be noted that the dynamic E modulus of CLT was derived from measurements of the bending wave velocity performed on that same plate, which can be generally considered valid for all CLT panels characterized by that thickness and layer composition. Conversely, the determination of the apparent dynamic stiffness of the resilient underlay is based upon the measurements of impact sound insulation, subsequently used to estimate airborne sound insulation for one specific case. Therefore, it will be possible to draw conclusions using this approach only after analysing several experimental tests performed on the resilient underlay with different floor configurations, and through the simulation of both impact and airborne sound insulation.

4. Conclusion

This paper has explored the influence of input parameters for the modelling of Cross Laminated Timber floors using the Finite Transfer Matrix Method. The investigation was conducted by asking two independent operators to perform simulations on a CLT floor that had previously been characterized in laboratory conditions. A first series of blind simulations (without having access to the experimental measures) was performed based on the assumed characteristics of the materials and a small number of assumptions made by each operator. These preliminary results provided a satisfactory agreement between measurement and simulation results for the bare CLT floor, while the complete floor simulations returned largely biased results. The optimization of the simulations was carried out through the introduction of dynamic values of the E modulus and of the dynamic stiffness of the material, leading to a significant reduction in absolute error between simulation and measurements.

Future work will address the joint effect of the floor modelling on airborne and impact sound insulation in order to provide a reliable characterization of the frequency-dependent mechanical properties of the resilient underlay.

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