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Numerical simulation of CLT floors and comparison with empirical predictive models and measurements

Marco Caniato[1]; Federica Bettarello[2]; Andrea Gasparella[1]

[1] Free University of Bozen, Italy

[2] University of Trieste, Italy

ABSTRACT

Wooden constructions are becoming more and more present in the global building market. They are built very quickly, combining structural and thermal performance in a single layering. They are industrially produced and then assembled on site to minimize building yard problems and increase construction speed. In this scenario, acoustics is often not addressed or is delegated to additional layers that are often inserted without a studied ratio. Many studies have been carried out to predict the acoustic behavior of walls and floors using numerical or empirical methods. Recently, by means of validation with in situ measurements, the acoustic behavior of raw wooden partitions has been defined with empirical or semi-empirical laws. In this work, a new method for the determination of the floor noise of raw CLT floors comes through the use of numerical simulation with transfer matrices. Then, the results are compared to the available empirical forecasting models and real measurements.

Keywords: Cross Laminated Timber; Impact force; Impact noise; Transfer method matrix; numerical simulation

1. INTRODUCTION

Over the years, timber buildings have become a reference point for new sustainable, lightweight, prefabricated and energy-saving buildings. The growing environmental awareness of ordinary people, as well as of designers and builders has enhanced the popularity of these buildings have in both the European and Italian scenarios.

However, the increasing presence of wooden buildings has posed a series of questions about how such buildings can and should be designed. In the field of acoustics, few innovations in design methods have been introduced in recent years for this type of element. For example, in the revision of the ISO 12354 series of standards [1,2] in 2017, little more information, based on laboratory experience [3], was included as regard to timber elements for airborne and impact noise.

The classic numerical modelling approaches, often used for heavy constructions in the traditional system, are advantageous for predicting the acoustic behavior of homogeneous walls or walls with an addition of few layers. Moreover, the methods used today relate to well-defined products or layers and are not extensible to different geometries, shapes or layers. The only versatile and generalizable mathematical model is that of progressive impedances, which, as has already shown [4,5], is effective until the succession of layers does not become too complex or does not include rigid connections between different layers. However, this method only applies to airborne noise insulation and not to impact noise forecasting. In the timber buildings research related to numerical simulation , many attempts have been made, using Combined Finite Element FE and Statistical Energy Analysis SEA dedicated exclusively to wood components [6], as well as mathematical models of both floors and ceilings [7] and impact sources modelling [8]. Many simulations have been validated for specific cases both in the laboratory and in the field [9], but no general method has been applied so far for the prediction of the reduction of impact noise on timber floors made of Cross Laminated Timber (CLT).

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[1] marco.caniato@unibz.it; andrea.gasparella@unibz.it

[2] fbettarello@units.it

In fact, for the determination of impact noise reduction, the formula provided by the international standard [2] is usually used, which provides for the knowledge of the bare floor noise the resonance frequency of the floating floor according to eq. (1)

$$L_n = L_{n,0} \quad - \quad \Delta L_n \tag{1}$$

where L_n is overall impact noise (dB), $L_{n,0}$ is the noise produced by the bare floor (dB) and ΔL_n is the impact noise reduction provided by a floating floor (dB).

The determination of such parameters is not always immediate. The standard provides a forecast formulation for solid concrete slabs or beam and pot type slabs, but not a model for timber slabs. In addition, it has been demonstrated that the reduction of theoretical impact noise cannot be applied to such lightweight structures, because the relationship between mass - spring - infinite mass is not respected.

One possible method of investigation is the use of transfer matrices (TMM). Using this technique, in fact, the addition of layers, structural connections and impact sources of different nature is easy to implement. Within this numerical simulation, it is also possible to make use of the equivalent homogeneous medium technique. This method allows adding additional layers to the basic structure, modifying its mechanical properties in frequency and incorporating the properties of the second layer within the first, which becomes an equivalent homogeneous medium that has acoustic characteristics formed by the superposition of the two layers. With the addition of another layer, the procedure is repeated until all layers are considered [10]. The use of the equivalent homogeneous medium provides clear advantages as long as you know all the acoustic properties in frequency of the materials used. However, if these characteristics are not known and if you want to proceed to an optimization of the given stratigraphy, the equivalent medium is not a good choice, because it will incorporate all the characteristics of the various layers into a single equivalent one, not allowing the study of single influences.

For these reasons, the purpose of this work is to use the TMM method without the use of equivalent media and to verify its possible application first to the impact noise generated by a bare CLT floor and then to the complete structure with floating floor. The numerical simulations have been compared with previous experimental measurements by the authors, using a standard ISO tapping machine on 6 different bare floors and the equivalent complete structures.

2. MATERIALS AND METHODS

A TMM model was implemented to investigate the impact noise produced by (i) a bare CLT floor and (ii) a complete CLT with the addition of a floating floor.

CLT floors are composed by 5-ply panels of a total thickness of 18 cm, with area of 3 m x 4 m.

The acoustic and mechanical properties of the used materials are reported in Table 1.

Table 1 – Acoustical mechanical parameters

Medium	Young's Modulus [GPa]	Density [kg/m^3]	Poisson Ratio [-]	Damping [-]	Thickness [cm]
CLT	11	450	0.01	0.02	18
Foamed screed	0.8	500	0.01	0.01	10
Resilient layer	eq. (2)	30	0.20	0.40	1
Heavy screed	25	1500	0.01	0.01	5

For the determination of the Young's Modulus of the resilient layer, the equation (3) was used, inverting the impact noise reduction model (ΔL_n):

$$E = \left(\frac{f \cdot 2 \cdot \pi}{10^{\frac{\Delta L_n}{30}}} \right)^2 \cdot \quad m' \cdot d \tag{2}$$

where f is the frequency of the excitation [Hz], m' is the mass per unit area of the heavy screed [kg/m^2] and d is the thickness of the resilient layer [m].

In a general TMM simulation, the materials within the various coupled layers are assumed in the first instance to be infinite in the lateral direction, possibly leading to a significant differences between the measured values and the simulated ones, especially at low frequency. This has been avoided by using the windowing with finite limitations [13].

In order to reproduce the measurement correctly, the right impact force by single hammers has to be determined. In literature, for a perfect homogeneous rigid floor Cremer and Heckl [13] proposed a model for this force using the hypothesis that a perfect rebound was verified. In the present research, this cannot be assumed, because the interaction between the hammer and the timber floor will not produce such rebound. In literature, it could be found that a hammer impacting timber structures provides a bell-shaped frequency trend, so that such trend is more reliable for simulation purposes than a linear one [15]. In a more recent view, Lietzén et al. [16] highlighted the difference between the impact force imposed by a hammer of the tapping machine on a bare timber CLT floor from the one on a concrete floor. The first one is linear only at low frequencies and then it assumes a logarithmic drop from the middle-high range. In the second case, the force shows a linear progression, but in a very reduced range, compared to the timber one.

For these reasons, a punctual stimulus was chosen as an acting force, modeling individually the hammers of the ISO tapping machine, using a variable imposed force in frequency (Figure 1).

Conversely, when applying the impact stimulus to a heavy screed, the perfect rebound hypothesis is more appropriate and a linear trend is preferred (Figure 2). All the forces were derived from the comparison of the measured trends with the simulated ones. The models where then adjusted to fit the agreement between measured and simulated trends, in order to verify the initial hypothesis related to the force variation in frequency.

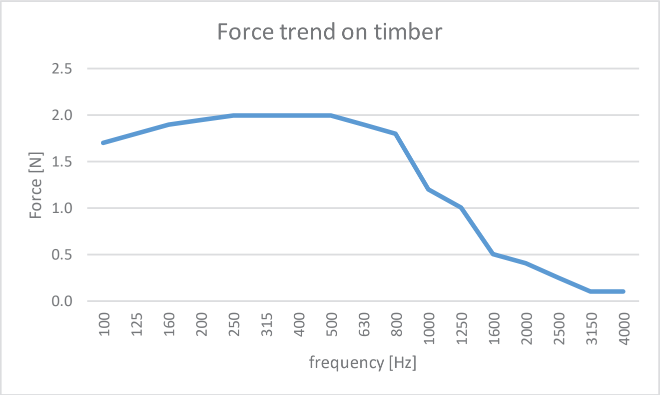

Figure 1 – Frequency spectrum of the imposed punctual stimulus for bare timber floor

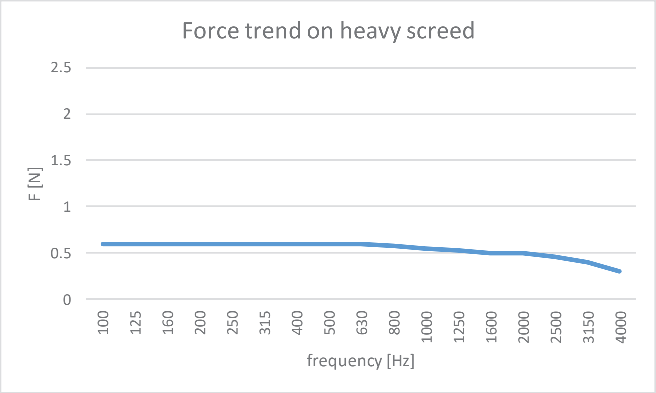

Figure 2 – Frequency spectrum of the imposed punctual stimulus for bare timber floor

3. RESULTS AND DISCUSSION

In this section, the reliability of the proposed TMM numerical simulation is compared with measured results.

The measured impact noise frequency trend is reported in Figure 3. In Figure 4 the average measured trend with the corresponding uncertainty is compared to the literature one for a 25 cm bare floor [11]. As it is evident, at medium-high frequencies, the two trends are in good agreements, while for lower ranges the influence of the thickness is highlighted. This result is in agreement with previous studies [12].

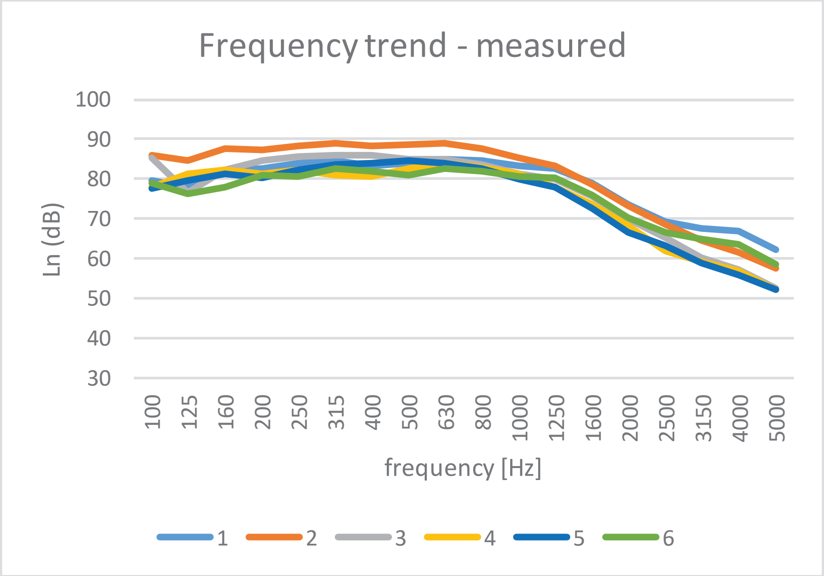

Figure 3 – Impact noise frequency trend of the measured bare CLT floors

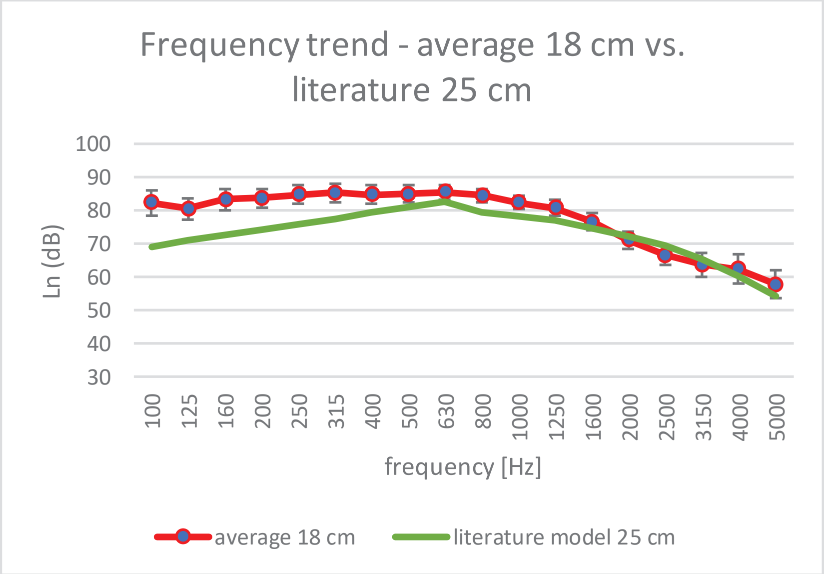

Figure 4 – Average impact noise frequency trend compared to literature one

In Figure 5, the impact noise frequency trend of the complete structure with floating floor is reported.

In Figure 6 the comparison between the ΔL_n measured and calculated values is reported, highlighting how the traditional and most used formulation for the sound reduction of impact noise could not be applied to timber floors. It is worthy to note that the ΔL_n values obtained by the measurements really differs from the one forecastable by the Cremer equation [17]. This result strengthens the thesis that a variable force in frequency has to be used, coupled with a punctual noise source.

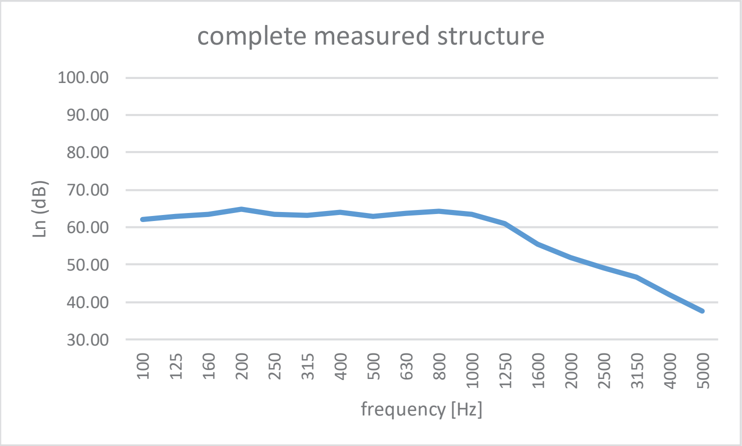

Figure 5 – measured impact noise on complete floor

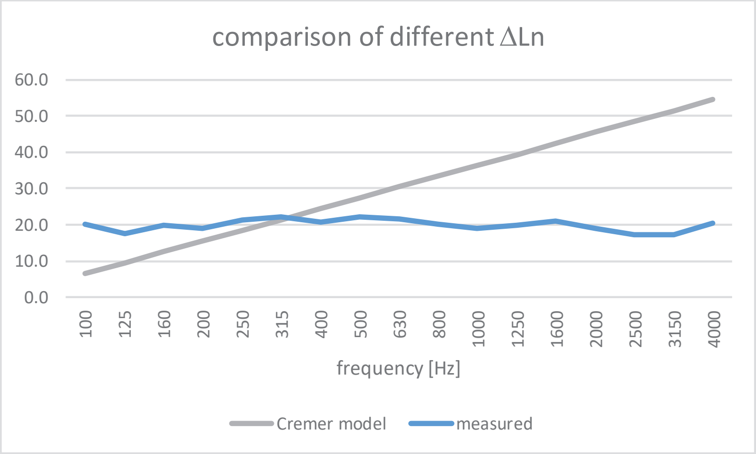

Figure 6 – comparison between measured and calculated ΔL_n values for complete floor

In Figure 7, the comparison between bare floor numerical simulated values and measured ones is reported, while in Figure 8 the same procedure was applied to complete structure. Even though several approximations are made, especially regarding the determination of the exciting force, a satisfying agreement is found.

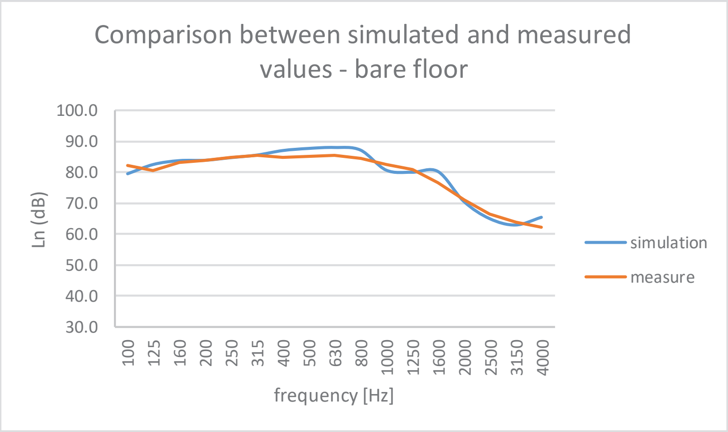

Figure 7 – comparison between measured and calculated values for the bare floor

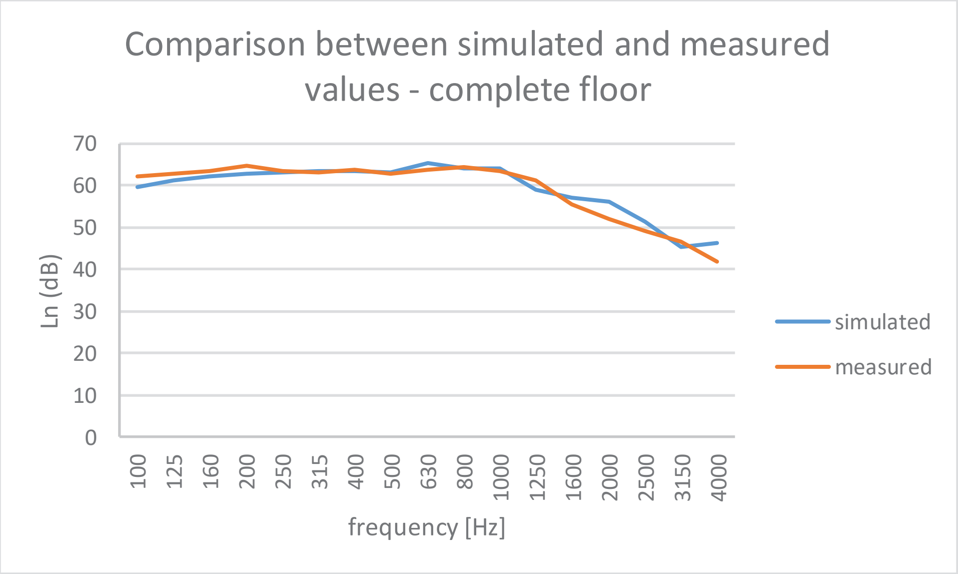

Figure 8 – Comparison between measured and calculated values for the complete floor

4. CONCLUSIONS

In this work, a TMM approach is applied to CLT floors, for the determination of impact noise. Measurements and numerical simulations are performed both on a bare structure and on a complete one, adding a floating floor.

A study on the force of tapping machine hammers is performed, because the impact impinged on the CLT bare floors (non-perfect rebound) is not equal to the one on the heavy screed (perfect rebound). For his reason, a punctual and frequency depending excitation is used in TMM simulation, in order to emulate the real behavior of the noise source.

Furthermore, a frequency dependent Young's modulus is associated to the resilient layer, basing on the inverse formula of the noise reduction.

The vibroacoustic response of the bare CLT panel is computed by means of a TMM numerical simulation, in order to evaluate the impact noise level generated by a standard tapping machine, using a bell-shaped frequency dependent punctual force excitation. Even though an approximate approach is used to determine the force spectrum, good agreement was found between numerical and experimental data. The same procedure, but with a linear frequency trend punctual force, is applied to complete structure, achieving again a good agreement between the two procedures.

Thus, the validation of the simulations demonstrates how TMM could be used to determine the impact noise of CLT bare and complete floors, using a frequency depending punctual excitation and a frequency dependent Young's modulus related to the resilient layer.

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