INTERACCIÓN ACÚSTICA/ESTRUCTURA EN LOS EDIFICIOS DE MADERA

ACOUSTIC/STRUCTURE INTERACTION IN TIMBER BUILDINGS

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Resumen

El desempeño acústico y estructural está estrechamente relacionado en los edificios de madera contralaminada (CLT). La baja densidad de los paneles relacionada con su alta rigidez son las razones que determinaron el éxito del CLT en áreas sísmicas de alto riesgo; sin embargo, estas mismas características son las razones del aislamiento acústico relativamente deficiente que proporcionan como elementos estructurales desnudos. Este artículo investiga los aspectos de la construcción masiva de madera en la que la optimización de uno es perjudicial para el otro. Dado que en ambas disciplinas una parte relevante de la transmisión de vibraciones (o cargas) se lleva a cabo por las conexiones metálicas, el trabajo se centra en el desempeño acústico y estructural de las uniones de CLT, a través del análisis de pruebas acústicas y estructurales y el modelado simplificado. Primero, se analiza la influencia del tipo y número de tornillos, angulares para fuerzas de tracción y de corte en relación con las restricciones estructurales y su desempeño acústico. Los resultados muestran que los diferentes sistemas de conexión afectan la transmisión de vibración de una manera relevante y deben compensarse mediante un diseño preciso de los revestimientos internos. Segundo, se discute el uso de las capas elásticas en la unión pared-piso. Si, por un lado, esa capa proporciona un aumento significativo del índice de reducción de la vibración, por otro lado, la aplicación de esta capa puede causar una reducción de la capacidad de carga final de la unión hasta un 38%, lo que sugiere que la elección del perfil de insonorización debe ser precisa.

Palabras-clave: acústica, madera contralaminada, uniones, capas resilientes.

Abstract

Acoustic and structural performance are closely related in mass timber buildings. The low density of the panels related to their high stiffness are the reasons that made Cross Laminated Timber successful in high-risk seismic areas; nevertheless, these same features are the reasons for the relatively poor sound insulation that they provide as bare structural elements. This paper investigates the aspects of mass timber construction in which the optimization of the one is detrimental to the other. Since in both disciplines a relevant part of the transmission of vibrations (or loads) is carried out by the metallic connections, the work focusses on the acoustic and structural performance of CLT junctions, through the analysis of acoustical and structural tests. First, the influence of the kind and number of screws, hold-downs and angle brackets is analyzed in relation to the structural constraints and their acoustic performance. The results show that different connection systems affect the vibration transmission in a relevant manner and must be compensated through an accurate design of the internal linings. Second, the use of the resilient interlayers at the wall-floor junction is discussed. If on one hand it provides a significant increase of the vibration reduction index, on the other the application of this layer can reduce the ultimate load capacity of the junction up to 38% - suggesting that the choice of the soundproofing profile must be accurate.

Keywords: acoustics, cross laminated timber, structural junctions, resilient interlayer.

1. INTRODUCTION

The market of timber construction is rapidly expanding in Italy, reaching the fourth place in Europe with a production value that touches 7 million euros (Federlegno Report 2019). The percentage of timber buildings among new buildings is 7.2%, the majority of which are detached houses, even though in recent years the realization of mid-rise buildings is increasing noticeably.

Timber demonstrated a distinguished performance as a structural material (Loss *et al*., 2018), and literature emphasized the excellent performance of timber construction in terms of thermal insulation, fire resistance and carbon footprint (Asdrubali *et al.*, 2017, Caniato *et al*., 2017). The acoustic performance of timber buildings is affected by the feature that make it a desirable material for structural purposes, such as low mass and high stiffness. In the case of timber frame buildings, the bare structural wall is characterized by a low mass, implying a poor acoustic insulation, especially at low frequencies; mass timber elements have a higher surface mass compared to framed structures, but the combination of low density associated to a high stiffness generates dips in sound insulation associated to the critical frequency of the plate, that occurs between 400 and 800 Hz depending on the thickness of the plate. These deficits can be compensated through the design of appropriate claddings.

Timber buildings provide high levels of comfort as perceived by the inhabitants. Within the Acuwood project (Späh *et al*., 2012), the degree of satisfaction towards timber houses was assessed through listening tests and questionnaires distributed to over 300 inhabitants. Out of the ten comfort factors considered, the judgment ranked as the least satisfactory the following features: acoustics, vibration protection, control/feedback and visual comfort. Considering that control/feedback and visual comfort cannot be directly related to the construction technology, one can infer that acoustics plays a relevant role in the perception of comfort for timber houses. Acoustic comfort in timber buildings is often confused with the disturb caused by the vibration of the structure (Johansson, 1995); structural vibration becomes therefore a field of cross-competence between the fields of acoustics and statics, as it regards perceived comfort (Sjöström *et al*., 2010).

These interactions emphasize the need for an integrated approach between acoustics and structural design. To this aim, this paper seeks to collect the experience that has been gathered in relation to the interaction between acoustics and structure, identifying possible topics for future investigation. The focus of this paper will be on Cross Laminated Timber (CLT) buildings, that are prone to develop mid- to high-rise elevation. In fact, sound insulation must be achieved between dwellings, rather than between partitions of a single house unit; similarly, the structural design of timber buildings becomes more challenging with increasing height.

2. STRUCTURAL JUNCTIONS IN CLT BUILDINGS

The most relevant interaction point between acoustic and structure in CLT buildings is represented by the junction between elements. In general, the vertical loads are transferred by CLT panels, screws and hold-downs, while horizontal loads are transferred through angle brackets.

3.1 Flanking transmission in structural junctions

The apparent sound insulation between two rooms can be described as the energy sum of the sound insulation of the partition that separates the rooms, and by all contributions that are transmitted into the receiving room from the adjoining partitions, the so-called flanking transmission (ISO 12354-1). Within the description of flanking transmission paths, one contribution is represented by the vibrational energy of coupled structural elements that is suppressed by the junction, namely the vibration reduction index K_{ij}, measured according to ISO 10848-1. Therefore, besides structural loads, the junctions play a role in the acoustic insulation of the building element.

In order to suppress flanking transmission, a resilient interlayer is placed at the junction between CLT elements. The experimental campaign conducted within the *flanksound* project showed that resilient interlayers can increase the vibration reduction index K_{ij} by 5 dB over a large frequency range (Morandi *et al*., 2018). The results of the tests are shown in Fig. 1, reporting the K_{ij} measured on a CLT junction without resilient interlayer (bare floor) and with the interposition of different resilient interlayers (Res 1, 2, 3). The different mechanical characteristics of the resilient interlayers cause the different performance.

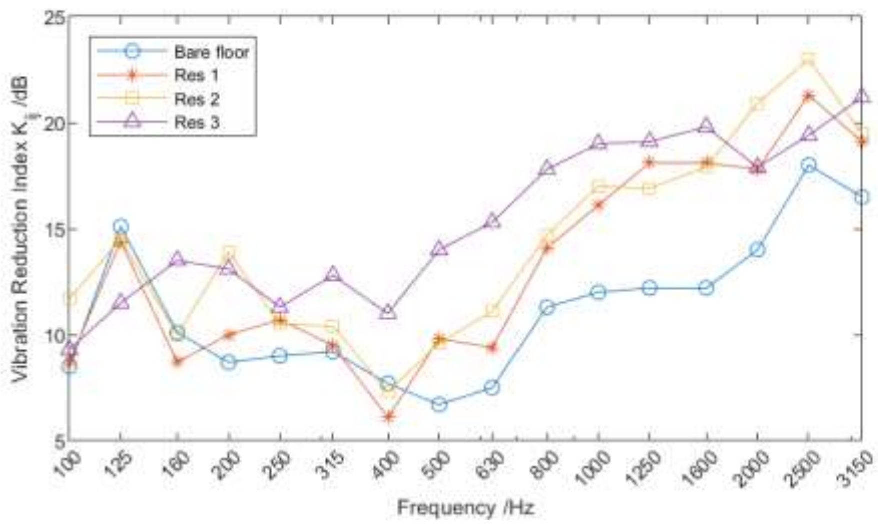


Figure 1: Vibration reduction index K_{ij} (dB) measured on a wall-floor junction without (bare floor) and with (Res1/2/3) the interposition of a resilient material, after (Morandi et al., 2018).

From a theoretical point of view, all flanking transmission paths should be suppressed. Therefore, considering a wall-floor-wall junction, the resilient interlayer should be placed both above and below the vertical walls. In practice, different choices can be made based upon acoustic/structural/economic concerns, as shown in Figure 2a. Considering the high cost of the resilient layers, many practitioners decide to place the material either only above or only below the vertical walls. For instance, one can argue that the greatest problems of sound insulation of CLT element derive from the impact sound insulation, and that therefore decide to use the layer only below the slab to prevent the transmission of impact sound.

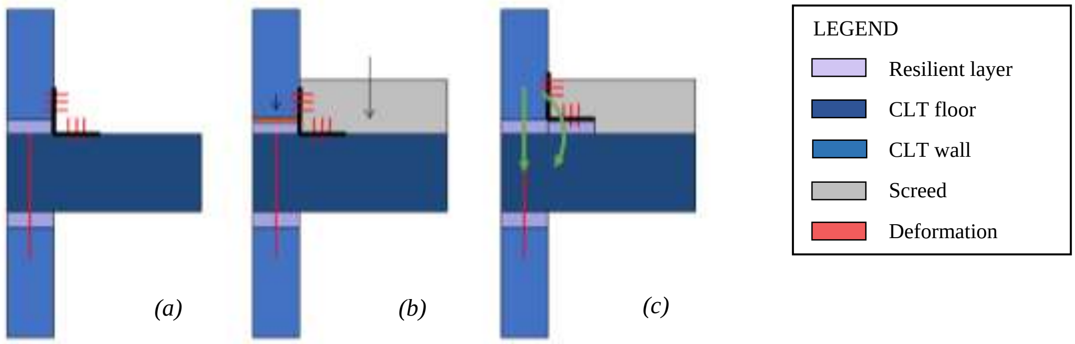


Figure 2: Schemes of CLT junction with the soundproofing profiles: (a) resilient stripes are places between timber elements; (b) the structure is loaded by permanent non-structural loads and the resilient layer is compressed; (c) the resilient layer is placed also below the metallic connectors, modifying the load transmission.

Other considerations can lead to opposite conclusions: evaluating the out-of-plane flexural rigidity of CLT, one can guess that most of the energy is radiated in the receiving environment directly from the floor itself, especially for impact sound insulation - and therefore the resilient layer is put only above the slab to prevent airborne transmission. Aesthetics also plays a key role in this decision, because when CLT is visible, it could be troublesome to place a colored stripe at the junction.

Resilient interlayers, as discussed so far, are only placed between timber elements: metallic connectors such as angle brackets remain directly screwed to the panel, providing a privileged transmission path. Resilient interlayers could also be placed also angle brackets (Figure 2b): experimental measurements determined that this does imply any improvement of the vibration reduction index.

These considerations only hold for CLT buildings that have a platform frame design: balloon frame buildings do not allow the use of resilient interlays, and the flanking transmission for these structures is a topic to address with specific research activities.

2.2 The mechanical resistance of the junction with resilient interlayer

The presence of a resilient interlayer in the junction, though beneficial for the sound insulation, separates the metallic connectors from the timber elements, and thus causes a decrease in mechanical performance of the junction from the structural side.

Within the *X-REV* project, experimental tests were performed at the CNR Ivalsa in order to investigate the mechanical performance of angle brackets in presence of the resilient interlayer with different thickness and stiffnesses (Rothoblaas Internal Report). Monotonic tests were performed with displacement-controlled loading procedures and the ultimate carrying capacity of an angle bracket fixed with nails was evaluated in combination with different soundproofing profiles, placed on both sides of the connector.

As reported in Table 1, the maximum and ultimate force and displacement of the connection are strongly affected by the presence of the resilient interlayer. The maximum force of the connection decreased by 7% and 38% respectively, depending on the material used. Since the stiffness of the resilient interlayer are extremely small compared to the stiffness of CLT and of the connectors, its contribution is not expected to affect the results as much as the layer's thickness. Therefore, these tests also provide an indication about the maximum acceptable thickness for a resilient interlayer to guarantee the proper behavior of the junction.

Table 1. Maximum and ultimate loads and displacement tested with and without the soundproofing profile (Rothoblaas Internal Report).

Test configuration	F_{max} [kN]	v_{max} [mm]	F_u [kN]	v_u [mm]
Angle bracket	70.0	15.4	57.2	8.4
Angle bracket + Mat 2 (7 mm)	65.1	30.0	65.1	30.0
Angle bracket + Mat 1 (12 mm)	43.5	23.0	40.3	19.3

The presence of the resilient interlayer can also affect the mechanical resistance of the wall assemblies (Schmidt, 2018). Tests performed at the Karlsruhe Institute of Technology aimed at characterizing the performance of dissipative connectors between vertical CLT panels when a soundproofing profile is inserted. Monotonic and cyclic tests were conducted on CLT elements, with different boundary and loading conditions.: The results showed that, when the assembly was tested for horizontal forces and no resilient layer was interposed, the connectors dissipated energy as predicted. Conversely, when a resilient interlayer was inserted, all the force injected on the system was absorbed by the resilient material, and the panels rotated rigidly as a single body, losing almost all dissipation capacity. A rough scheme of the different failure mechanism is presented in Figure 3.

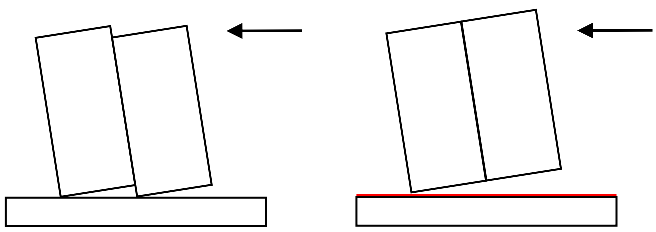


Figure 3: Scheme of the test results achieved at the Karlsruhe Institute of Technology. Left: the junction was assembled with no resilient interlayer and the connection correctly dissipates energy. Right: the resilient interlayer prevents the junction from dissipating energy.

2.2 Deformation of the resilient interlayer

In heavyweight structures, sound insulating profiles are placed below non-structural elements (such as brick walls) because the continuity in the junction of pillars and beams must be guaranteed. Therefore, a typical stripe, with a given modulus of elasticity, is used throughout the building. In timber construction, sound insulation profiles can also be placed below structural elements, and the continuity of the structure is granted by the connection. Therefore, the stripe below each static load must be chosen according to the elastic properties of each profile.

The design conditions for viscoelastic materials usually require a deflection ranging between 5 and 15%. Knowing the elastic modulus of the material and the vertical load, one can estimate the cutoff frequency of the mechanical system, to ensure it is working properly from the mechanical point of view. In real applications, the resilient layer is not free to deform under the vertical loads because it is fixed by screws, nails, staples. Therefore, it is important to verify if the material works properly in exercise conditions.

During the construction of a CLT building, the metallic connectors are fixed after the completion of the bare timber structure. A great share of the permanent loads is introduced after fixing the structural elements, with permanent non-structural loads (screeds, counter walls, etc.) and non-permanent loads. Therefore, two scenarios are possible: (i) either the resilient interlayer does not deflect because the connections "prevent" the deformation (therefore the resilient interlayer is not effective); (ii) alternatively, the layer deflects, and the vertical strain is compensated by the screws of the angle brackets and hold downs. In this case, the thickness of the layer plays a key role because, assuming a deformation in the range 15-20%, it could determine the additional stress that connections undergo and the total lowering of the structure.

The evaluation of the elastic properties of the resilient material deserves attention as well. It is well known that each testing procedure for the elastic modulus yields different results; moreover, materials are usually testes under standardized boundary conditions, while when applied at the interface between two timber elements, they could display extremely different behaviors.

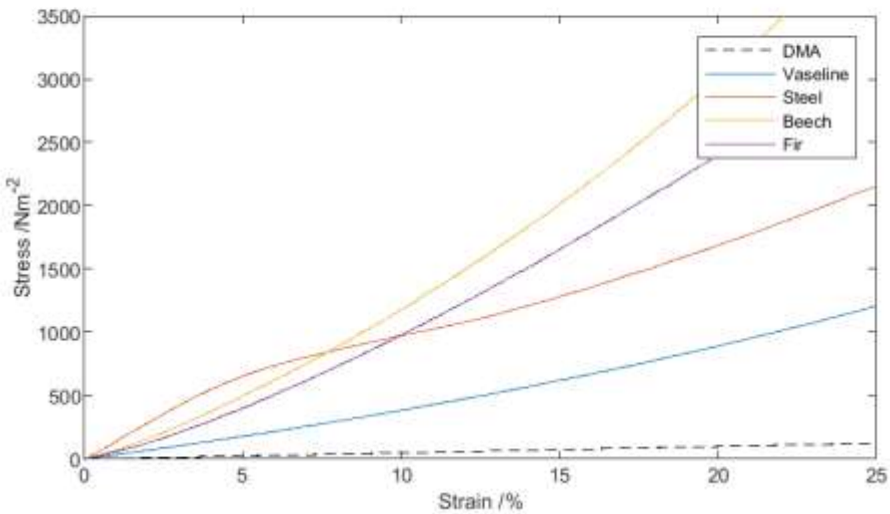


Figure 4: Stress-strain relations for a resilient interlayer tested under different friction conditions, after (Barbaresi et al., 2017).

Quasi-static strain-controlled tests have been conducted on a resilient material, pointing out that the elastic modulus of the same material measured with different friction conditions returns extremely different results (Barbaresi *et al.*, 2017). Four boundary conditions were analyzed: steel plate, steel plate with vaseline, beech wood and firwood. The stress-strain relations for these four boundary conditions are reported in Figure 4. Measurements showed that the elastic modulus of the resilient material evaluated through Dynamical Mechanical Analysis testing can be strongly underestimated compared to the real on-site condition. This means that the material in practice could be barely strained by the design loads.

It is also worth evaluating how the mechanical characteristics of the layer change with temperature, considering both working temperatures and fire events. The elastic modulus of viscoelastic materials decreases with increasing temperatures. Since this element carries structural loads, it is important to understand up to which temperatures it will be able to guarantee structural loading capacity, both via dynamical mechanical thermal analysis and through thermogravimetric analysis.

3. CONCEPTION AND DESIGN OF THE BUILDING

3.1 Wet or dry solutions?

One of the main advantages of building constructions is that construction times can be extremely fast compared to traditional structures. Besides the completion of the structure, one can chose to install a dry or a wet screed solution. This choice has obvious acoustic and structural implications. On the one hand, the increase in the mass of the building favors its inertial response to a seismic event; on the other hand, it increases the forces acting on the structure itself. The sound insulation is affected by the mass of the system, by the stiffness of the elements and the composition of the mass-spring-mass system represented by the floating floor. The addition of mass generally corresponds to an increase in the acoustic performance of the building element, but the realization of wet screeds translates into longer construction times.

Acoustic measurements were conducted at the University of Bologna aiming at comparing different construction solutions for CLT. The details of the floor solutions analyzed are reported in Table 2.

Figure 5 and 6shows the sound reduction index R and the normalized sound insulation index L_n measured on four CLT floors, two of which built using dry screeds (A and B respectively), and two using wet screed solutions (C and D respectively). For each design choice, two solutions were chosen, characterized by different surface masses.

The lowest airborne sound insulation is achieved with floor number C, characterized by the minimum surface mass. As it concerns impact sound insulation, it is clear from Fig. 5 that the dry solutions achieve better performance at high frequencies and provide lower insulation at low frequencies. Comparing floors C and D, it can be noticed that the presence of a heavier layer as subfloor increases the insulation in a relevant way.

Table 2. CLT floors tested in the Acoustic Laboratory of the University of Bologna.

	Floor A	Floor B	Floor C	Floor D
CLT	160 mm, 420 kg/m^3	160 mm, 420 kg/m^3	160 mm, 420 kg/m^3	160 mm, 420 kg/m^3
PE sheet	yes	yes	yes	yes
Subfloor	Lightweight screed, 100 mm, 120 kg/m^3	Lightweight screed, 100 mm, 617 kg/m^3	Loose grit, 10 mm, 600 kg/m^3	Loose grit, 100 mm, 1600 kg/m^3
Resilient interlayer	20 mm, s' = 13.5 MN/m^3	20 mm, s' = 13.5 MN/m^3	22 mm, s' = 28 MN/m^3	22 mm, s' = 28 MN/m^3
Screed	Sand and cement, 60 mm, 1945 kg/m^3	Sand and cement, 60 mm, 1914 kg/m^3	Dry screed, 18 mm, 1220 kg/m^3	Dry screed, 25 mm, 1250 kg/m^3
m'	197 kg/m^2	245 kg/m^2	154 kg/m^2	262 kg/m^2

It is worth recalling that the good impact insulation achieved in frequency for instance by solution D is strongly penalized by the conversion into a single number rating. Weighted indices are calculated through comparison with a reference curve that is designed after the insulation of a concrete floor, that is not representative of CLT floors.

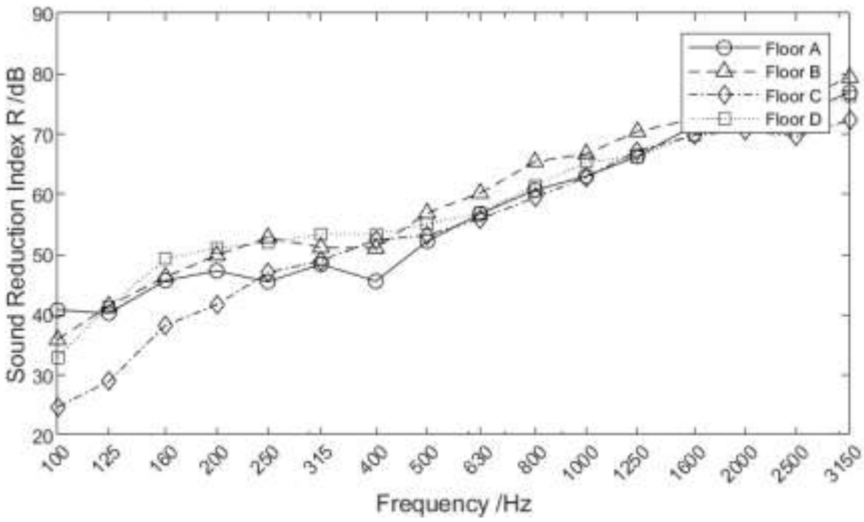
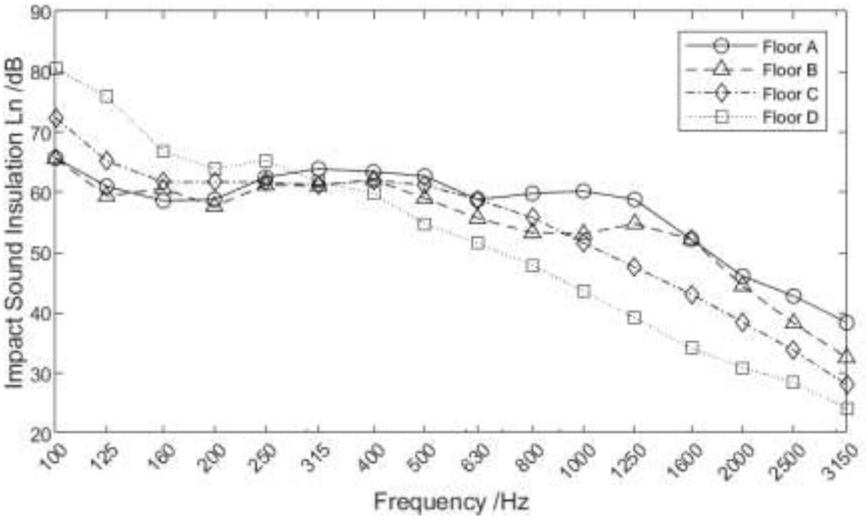


Figure 5. Sound Reduction Index R (dB) of the construction solutions listed in Tab. 2.



(b)

Figure 6. Normalized Impact Sound Insulation Level L_n (dB) of the construction solutions listed in Tab. 2.

3.3 Elastic moduli: acoustic or structural analysis?

The mechanical characteristics of CLT used for acoustical modelling can differ significantly from the values required for structural calculation purposes. According to the strength classes for construction timber established in the standard EN 338, typical mechanical characteristics of wood can be assumed as follows: $E_{0,mean}$ = 12000 N/mm^2, $E_{90,mean}$ = 370 N/mm^2 and G_{mean} = 690 N/mm^2. The mechanical properties of CLT can also be retrieved from the analysis of the dispersion relations of the material, that correlate the velocity of wave propagation to frequency. For acoustical problems, the most relevant waves are flexural waves, that can transform vibrational energy into sound pressure with a high efficiency. The dispersion relations can be measured through different techniques; then, fitting the experimental results with a theoretical model for wave propagation in thick plates, one can determine the E and G moduli of the plate (Santoni *et al.*, 2017). A study conducted on several CLT plates with different orthotropic ratios showed that the values that emerge from the acoustical analysis match well the elastic parameters provided in the datasheets, in particular as it concerns the G_{mean} and $E_{90,minor}$, displaying a variation within 10% tolerance; conversely, the $E_{0,mean}$ had significantly lower values (30%) compared to the data reported in the datasheet (Thies *et al.*, 2019). It is specified that acoustics and structural analysis work in two different domains, as acoustic excitation is based upon small stresses and small strains, hypotheses that are often not verified for structural testing.

4. CONCLUDING REMARKS

This paper presented a preliminary review of the fields of interaction between acoustic and structural design of timber buildings. The analysis concentrated on two topics: the junctions and the building elements. As concerns the CLT junction, the work analyzed the acoustical benefits of the resilient interlayer and the limitations that must be considered not to affect the mechanical resistance of the junction, the elastic deformation of the resilient layer and the determination of its elastic modulus. As regards the building elements, the design concept of the building was considered with reference to the choice of dry solutions (grit and dry screeds) versus wet solutions (lightweight screed and sand and cement screed), analyzing the surface mass and the acoustical performance of each solution. Finally, the elastic parameters of CLT elements used for structural analysis are compared to values that are retrieved and used for acoustical modelling. The discussion and presentation of the different topics outlined possible research topics to be addressed in future research.

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