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DIRECT AND FLANKING TRANSMISSION IN CLT BUILDINGS: ON SITE MEASUREMENTS, LABORATORY MEASUREMENTS AND STANDARDS

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ABSTRACT: The new revision of the EN 12354-1 standard provides prediction formulas for estimating the vibration reduction index (K_{ij}) of heavy weight junctions, based on laboratory and in situ measurements. At the same time, new K_{ij} prediction formulas for CLT junctions have been added to this revised standard. The goal of this research is to study if the same approach based on numerical models used for heavyweight junctions can be extended to CLT elements junctions. This step is not straightforward because the modelling of CLT structures implies a list of non-trivial aspects to take into account: 1) the details of the junction construction, i.e. direction and type of screws, presence of angle brackets and plates; 2) the orthotropy of CLT panels in terms of mechanical properties and 3) how damping must be considered in the numerical model. The contribution presents the advances made in this direction discussing a comparison among available experimental data, the analysis of specific features of CLT junctions, the comparison with the standard formulation and the extension to different types of junction.

KEYWORDS: Sound insulation, Cross Laminated Timber, flanking transmission, ISO 12354.

1 INTRODUCTION

Flanking transmission in CLT structures has recently been addressed by the update of the EN 12354 standard [1]. CLT junctions are modelled as type B elements junctions, but the differences among the constructive systems and the relative junctions are relevant. Different studies have investigated sound transmission through CLT junctions, considering different transmission paths and the mechanical connection of the junctions [2-5].
This contribution seeks a connection between laboratory measurements, on site measurements and standard for the characterisation of flanking transmission on CLT junctions. It discusses the results of a measurement campaign conducted in the Sternaeckerweg complex, a big timber construction site located in Graz. The measurements regarded sound insulation between dwellings including the evaluation of the flanking transmission in the bare structure and in the finished structure through vibration velocity measurements.

2 THE ISO 12354 MODEL

The apparent sound reduction index R' is determined through the logarithmic summation of all direct and flanking transmission terms through Eq. 1.

$$R' = -10log\left(10^{-\frac{R_{Dd}}{10}} + \sum_{j=1}^{n} 10^{-\frac{R_{ij}}{10}}\right) \quad [dB] \tag{1}$$

The contribution of the direct transmission is given by the sum of the sound reduction index of the separating element $R_{s,situ}$ and of the contribution of additional layers $\Delta R_{D,situ}$ and $\Delta R_{d,situ}$ as in Eq. 2.

$$R_{D,d} = R_{s,situ} + \Delta R_{D,situ} + \Delta R_{d,situ} \quad [dB] \tag{2}$$

For each transmission path, the respective sound reduction index can be calculated according to Eq. 3.

$$R_{i,j} = \frac{R_{i,situ} + R_{j,situ}}{2} + \Delta R_{i,situ} + \Delta R_{j,situ} + \overline{D_{v,ij,situ}} + 10log\left(\frac{S_s}{\sqrt{S_i S_j}}\right) \quad [dB] \tag{3}$$

where $R_{i(j),situ}$ is the sound reduction index of element *i (j)*, $\Delta R_{i(j),situ}$ is the increase of sound reduction index of element *i (j)* due to additional linings, $D_{v,ij,situ}$ is the average insulation of vibration in the junction between elements *i* and *j*, S_s is the surface of the separating element, S_i is the surface of element *i* in the source room, S_j is the surface of element *j* in the receiving room.
Similarly, the prediction of the normalised impact sound insulation L_n' can be expressed through Eq. 4:

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$$L'_n = 10log\left(10^{\frac{L_{n,d}}{10}} + \sum_{j=1}^{n} 10^{\frac{L_{n,ij}}{10}}\right) \quad [dB] \tag{4}$$

where the contribution of direct transmission $L_{n,d}$ is given by the summation of the normalised impact sound insulation of the separating element $L_{n,situ}$, of the attenuation due to the presence of a floating floor ΔL_{situ} and the attenuation due to the presence of additional linings on the side of the receiving room (counter ceiling) $\Delta L_{d,situ}$, as in Eq. 5.

$$L_{n,Dd} = L_{n,situ} + \Delta L_{situ} + \Delta L_{d,situ} \quad [dB] \tag{5}$$

For each flanking transmission path, the normalised impact sound insulation can be calculated using the formulation in Eq. 6.

$$L_{n,ij} = L_{n,situ} - \Delta L_{situ} + \frac{R_{i,situ} - R_{j,situ}}{2} - $$
$$-\Delta R_{j,situ} - \overline{D_{v,ij,situ}} - 10log\sqrt{\frac{S_i}{S_j}} \quad [dB] \tag{6}$$

3 MEASUREMENT SETUP

Measurements were conducted in the Sternaeckerweg complex, a big timber construction site located in Graz, designed by the local architect offices gaftonion ZT-KG and balloon architeken ZT-OG.
The rooms, shown in Fig. 1, have dimensions of 7.01 x 3.73 x 2.70 m for a volume of 70.60 m^3.

Figure 1: *Measurement of sound insulation*

The floor under analysis is made by: 10 mm wooden floor, 65 mm screed, PE sheet, 30 mm resilient underlay, 50 mm EPS, 45 mm loose gravel, 160 mm CLT by Stora Enso, 60 mm false ceiling with 50 mm mineral wool, 12.5 mm gypsum board.
The adjacent walls were two external walls and two internal walls. External walls are made with 5 mm internal finishing, 140 mm rock wool, 100 mm CLT, 40 mm acoustic layer, 25 mm double fire-resistant gypsum board.

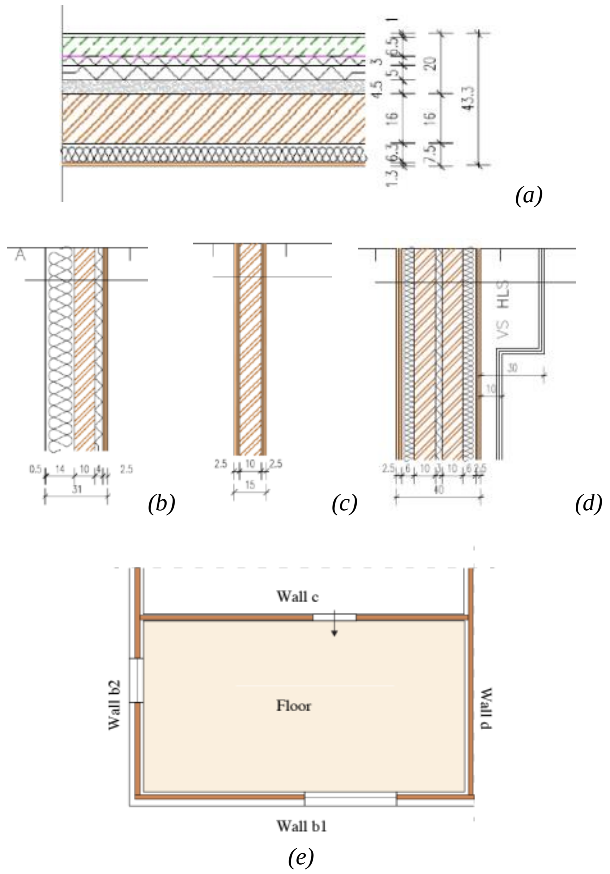


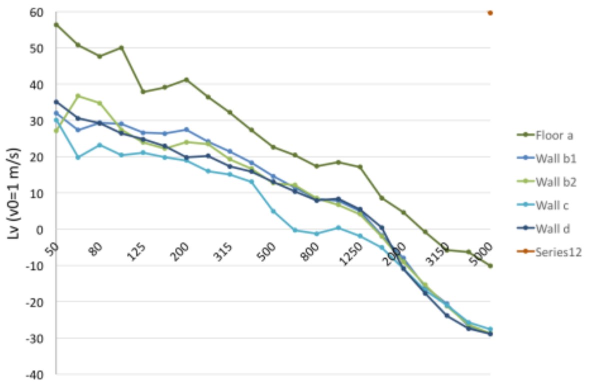
Figure 2: *Separating floor (a), external walls (b), internal separating walls (c, d) and distribution of the elements (e) in the plan.*

One internal wall had the following characteristics: 25 mm double fire-resistant gypsum board, 100 mm CLT by StoraEnso, 25 mm double fire-resistant gypsum board.
The other internal wall is a double wall with the following characteristics: 25 mm double fire-resistant gypsum board, 100 mm CLT bu Stora Enso, 25 mm double fire-resistant gypsum board.
The graphical description of the elements is provided in Figure 2.
Airborne and impact sound insulation tests were conducted in accordance with ISO 16283-1 [6] and ISO 16283-2 [7] respectively. The vibration velocity levels of the walls and the ceiling in the receiving room were measured while the source room was excited both using a sound source and a tapping machine. Moreover, the flanking transmission of the CLT junctions have been measured in an area of the construction site that was still under construction.
In the discussion of the results, these three measurements will be combined to optimise the modelling of the partition under study.

4 VIBRATION VELOCITY LEVELS IN THE RECEIVING ROOM

In order to determine which walls provided the most relevant transmission path, vibration velocity levels were measured on the internal linings on the receiving room. Measurements were performed using the dodecahedron and the tapping machine as sources (Fig. 3). The letters identifying the walls match the nomenclature followed in Fig. 2e. In both cases the velocity levels measured on the floors are greater than those measured on the side walls by at least 10 dB in all frequency range. In CLT buildings the contribution of flanking transmission seems less relevant than in concrete or masonry structures [8].

(a)



(b)

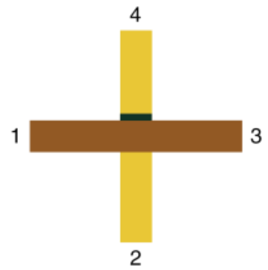
Figure 3: *Vibration velocity levels measured inside the receiving room when a loudspeaker (a) or a tapping machine (b) was active in the source room.*

5 VIBRATION REDUCTION INDICES

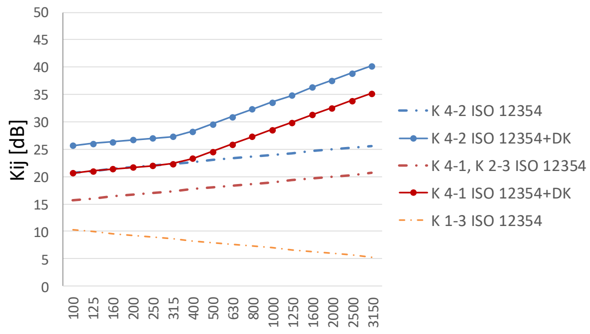
The values of K_{ij} calculated according to the formulas contained in the annex F of the ISO 12354-1 standard do not include the presence of different types of fastening systems or resilient layers. [9-11].

In order to estimate the contribution of the resilient interlayer, the corrective term ΔK - described for the rigid junctions as in annex E - was used [12].

Figure 4a shows the arrangement of the CLT panels for which the vibration reduction indices were measured on site. The resilient interlayer, represented by the black strip, was placed between the floor and the upper wall.



(a)



(b)

Figure 4: *Arrangement of the panels (a) and vibration reduction index on the X horizontal junction (b). The black strip represents the resilient interlayer.*

Fig. 4b shows the values derived from the standard with and without the use of the resilient interlayer.

6 MODELLING THE ELEMENTS ACCORDING TO ISO 12354

6.1 INPUT DATA

The definition of the input data is extremely important for the correct application of the model. As shown in Fig. 3, the transmission of sound is mainly characterised by the direct transmission through the separating floor. In this paper, the input data for the four side walls are kept constant throughout the analysis, while variations on the input data of the floor and of the flanking transmission is analysed.

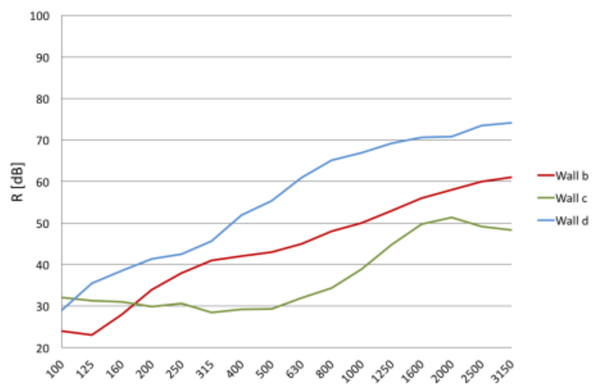


Figure 5: *Input data for the side walls.*

The input data for the four sidewalls is shown in Fig. 5. Part of these data was retrieved from laboratory measurements, while others are calculated using the INSUL software [13].

The input data for the floor is more complicated to model, due to the lack of information relative to the behaviour of the layer of EPS placed below the resilient underlay.
A detailed description of the floors used as input data is presented in Tab. 1.
The availability of laboratory data with a CLT floor include wet subfloor and wet screed, dry subfloor and dry screed, dry subfloor and wet screed; none of those configurations include the EPS layer. The choice to include in the calculation those values stems from the fact that the flanking transmission is evaluated through the basic structure, considering the floating floor separately. Therefore, also configurations that did have a similar surface mass of the base structure have been compared. [14]

Table 1: *Description of the floors used as input data for the calculation. Name of the solution, description, surface mass of CLT+substrate (m_{inf}) and of the floating floor (m_{float}) expressed in kg/m².*

#	Description	m_{inf}	m_{float}
1	INSUL | Ut est	144	144
2	LAB | CLT 160 mm, PE sheet, wet substrate 120 mm, resilient undelay, PE sheet, sand and cement screed 50 mm + counter ceiling	140	95
3	LAB | CLT 160 mm, PE sheet, wet substrate 120 mm, resilient undelay, PE sheet, sand and cement screed 50 mm + counter ceiling*	140	95
4	LAB | CLT 160 mm, PE sheet, loose gravel 45 mm, resilient undelay, sand and cement screed 70 mm + counter ceiling	154	163

The counter ceiling is a critical element to model; in the calculations performed in this paper, the increase in sound insulation provided by the counter ceiling has been measured in the laboratory by applying the lining on the CLT floor, without any substrate or screed. Configurations 2 and 3 (see Tab. 1) show the different results that the same floor provides when the contribution of the same false ceiling is measured on the CLT only (case 2) or on the full floor (case 3).

6.2 THE CONTRIBUTION OF THE FLANKING TRANSMISSION

For each of the input floors described in Table 1, Fig. 6 represents the apparent sound reduction index modelled according to the ISO 12354-1 standard.
The flanking transmission has been evaluated in two different ways: in Fig. 6a the K_{ij} provided by the ISO 12354 have been used, taking into account the presence of the resilient interlayer and the direction averaged velocity level difference has been normalised with mecanical proprieties of CLT. In Fig. 6b, the direction averaged velocity level difference has been normalised only with respect to the surface of the elements.
As far as it concerns the apparent sound reduction index, configurations 4 is the one that better fit the measured data. Configuration 4 regards the measurements performed on the slab measured in the laboratory, differing from the one measured on site only by the presence of the EPS layer. This element seems not to have a relevant effect on the airborne sound insulation. It is interesting to notice the differences between configurations 2 and 3, i.e. when the increase in sound insulation provided by the false ceiling is measured on the complete construction solution or separately on the CLT floor.

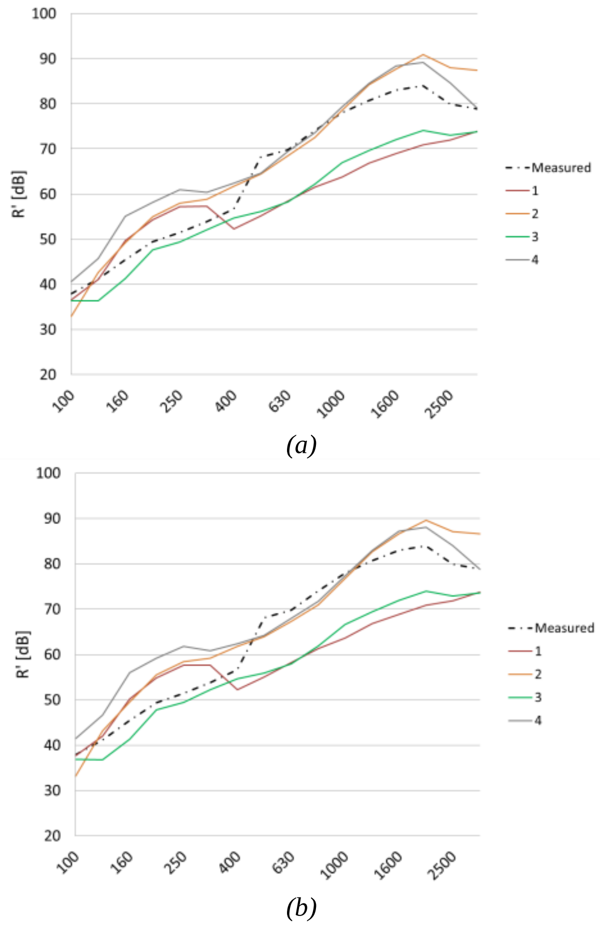
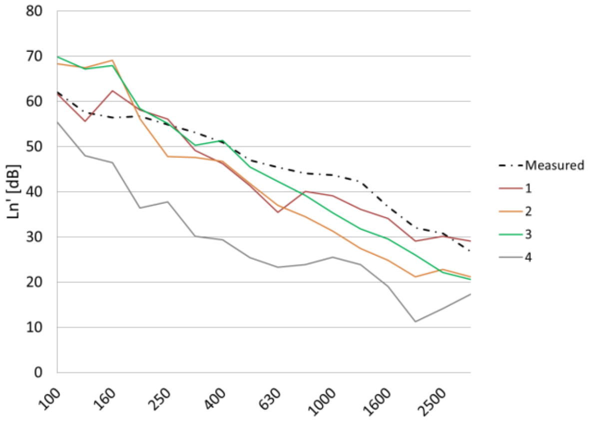


Figure 6: *Apparent sound reduction index measured on site and estimated through the EN ISO 12354 calculation method; (a) flanking transmission evaluated through the K_{ij}; (b) the direction-averaged velocity level has been normalised with respect to the surfaces of the elements.*

The two cases, *a* and *b*, show the same behaviour; i.e. the vibration reduction index can be normalised with respect to the surface of the elements instead to their structural reverberation time, without losing accuracy. Some limitations relative to this hypothesis have been shown on continuous crossings of CLT floors [15].
The results for the impact sound insulation (Fig. 7) show that there is a huge dispersion of the data. The configurations that mostly match with the measured data are configurations 1, 2 and 3. In this case, the normalisation of the vibration reduction indices does not have any influence on the results.
It is interesting to notice that configuration 4, which is the one that on the returned the best results for airborne sound insulation, returns the worst-matching results for the impact sound insulation. That means that the EPS layer strongly influence the performance of the construction solution. The estimate provided by INSUL matches better to the measured results.



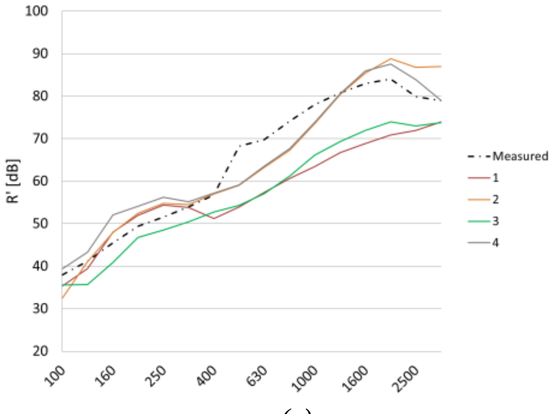
(a)

(b)

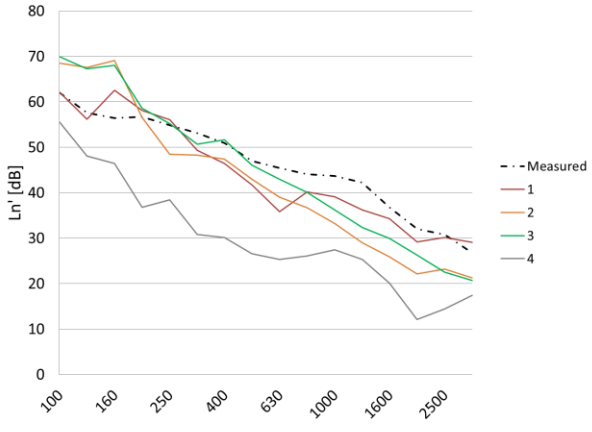
Figure 7: *Apparent impact sound insulation measured on site and estimated through the EN ISO 12354 calculation method; (a) flanking transmission evaluated through the K_{ij}; (b) the direction-averaged velocity level has been normalised with respect to the surfaces of the elements.*

In all the configurations analysed so far, the radiation factor of the CLT panel had been considered for all the elements. When the radiation factor of the external linings of the walls is calculated instead, the results show a good match in the lower frequency range, as shown in Fig. 8.

Finally, Fig. 9 shows the results of the calculation method applied to the different input floors when using the values of the K_{ij} calculated without ΔK correction and the radiation factor of CLT is taken into account.



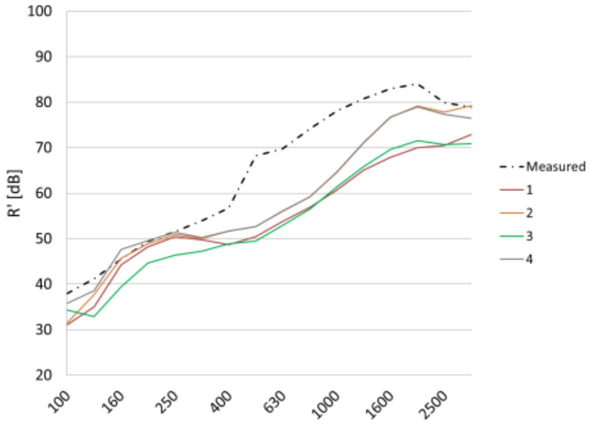
(a)



(b)

Figure 8: *Apparent sound reduction index (a) and impact sound insulation (b) measured on site and estimated through the EN ISO 12354 calculation method; the radiation factor of the CLT is used for the main wall, while the radiation factors of the linings are used on the side walls.*

(a)



(b)

Figure 9: *Apparent sound reduction index estimated through the EN ISO 12354 calculation method using the K_{ij} without ΔK correction. The direction-averaged velocity level has been normalised respect to the material proprieties of CLT (a) and the surfaces of the elements.*

7 CONCLUDING REMARKS

The paper shows the results obtained from the comparison between the measured values of the Apparent sound reduction index and impact sound insulation calculated with the calculation model described in the new version of the EN ISO 12354 standards.

The results show that for K_{ij} calculated it is necessary to consider the contribution of the resilient strips and in general of the fastening system. Also it was noted the reliance of the calculations on the input values, especially on the laboratory data. This is generally valid for all types of structures (concrete, bricks), and it is even more so for CLT structures, where the high number of layers and fixing technologies requires the use of measured data.

In the cases studied in this article, the correction for the resonant transmission was not applied, according to the most recent literature on CLT, because the results obtained differed further from the measures in situ.

The results showed that in the case of CLT the correction of $D_{v,ij,situ}$ based on the mechanical properties of CLT or only the surfaces of the elements involved is very similar. The best match between the measured and calculated results was observed when the mechanical properties of plasterboard coatings were considered in the calculation of the lateral transmission.

However, in all combinations of floor slabs used and in different calculation assumptions, there has always been a variance between the results either at low frequencies or at high frequencies.

The results show that the use of the new calculation model based on corrections of laboratory data with the structural reverberation time allows a more accurate predictive calculation. However, laboratory input data are necessary for a better accuracy of the calculations an it is extremely important to increase the number of case studies.

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