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LOAD EFFECTS IN FLANKING TRANSMISSION OF CLT STRUCTURES WITH RESILIENT INTERLAYER

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ABSTRACT

With the increasing construction of Cross Laminated Timber (CLT) buildings, the demand for enhanced acoustic performance is also rising. To improve the sound insulation, resilient interlayers are inserted in the structure, which decreases the flanking transmission. These interlayers are generally placed between the floor and the wall and are under a static load, which depends on the relative floor. Interlayers are usually viscoelastic materials with non-linear behaviour. This is why the vibroacoustic behaviour under different loading conditions is investigated in this paper. Through a full-scale mockup, the vibration reduction index K_{ij} of some resilient material with different elastic modulus is measured by placing various static loads over the junction to evaluate different performances.

The results reveal significant differences depending on the load applied to the junction. In particular, in the mid-high frequencies, the higher the load, the lower the K_{ij} due to the increase in the dynamic stiffness of the resilient layer in the compression. This supports the importance of choosing the proper resilient material in the design step and carrying out laboratory measurements of K_{ij} with the test conditions as close as possible to the actual conditions of use.

Keywords: *cross laminated timber - resilient interlayer - flanking transmission*

1. INTRODUCTION

Obtaining good acoustic comfort also requires consideration of flanking transmission in addition to wall, floor and façade sound insulation. Wooden buildings like CLT (Cross Laminated Timber) have high radiation efficiency and low mass, which makes them particularly challenging to solve in terms of sound insulation. Engineered cross laminated timber (CLT) constructions permit the reduction of the acoustic vibrations transmitted into the structure by inserting resilient strips, usually elastomers, between the floor and wall [1] [2] [3].

CLT, in the past, was mainly used for small buildings with a few storeys, but today, it is also used for large buildings up to 18 storeys. The resilient strips under the supporting walls are, therefore, subjected to large loads, particularly on the lower floors. Also, the load on the resilient strip varies depending on the floor it is located on due to the weight of the upper floors.

Nilsson et al. [4] give an in-depth overview of the current literature on vibration reduction index, in particular on CLT, and analyse the effects of loading in junctions with resilient strips and fastening systems by comparing in-situ measurements of junctions in the first floors (higher load) with junctions with similar boundary conditions in the upper floors (lower load). The effects of loading on vibration reduction index were also studied by Crispin et al. [5], but for lightweight masonry constructions.

Schoenwald et al. [6] show that the vibration reduction index of junctions without resilient interlayers and with a fastening system is influenced to a considerable amount when

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the weight of the first storey is added, while the effect on the K_{ij} decreases significantly when additional storeys are added.

In the standard ISO 10848-1 (under revision) [7] for measuring the vibration reduction index K_{ij} there is no standardised methodology for measuring structures with resilient strips.

Also measuring the properties of elastomers in the dynamic regime under high loads with equipment is not easy, and there is a lack of suitable instrumentation [8]. Currently, there is the standard ISO 4664-1, also known as DMA, of which it is difficult to find ready-built machines that can perform analyses with high loads. This standard is designed for measurements at frequencies up to 200 Hz and applies to samples with a form factor of *h:d=1:1.5*, where *h* is the height of the sample and *d* is the diameter of the cylindrical sample. The results obtained are influenced by this form factor. The deformation considered is only 10%. Another standard is ISO 9052-1, which, however, is only intended for loads similar to a screed.

In this article, experimental measurements were carried out in the laboratory to see the effects of loading on the vibroacoustic properties of CLT junctions with resilient strips and without a fastening system. First by measuring the characteristics, such as the elastic modulus, of certain elastomers and then by measuring the K_{ij} after inserting them into a mockup junction.

2. BACKGROUND THEORY

Cross-laminated timber (CLT) structures are classified as Type A and therefore the descriptor for expressing the insulation effectiveness at the passage of acoustic vibrations through the junction is the vibration reduction index K_{ij} defined in ISO 10848-1 as:

$$K_{ij} = \overline{D_{v,ij}} + 10lg\left(\frac{l_{ij}}{\sqrt{a_i a_j}}\right) \quad [\text{dB}] \qquad (1)$$

with

$\overline{D_{v,ij}}$ [dB]: direction-averaged velocity level difference between elements i and j;

l_{ij} [m]: junction length between elements i and j;

a_i, a_j [m]: equivalent absorption lengths of elements i and j.

3. METHOD

3.1 Compressive elastic modulus

The compressive modulus of elasticity was measured according to ISO 844 [9] with the specifications of the EAD 042232-00-0503 [10]. In this EAD, the compressive elastic modulus is defined as:

$$E_c = \frac{\sigma_{15} - \sigma_5}{\varepsilon_{15} - \varepsilon_5} \quad [\text{MPa}] \qquad (2)$$

with

σ_{15} [MPa]: compressive stress at 15% strain (ε_{15});

σ_5 [MPa]: compressive stress at 5% strain (ε_5).

The samples had square dimensions of 50x50mm² and a thickness of 6mm. Five unlubricated samples of each material were tested. The tests were carried out using an INSTRON 8023 hydraulic press with steel plates and a compression speed of 0.01mm/s. This test was conducted under static conditions.

3.2 Vibration reduction index

A full-scale mockup of a horizontal L-junction (Figure 1) was built in the laboratories of Buildwise in Belgium. The floor is a 0.14m thick 5-ply CLT panel (panel i) with a width of 2.25m and a length of 4.93m. The wall is a 0.12m thick 5-ply CLT panel (panel ii) with a width of 2.4m and a length of 3.94m. The mockup is inside a warehouse, with the floor (panel i) supported on one side by three columns of cellular concrete blocks (height approx. 0.6m) and on the other side by panel i. Only the top 0.6m of the wall (panel i) is visible in the warehouse as it is inserted between two transmission chambers normally used for laboratory sound insulation tests. Three source points and eight receiver points were chosen for each panel. A hammer was used as the source. The velocity levels of the panels were measured using accelerometers placed at the receiver points and glued to the panel's surface with a two-component glue. Panel dimensions, source and receiver positions are compliant with ISO 10848-1. The structural reverberation time of the panels was determined from the impulse response of a hammer.

First, the vibration reduction index K_{ij} was measured for the rigid junction (without resilient strip), with panel ii just placed on panel i. Next, measurements were made by placing resilient materials in the junction between the two panels. Several resilient strips were tested, each with an equivalent length to the junction, i.e., 2.2m, width 0.08m and uncompressed thickness of 0.006m. In this case, a load is applied on the resilient material equivalent to the self-weight of the structure and thus half the weight of the floor, corresponding to 377kg and, therefore, a pressure on the resilient material of 0.021MPa.

Next, measurements were made by varying the load applied to the junction. To do this, starting with one, then two and then three reinforced concrete blocks were placed on the floor slab right above the junction (Figure 1, right). The concrete blocks were placed vertically and have a

Table 1. Measured configuration for vibration reduction index.

Configuration	Resilient interlayer	Number of concrete blocks	Pressure on the junction [MPa]	Deformation of the resilient interlayer	$K_{ij,high}$ [dB] (average 1250-5000HZ)
Conf.rigid_0	no	0	0.014	-	22.2
Conf.rigid_1	no	1	0.027	-	20.6
Conf.rigid_2	no	2	0.040	-	16.8
Conf.rigid_3	no	3	0.053	-	15.5
Conf.A_0	A	0	0.021	10%	35.8
Conf.A_1	A	1	0.040	19%	33.4
Conf.A_2	A	2	0.060	28%	32.5
Conf.A_3	A	3	0.079	35%	31.8
Conf.B_0	B	0	0.021	4%	34.6
Conf.B_1	B	1	0.040	5%	30.3
Conf.B_2	B	2	0.060	7%	28.5
Conf.B_3	B	3	0.079	9%	27.5
Conf.C_0	C	0	0.021	< 2%	29.4
Conf.C_1	C	1	0.040	< 2%	26.5
Conf.C_2	C	2	0.060	< 2%	25.3
Conf.C_3	C	3	0.079	< 2%	24.1

parallelepiped shape with dimensions: height 1m, width 0.25m and length 0.6m. Each block weighs 346kg, which in total, with the weight of the structure, becomes a pressure on the resilient material of 0.040MPa for one block, 0.060MPa for two blocks, and 0.079MPa for three blocks (assuming that the load is evenly distributed). The configuration with one block has the block placed in the centre of the junction, while the configuration with two blocks has them placed at the extremes of the junction.

All measurements were carried out within 10 minutes of the resilient material being loaded in an attempt to have approximately the same creep effects given by the loading time. All configurations are without a fastening system.

The maximum weight applied (3 blocks) to the junction is approximately 1000kg (without the self-weight of panel i). In a real service condition, we would also have other weights bearing down on the junction. For example, considering the partitions (an upper CLT wall, insulation, lining), the floating floor (floor, screed, floor finish), a ceiling, and the residential loads of normal use that would weigh on a floor with dimensions like those of the mockup, we would have an addition of approximately 2000kg on the junction. This would correspond to a pressure of 0.13MPa on the resilient strip. This load would only be that of a single storey and thus the typical load for the upper storey, in lower storeys the loads can be considerably higher as all the weights of the individual storeys are added together in load-bearing wall structures such as CLT.

4. RESULTS

Three different resilient materials (with different shore) were tested, two expanded EPDM (A and B) and one extruded polyurethane (C). Materials A (Figure 2), B (Figure 3) and C (Figure 4) were measured in compression to determine the compressive elastic modulus in static conditions. The typical non-linear behaviour of elastomers is recognisable in the graphs comparing pressure and deformation.

The summary of the configurations tested for the vibration reduction index K_{ij} has been schematised in Table 1. The measurement results are shown in Figure 5 to Figure 8.

Figure 1. Horizontal L-junction CLT mockup. On the left without extra weight. On the right with three concrete blocks.

5. DISCUSSION

It is desirable to use elastomers with low deformations and within their elastic range in building structures in order to have greater predictability of behaviour and to limit permanent deformations and structural stresses. Figure 2 to Figure 4 show the linear regression from 5% to 15% strain as in (2) to find the elastic modulus of the respective materials, indicated as the angular coefficient in the graph formula.

Figure 2 shows that for elastomer A, a pressure of 0.021MPa corresponds to a deformation of 10% (equivalent to 0.6mm), while for a pressure of 0.040MPa there is a deformation of 19% (1.14mm), with 0.060MPa it is 28% (1.68mm), and with 0.079MPa it is 35% (2.1mm). For elastomer B (Figure 3), there is a deformation of 4% (0.24mm) at a pressure of 0.021MPa, 5% (0.3mm) at 0.040MPa, 7% (0.42mm) at 0.060MPa, 9% (0.54mm) at 0.079MPa. For elastomer C (Figure 4), all loads applied in the K_{ij} tests are under 2% deformation. In Table 1 there is a summary of the relative deformation.

During the K_{ij} tests, we are within the elastic range of 5-15% deformation for elastomer A without concrete blocks and almost with one block; for elastomer B with one, two and three blocks; and for elastomer C we are significantly outside this elastic range. Although the weights are added by linear steps of 0.02MPa this is not reflected in a direct correlation of the K_{ij} measurements. There are different behaviours between the static regime (ISO 844) and the dynamic regime (ISO 10848-1).

It should be pointed out that the compressive elastic modulus measurements, following the roughness requirements of the standard ISO 844, were carried out with steel plates which produce different friction compared to wood and elastomer.

Figure 5 shows the measured results of the vibration reduction index K_{ij} of the rigid configurations without interlayer. It can be observed that there are differences in adding load to the junction. This is because adding weight will smooth out any possible gaps between panel i and panel ii caused by the roughness of the wood and the concavities in panel i. It seems that above a certain load (in this case from the second block), almost any imperfections in the contact surface between the two panels are smoothed out, resulting in a large decrease in the junction insulation. Beyond this threshold, the effects of further loading diminish drastically, as already seen in [6].

For configurations with the interlayer, the effects of the load are seen above the 400Hz band (Figure 6, Figure 7, and Figure 8). In general, as the load increases, the junction insulation decreases.

Below 125Hz, the vibration of the panels is determined by global modes, i.e. the two panels of the mockup behave as a single system and the resilient interlayer is not effective. From 160Hz local plate modes appear and the two panels operate as two subsystems. The two panels are effectively decoupled by the resilient interlayer, which is reflected in the sudden increase of the K_{ij} at this frequency (Figure 6, Figure 7, and Figure 8). Around the 250Hz band, there is an insulation gap due to parasitic airborne noise that is emitted from

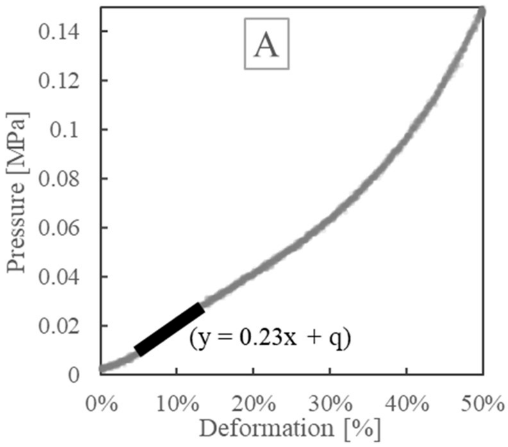

Figure 2. Compressive elastic modulus of interlayer A.

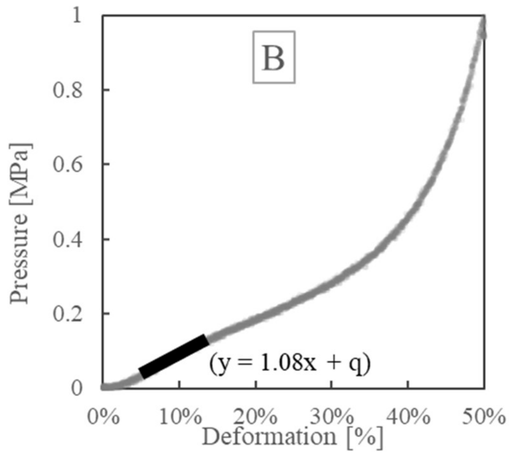

Figure 3. Compressive elastic modulus of interlayer B.

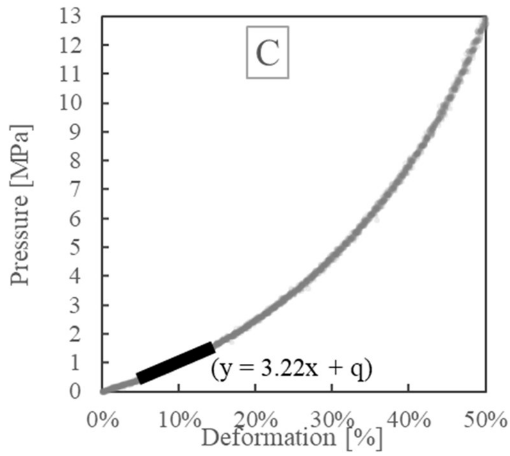

Figure 4. Compressive elastic modulus of interlayer C.

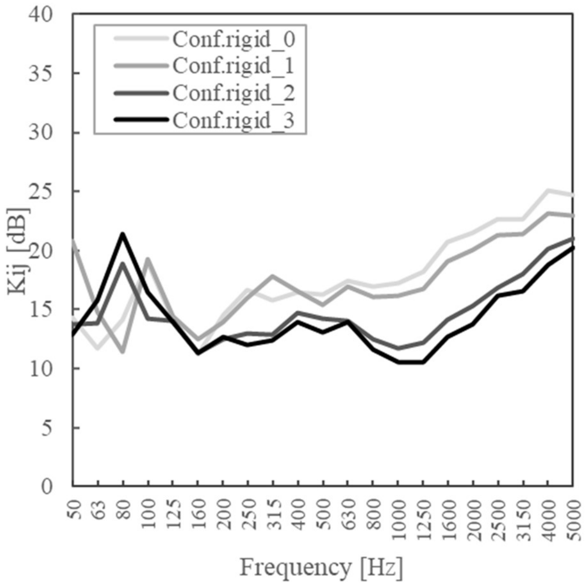

Figure 5. Vibration reduction index K_{ij} of the rigid configuration of the junction (no interlayer).

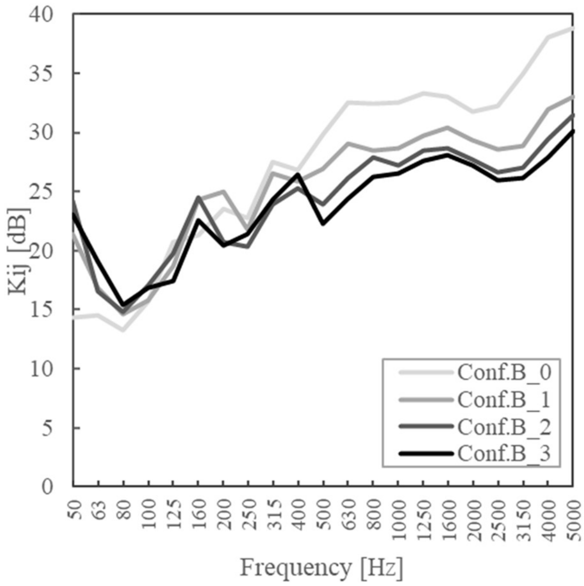

Figure 7. Vibration reduction index K_{ij} of the junction with resilient interlayer B.

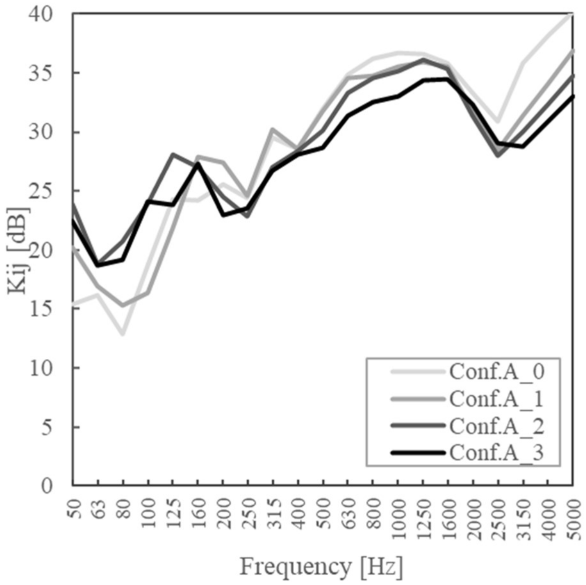

Figure 6. Vibration reduction index K_{ij} of the junction with resilient interlayer A.

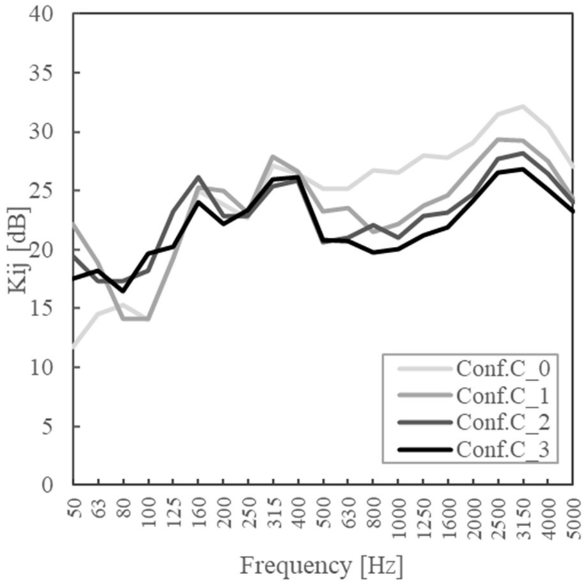

Figure 8. Vibration reduction index K_{ij} of the junction with resilient interlayer C.

the source panel and passes through the air to re-enter the receiving panel [11].

In elastomers A and B (Figure 6, Figure 7), a dip is observed in the frequency range of 2500-3150Hz for the K_{ij} values. This dip is attributed to the thickness resonance of the resilient interlayer [11]. The resonance frequency, which depends on the elastic modulus of the resilient interlayer, increases as the load on the resilient material rises.

To compare the different configurations with a single index, it is possible to use the division made by Hopkins [12] of $K_{ij,high}$ for the frequency range 1250-5000Hz, whose values for the tested configurations are summarised in the Table 1. This range is designed for isotropic homogeneous structures, whereas CLT is orthotropic and composed of several cross-layers. Indeed, the measurements shown in this article do not have a linear behaviour in this range. However, it was decided to use this method for coherence with the scientific literature and to have a curve comparison number. The difference of the unique index $K_{ij,high}$ between the configuration without added load and with loads is then made to have an easy indication of how much the performance is varying.

The difference between the $K_{ij,high}$ of the rigid configuration (Conf.rigid_0) and that with one block (Conf.rigid_1) is 1.6dB, adding a second block (Conf.rigid_2) loses another 3.9dB (5.4dB compared to Conf.rigid_0), while with three blocks (Conf.rigid_3) another 1.2dB (6.7dB compared to Conf.rigid_0) is lost.

Elastomer A comparing the configuration without added loads (Conf.A_0) with that with one block (Conf.A_1) loses 2.4dB, with two (Conf.A_2) another 0.9dB (3.3dB relative to Conf.A_0), with three (Conf.A_3) a further 1.1dB (2.3dB relative to Conf.A_0). The dynamic stiffness of the resilient strip increases significantly due to the loading and related thickness loss, reducing performance.

Elastomer B comparing the configuration without added loads (Conf.B_0) with the one block configuration (Conf.B_1) loses 3.3dB, with two (Conf.B_2) a further 1.4dB (4.6dB over Conf.B_0), with three (Conf.B_3) a further 0.8dB (5.5dB over Conf.B_0).

Elastomer C comparing the configuration with no added load (Conf.C_0) with the one block configuration (Conf.C_1) loses 3.8dB, with two (Conf.C_2) another 1dB (4.9dB relative to Conf.D_0), with three (Conf.C_3) a further 1.3dB (6.2dB relative to Conf.C_0).

For elastomers B and C, the most significant changes occur with the addition of the first block, as any gaps or lack of contact at the wood-elastomer interface are eliminated.

6. CONCLUSION

This article discusses the fact that the vibration reduction index, K_{ij}, of junctions with resilient interlayers is influenced by the load applied to the junction (for example, in this article, up to 7dB). Elastomers, usually used as resilient strips, do not have linear pressure-deformation behaviour. It is, therefore, difficult to make exact predictions of their behaviour in the dynamic regime under the design loads without measuring the appropriate conditions.

An important point to consider is the fact that in-situ measurements of K_{ij} are often performed during the construction phase when linings are not yet present. The linings (including the floating screed) can have a significant influence on the masses involved, especially for lightweight CLT structures. The measurement that is taken is, therefore, biased by a different load condition than the one that will be found when the building is finished (and foreseen in the design phase for the correct choice of resilient material based on its optimal load range) encountering the problems noted in this article. It is, therefore, important to find a method for predicting the effects to correct in situ measurements.

A method would also need to be found to measure a parameter in a dynamic regime under the right design load. One idea could be the dynamic stiffness, but the current ISO 9052-1 standard does not allow measurement under loads other than those typical of a screed (8±0.5kg on a 200x200mm², so in the range of 0.002MPa). Another possible standard could be the ISO 4664-1, but this standard is not meant for different loads and for measuring frequencies above 200Hz.

As loads in CLT buildings vary greatly, for example, between the first floors and the upper floors, there is a need to conduct K_{ij} measurements in the laboratory with the right design load to avoid overestimating the junction insulation.

It is therefore planned in the current revision of ISO 10848-1 to include a common standardised procedure for measuring the K_{ij} of structures with resilient interlayers.

It has to be said that in a real CLT building there will always be a fastening system in the junction. It is expected that the differences with varying load for such junctions are smaller as the performance of the junction is obviously lower.

7. ACKNOWLEDGMENTS

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