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SOUND INSULATION PERFORMANCE OF TIMBER FLOORS WITH ELASTICALLY MOUNTED AND SUSPENDED LAYERS

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ABSTRACT

Massive timber buildings are often equipped with concrete or cement screed floors to increase the mass of the structures and to improve the sound insulation between rooms. However, the use of concrete is more and more often seen as an unfavourable option due to the increasing need to decrease the carbon dioxide emissions of the construction sector. A recent field study performed in a mock-up CLT-framed building showed that the sound insulation can drastically be improved without concrete by mounting the upper layers of the floor and the suspended ceiling elastically to the load-bearing timber slabs. In comparison with the conventional screed solution, the vertical airborne and impact sound insulation was improved with the elastically mounted floor up to 13 and 20 dB in terms of the single-number quantities $D_{nT,w}$ and $L'_{nT,w}$. This study aims to investigate the sound insulation performance of the conventional and elastically supported floors by conducting computational assessments which were compared with the field measurement results. Furthermore, the assessments were broadened to study the sound insulation between rooms in the horizontal direction. These computations based on FEM and parametric models reveal the superior performance of the elastically mounted floor both in horizontal and vertical directions.

Keywords: *timber floor, elastic mounting, suspended ceiling, sound insulation, finite element method*

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1. INTRODUCTION

Massive timber such as cross-laminated-timber (CLT) is a typically applied load-bearing frame solution in different timber building types. When timber apartment buildings with high sound insulation requirements are considered, the frame is usually partly decoupled and supported with elastic bearings and partly covered with sound insulating structural layers such as elastically suspended ceilings. The reason for these solutions is to avoid flanking sound transmission between adjacent rooms.

One conventionally applied solution to improve sound insulation performance of massive timber buildings is to pour concrete or cement screed on the massive timber floors. This increases the mass of the floors, but on the other hand, the use of concrete or cement increases the carbon dioxide emissions of the building.

An alternative solution to improve sound insulation is to cover the massive timber floors with elastically attached building board layers. A recent field study performed in a CLT framed mock-up building showed that the sound insulation of the building can be improved in comparison with the conventional concrete solution [1]. Based on the study, the improvement of sound insulation in vertical direction due to the elastically mounted floor was up to 23 and 36 dB in terms of the single-number quantities (SNQ) $D_{nT,w}$ and $L'_{nT,w}$.

The purpose of this paper is to further compare the sound insulation of CLT floors with cement screed, and elastically mounted floor. In the first part, the sound insulation of the floors was computationally assessed in vertical direction. Second part of the study involved application of the results to predict the horizontal sound insulation between two adjacent rooms in an imaginary CLT framed building. The computational assessments were performed with the finite element method and with parametric calculation models.

2. MATERIALS AND METHODS

2.1 Studied floors

2.1.1 Floor assemblies

The sound insulation of five timber floors F0–F4 was studied. In all the cases, the load-bearing structure was a 140 mm thick 5-layered CLT slab, which also acted as the reference floor F0. The rest of the studied floors had either a cement screed (F1–F2) or an elastically mounted floor (F3–F4) as floor toppings. Two of the studied floors (F2 and F4) had also elastically suspended ceilings installed below the CLT slab. None of the floors had floor coverings in the study. Briefly, the studied floors were:

- F0: CLT 140 mm
- F1: Screed 50 mm + underlayment 3 mm + F0
- F2: F1 + elastically suspended ceiling
- F3: Elastically mounted floor + F0
- F4: F3 + elastically suspended ceiling

The study aimed to compare the sound insulation performance of the floors F1 and F3 (Fig. 1). Floors F1 and F2 were equipped with the cement screed on the CLT slab. An elastic underlayment of thickness 3 mm (a bitumen-based product with dynamic stiffness 120 MN/m^3) was installed below the screed. Floors F3 and F4 had an elastically mounted floor topped with 18 mm OSB and two 12,5 mm Fermacell fibre gypsum boards. The elastic floor mounts (AMC Mecanocaucho Akustik+Sylomer® 25 Floor Mount) were installed between the CLT slab and the 50 mm timber battens in a 500/600 mm spacing. The space between the CLT slab and the elastically mounted floor was filled with 75 mm thick glass wool.
Floors F2 and F4 were equipped with a suspended ceiling. Two 13 mm thick plasterboards were hanged from the CLT slab with elastic elastomer hangers (AMC Mecanocaucho Akustik+Sylomer® 15 Type B) which were installed in a 500/1200 mm spacing and attached to metal frames (spacing c/c 1200 mm) for the plasterboard installation. The air gap between the gypsum boards and the CLT slab was 100 mm including 75 mm of glass wool.

2.1.2 Measurements

Airborne and impact sound insulation of the floor assemblies F0, F1 and F3 has previously been measured in a timber mock-up building [1]. The measurement results for the floors have been presented in Tab. 1 in SNQs, in a case where the main flanking sound transmission routes were covered with sound insulating wall linings.

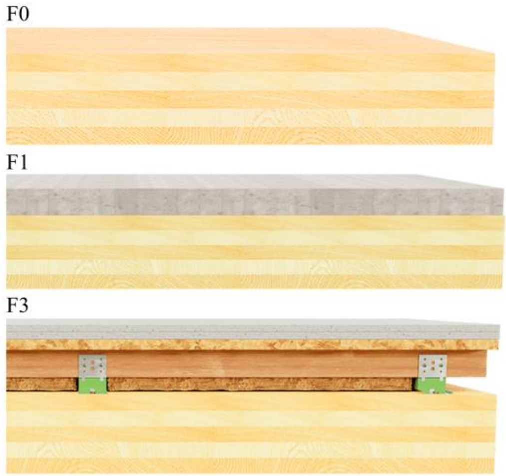

Figure 1. Studied floor assemblies F0, F1 and F3.

Table 1. Airborne and impact sound insulation of the floors F0, F1 and F3 measured in vertical direction in a timber mock-up building [1].

Floor	$D_{nT,w}$	$L'_{nT,w}$
F0: CLT 140 mm	39 dB	86 dB
F1: Screed 50 mm + underlayment 3 mm + F0	49 dB	70 dB
F3: Elastically mounted floor + F0	62 dB	50 dB

The measurements were performed in the field in the vertical direction in a three-story high timber building. In the measurement situation, the source room (V = 51 m^3) was located on the second floor and the receiving room (V = 26 m^3) on the ground floor. The area of the measured floor structures was 9,5 m^2. However, it must be noted that the flanking structures were not equivalent with each other in different measurement arrangements.
The measurement results clearly indicate a superior performance of the elastically suspended floor (F3) compared to the screed floor (F1) in vertical direction. In terms of $D_{nT,w}$ and $L'_{nT,w}$, the improvement of sound insulation of the elastically mounted floor was 23 and 36 dB whereas the effect of the screed floor on the sound insulation was only 10 and 16 dB, respectively.
The sound insulation performance of the floor solutions was not compared in a horizontal direction, although the effectiveness of the elastically mounted floor in this respect has previously been shown [2]. Because of this, the effect of the solutions on the horizontal sound insulation was studied computationally in this paper.

2.2 Sound insulation between adjacent rooms

In a complete building, the sound insulation between adjacent rooms depends on the room properties and flanking sound transmission between rooms. Thus, the effect of the studied floors on the horizontal sound insulation cannot directly be explained by the performance of the floors. To study further how the floors influence the horizontal sound insulation between rooms, a flanking transmission analysis was carried out for an imaginary timber building setup.

In the analysis, airborne and impact sound insulation between two rooms (Fig. 2) was computationally determined applying the methods presented in the parts 1 and 2 of the ISO 12354 [3,4] and the computational results for the floors based on the methods presented in Section 2.3. All the load-bearing structures surrounding the studied rooms were 140 mm thick CLT plates and the T- and X-junctions between the CLTs were rigid. The dimensions of the adjacent rooms were 3 m x 2.8 m x 3.8 m of which the area of the wall separating the rooms was 3 x 2.8 m^2.

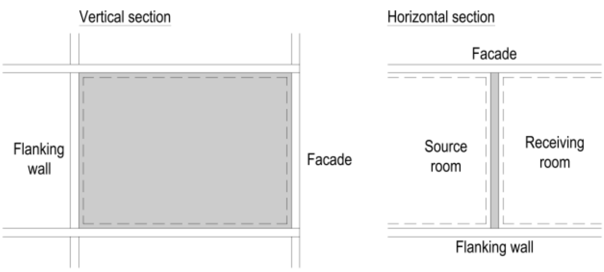

Figure 2. Flanking sound transmission setup. Rooms were surrounded with 140 mm thick CLT plates with rigid junctions. The grey areas represent the wall separating the rooms, and the dashed lines illustrate the ceilings, wall linings and floor coverings.

Sound insulation between the rooms was determined in six different cases: for the floors F0, F1, and F3 with two different partition walls. The studied walls were:

- A: 2 plasterboards 13 mm + steel frame 45 mm and mineral wool + air gap 27 mm + steel frame 45 mm and mineral wool + 3 plasterboards 13 mm
- B: CLT 140 mm + air gap 30 mm + 45 mm and mineral wool + 2 plasterboards 13 mm

In all the cases, except for the case with the floor F0, the other indirect flanking transmission routes were covered with wall linings (the same CLT lining as in wall B), or suspended ceilings (see floors F2 and F4, in Section 2.1).

2.3 Simulation procedures and model descriptions

The sound insulation of floors F0, F1 and F3 was examined using a similar approach as in a previous study [5], in which the benefits of an elastically suspended ceiling was investigated. Similarly to the previous study, both parametric calculation models as well as the finite element method were used to examine the impact and airborne sound insulation of the floors.

The analytical models were used to analyse the frequency range 250–5000 Hz, whereas the FE-model was used in the low frequencies between 50–200 Hz 1/3-octave bands.

In addition to floors F0, F1 and F3 the aforementioned calculation methods were used to examine the partitions and other flanking constructions of the CLT building setup described in Section 2.2.

2.3.1 Material properties

The material properties used in the calculation of sound insulation have been presented in Tab. 2.

Table 2. Applied elastic material properties.

Material	ρ [kg/m^3]	E [MPa]	ν [-]	η_s [-]
CLT	510	4600*	0.28	0.02
Screed	2200	30000	0.20	0.01
Fermacell	1270	3800	0.28	0.01
OSB	490	2210	0.28	0.01
Plasterboard	710	3100	0.28	0.01

* Equivalent isotropic value based on the ref. [6].

The static airflow resistivity of the glass wool was 10000 Pa·s/m^2. Spring constant and structural loss factors of the elastic floor mounts and the elastic hangers were 122990 N/m and 0.07 and 29960 N/m and 0.07, respectively.

The CLT plate and the floor topping of floor F3 were modelled as equivalent isotropic plates in an approach similar to the one used in [6]. The bending stiffnesses of the structure in the different main directions B_x and B_y were first determined, and the equivalent bending stiffness was:

$$B_{eq} = \sqrt{B_x B_y} \tag{1}$$

From the equivalent bending stiffness, the equivalent Young's modulus can then be determined from:

$$E_{eq} = \frac{B_{eq}}{I} \tag{2}$$

where E_{eq} is the equivalent Young's modulus, and I is the second moment of area.

2.3.2 Finite element method

The FE-modelling of floors F0, F1 and F3 was carried out using COMSOL Multiphysics 6.2. The same finite element model was used for both airborne and impact sound insulation, with the only difference being the type of excitation used. The model was a fully coupled analysis with two-way acoustic-structural interaction between the structural and acoustical parts of the model, and it was built to correspond to laboratory conditions. The CLT was simple supported and the other structural parts were connected to the CLT but otherwise the boundary conditions were free. The geometries of the FE-models of the floors F1 and F3 are presented in Fig. 3.

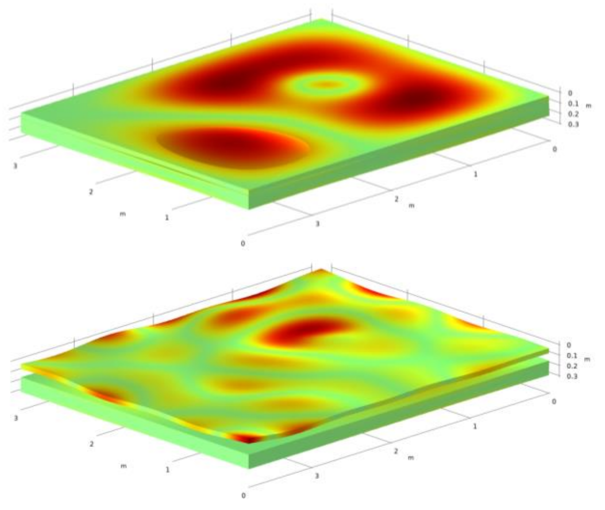

Figure 3. The FE-models of the floors F1 (above) and F3 (below) presenting the floor displacements at 100 Hz during the impact excitation.

The governing equation of motion for the structural parts of the model was:

$$\nabla \cdot \boldsymbol{S} = -\rho\omega^2 \mathbf{u} \qquad (3)$$

where $\boldsymbol{S}$ is the second Piola-Kirchhoff stress tensor, ρ is the material density, ω is the angular frequency and $\mathbf{u}$ is the displacement vector [7]. The acoustical domains were governed by the Helmholtz equation:

$$\nabla \cdot \left(-\frac{1}{\rho_0}\nabla p\right) - \frac{\omega^2 p}{\rho_0 c_0} = 0 \qquad (4)$$

where p is the time harmonic sound pressure, ρ_0 is the density of air and c_0 is the speed of sound in air [8].

The sound absorbing materials in the air cavities of the suspended ceiling and the floor topping of floor F3 were modelled using the modified Champoux-Allard equivalent fluid model [8, 9].

The elastic floor mounts and ceiling hangers were modelled as spring-damper components as in [5, 10, 11]. The use of spring-damper components as a substitute for a full 3D-model of an elastic ceiling mount was previously found to yield good results [5]. The spring-damper components were given a spring coefficient k and loss factor corresponding to the pre-loaded state of the elastic mount. The natural frequency f_0 of the ceiling hangers was 9,5 Hz and the mass per hanger was 8,4 kg. The natural frequency of the floor mounts was 16 Hz and the mass per mount was 12,2 kg.

To solve the radiated sound power, a half-infinite acoustic domain representing the receiving airspace was modelled on the receiving side of the floor constructions. The fully absorptive boundary condition of the half-infinite domain was achieved using perfectly matched layers.

The mesh of the FE-model was built using hexahedral quadratic elements. The mesh was frequency dependent with the element size being a fifth of the wavelength of sound according to [8].

The airborne sound insulation of the floor constructions was assessed by applying a diffuse sound field excitation modelled after [12]. The excitation applied on the surface of the floor construction was a sum of N plane waves evenly distributed over a half-sphere with random phase. The FE-model was then used to determine the radiated sound power. Then the sound reduction index of the floor construction was determined from:

$$R = 10 \log\left(\frac{P_{dif}}{P_{rad}}\right) \qquad (5)$$

where P_{dif} is the sound power generated by the diffuse field excitation on the sending side of the structure and P_{rad} is the radiated sound power on the receiving side.

The impact sound insulation of the floors was determined using an ISO tapping machine excitation modelled as a series of point forces on the floor surface after [13]. Again, the sound power radiated by the structure was solved from the FE-model. The normalized impact sound pressure level was then determined from:

$$L_n = \log\left(\frac{P_{rad}}{P_0}\right) + 10 \log\left(\frac{A_{ref}}{A_0}\right) \qquad (6)$$

where P_0 is the reference sound power 10^{-12} W, and A_{ref} and A_0 are the reference sound absorption areas 4 and 10 m^2.

2.3.3 Parametric models

The airborne and impact sound insulation of the were examined in the mid and high frequency range with parametric calculation tools developed by AINS Group.
The airborne sound insulation of the floor constructions was examined with a tool that combines a number of different calculation models based on statistical energy analysis, lumped mechanical models and forced transmission approaches. The calculation method is based on Refs. [3, 14–18].
The impact sound insulation of the floor structures was calculated using a method based on Refs. [4, 19–23]. In addition to the features of the airborne sound insulation model, the impact sound insulation model takes into account the force interaction of the ISO tapping machine and the floor surface.

3. RESULTS

3.1 Sound insulation of the floor assemblies

Simulated sound reduction index R and normalised impact sound pressure level L_n of floors F0, F1 and F3 are presented together with the measured standardised level difference D_{nT} and standardised impact sound pressure level L'_{nT} results in Fig. 4 and Fig. 5. Thus, discrepancies between the results are partly explained by the differing quantities.
Fig. 4. shows that the calculated sound reduction index correlates well with the measured level difference. The effect of the bare CLT slab (F0) accumulates to the results of F1 between 80 and 400 Hz in both the measured and simulated results. Having an elastically mounted floor (F3), the effect of the CLT slab is no longer displayed.
The correlation between the simulated and measured impact sound pressure levels is weaker than for airborne sound yet acceptable (Fig. 5). The calculation result for F0 seems to have shifted to lower frequencies compared to the measured result. The effect of the CLT slab can be seen also on the other simulated results.
Calculation results underestimate the sound insulation of floor F3 on low frequencies below 250 Hz. The resonance frequencies of floor F3 are shifted higher by 1/3 octave on the simulated results compared to measurements.

3.2 Sound insulation between adjacent rooms

The predicted total sound insulation between rooms and all flanking transmission paths between rooms are presented in Fig. 6 and Fig. 7 for all examined cases.

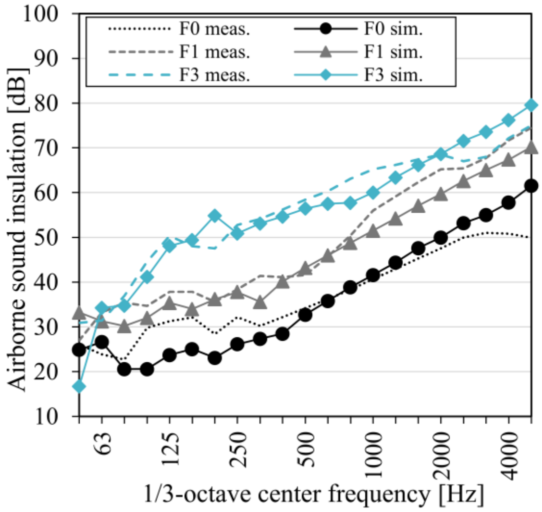

Figure 4. Measured standardised sound level difference D_{nT} and simulated sound reduction index R of floors F0, F1 and F3.

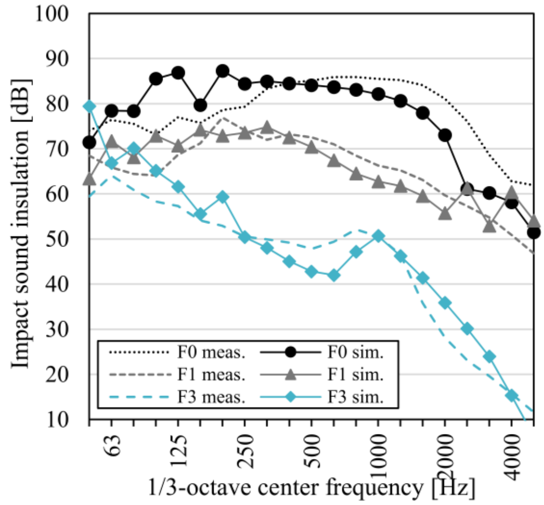

Figure 5. Measured standardised impact sound pressure level L'_{nT} and simulated normalised impact sound pressure level L_n of floors F0, F1 and F3.

In case of the horizontal airborne sound insulation, the main limiting factor is the flanking path Ff through the floor structures (see Fig. 6). Covering the floor with the screed (F1) (and other flanking paths with the linings) improves the horizontal airborne sound insulation. However, the total sound insulation is still limited due to the flanking sound transmission via the floor-to-floor route. In case of the floor F3, the limiting factor is the sound reduction index of the wall itself.

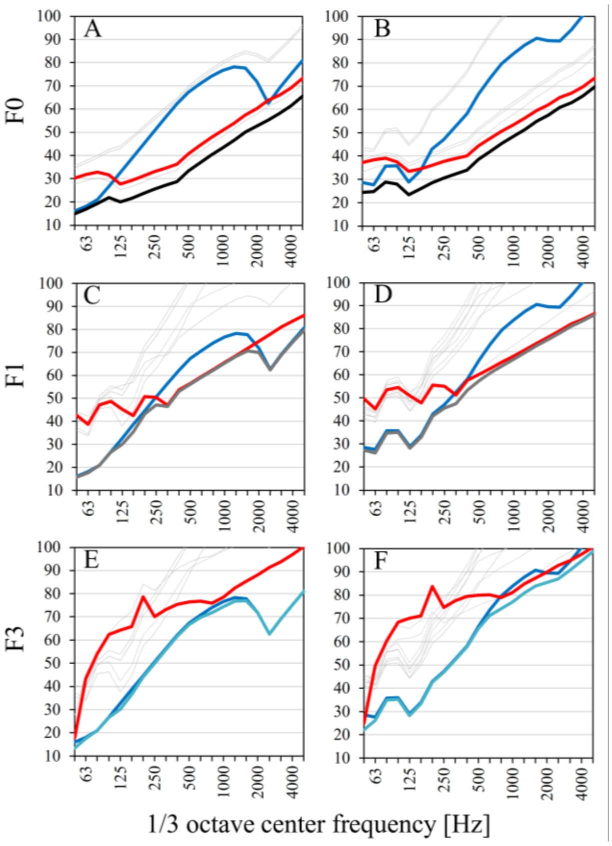

Figure 6. Airborne sound insulation (D_{nT} [dB]) between rooms. Dark blue line denotes the direct path Dd of wall A or B, red line indicates flanking path through floor, light grey lines indicate other flanking paths, and bold line denotes the total sound insulation. A. floor F0, wall A, B. floor F0, wall B, C. floor F1, wall A, D. floor F1, wall B, E. floor F3, wall A, F. floor F3, wall B. On figures A and B, the flanking elements are bare CLT. Figures C-F have linings and suspended ceiling on flanking structures.

The horizontal impact sound insulation is determined mostly by the impact sound insulation of the floor structure (see Fig. 7). For elastically mounted floor F3 the total impact sound insulation is a combination of different flanking paths: path Fd from floor to wall below 500 Hz and path Ff from floor to floor above 500 Hz. In case of the floor F1, a soft floor covering should be applied to reach reasonable impact sound insulation between rooms.

The results show that by applying the elastically mounted floor, better sound insulation can be achieved also between rooms.

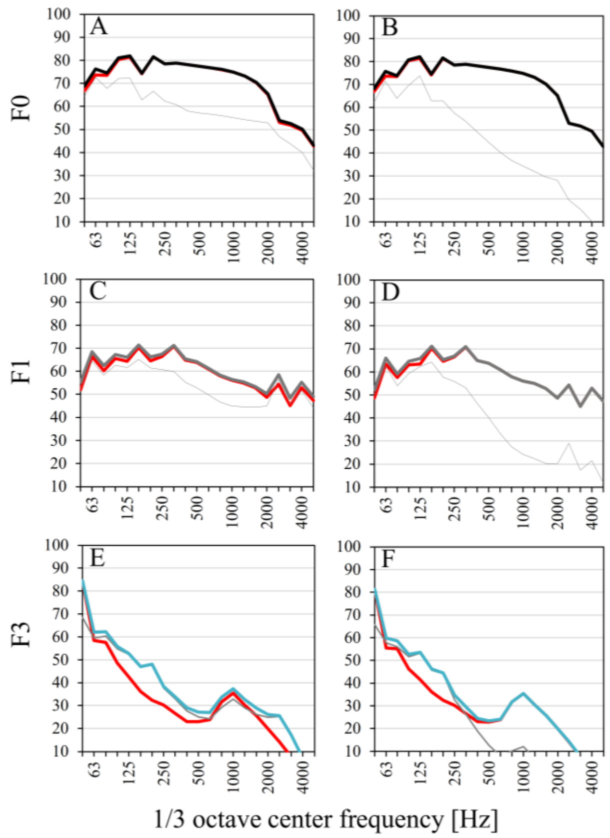

Figure 7. Impact sound insulation (L'_{nT} [dB]) between rooms. Dark blue line denotes the sound insulation of wall A or B, red line indicates flanking path through floor, light grey lines indicate other flanking paths, and bold line denotes the total sound insulation. A. floor F0, wall A, B. floor F0, wall B, C. floor F1, wall A, D. floor F1, wall B, E. floor F3, wall A, F. floor F3, wall B. On figures A and B, the flanking elements are bare CLT. Figures C-F have linings and suspended ceiling on flanking structures.

The total horizontal sound insulation results that were presented in the Figs. 6 and 7 are repeated in Figs. 8 and 9. The corresponding SNQs are presented in Tab. 3.

Table 3. Predicted single-number quantities.

Floor, wall	$D_{nT,w}$ (C, $C_{50\text{–}3150}$)	$L'_{nT,w}$ (C_I, $C_{I,50\text{–}2500}$)
F0, A	37 (-1, -2) dB	76 (-2, -1) dB
F0, B	42 (-2, -2) dB	76 (-2, -1) dB
F1, A	54 (-3, -7) dB	64 (-1, -1) dB
F1, B	55 (-4, -5) dB	63 (-1, -1) dB
F3, A	56 (-4, -9) dB	41 (2, 29) dB
F3, B	56 (-5, -5) dB	40 (2, 26) dB

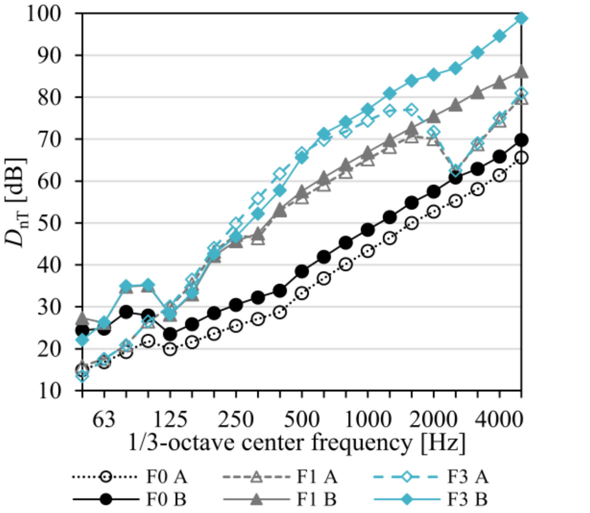

Figure 8. Standardised level difference between rooms for walls A and B.

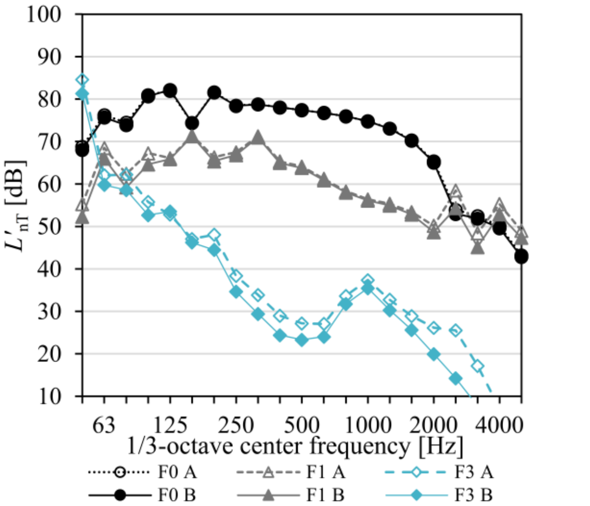

Figure 9. Standardised impact sound pressure level between rooms for floors F0, F1 and F3. The weak results for the floor F3 at 50 Hz cumulate from the simulation result (see Fig. 5), and are likely to underestimate the performance of the solution at this frequency band.

The standardized level difference $D_{nT,w}$ is significantly higher when using sound insulating linings on room surfaces. Compared to the reference case F0 with no linings, the airborne sound insulation is improved by 13–17 dB with floor F1 and 16–19 dB with floor F3. The standardized impact sound pressure level $L'_{nT,w}$ is improved by 12–13 dB with floor F1 and 35 – 36 dB with floor F3.

4. DISCUSSION

In the first part of this study (3.1) the airborne and impact sound insulation of floors F0, F1 and F3 were examined with FEM and parametric calculation methods. The calculation results were then compared to vertical field measurement results acquired in [1] (Figs. 3 and 4). The agreement between the simulated and measured results was good apart from the 50 Hz 1/3-octave band for floor F3, where a significant increase in the impact sound pressure level can be seen in the simulation result. The spectrum adaptation term $C_{I,50–2500}$ for structure F3 is determined by the divergent 50 Hz result and has a significant effect on the single-number quantities. From Figs. 3 and 4 the same decrease in sound insulation is not visible in the corresponding measurement results.

The discrepancy in the lower frequencies for F3 could be due to the boundary conditions in the FE-model. The results of [2] indicate the building boards of the elastically mounted floor were connected to the partition wall. This causes the floor assemblies to not perform as intended and affects the measured sound insulation. The building boards of the elastically mounted floor in F3 were modelled in FEM as freely supported, which differs from the *in-situ* conditions.

Floor construction F1 seems to perform better at low frequencies, which could be due to F1 not being a conventional screed floor. Typically, the cement screed is cast on top of a protective layer, and sometimes additional connectors are used to make the joint between CLT and screed stiffer. In this case, however, the underlay was a elastic bitumen-based product, which lead to the screed working as a floating floor structure rather than a compound structure. Therefore, floor F1 might have better sound insulation qualities than a conventional CLT-screed compound floor.

The CLT was modelled in FEM as a ~10 m^2 plate, whereas the CLT in the ADIVBois mock-up connected to the surrounding structures. Therefore, the total losses of the CLT were higher than in a laboratory setting, and the sound energy was spread to a wider area instead of being completely transmitted to the room below.

The sound insulation between rooms in the mock-up building, including flanking transmission, was investigated in [25] with both measurements and predictions using ISO 12354 [3, 4]. It was found that the agreement between measurement and prediction was reasonable. However, there was rather significant uncertainty in the measured vertical impact sound insulation, especially at low frequencies. Additionally, the accuracy of the predictions in [25] was worse at lower frequencies.

The horizontal sound insulation between rooms was also investigated in [25], but no comparison was done between different floor structures. Horizontal sound insulation between rooms with floors F1 and F3 was compared in Figs. 7 and 8. Fig 7 shows that the horizontal airborne sound insulation is greatly improved with the use of wall linings, floor toppings and suspended ceilings. It is also worth noting that F3 performs better than the screed solution F1.

The horizontal impact sound insulation is also significantly improved with the use of either the screed floor or the elastically mounted floor (Fig. 9). However, the elastically mounted floor again performs better than the screed floor in most of the building acoustics frequency range. The weaker apparent impact sound insulation at 50 Hz is due to the calculated impact sound insulation of floor structure F3, which was discussed above.

The elastically mounted linings effectively reduce flanking transmission via the load bearing CLT frame. According to calculation results in Figs. 5 and 6 the joints of the CLT frame can be rigid, when wall linings, suspended ceiling and floor are connected elastically. This solution is essentially a room-in-room solution, where the choice of partition wall becomes the limiting factor for horizontal airborne sound insulation.

Horizontal impact sound insulation is dependent on both the partition wall and the floor assembly. Since all impact sound is transmitted via the floor, it's the most important element. However, the performance of the floor may be superseded by a particularly weak wall structure, causing sound to be transmitted via the floor-wall path instead of the floor-floor path. An example could be a bare CLT partition rigidly connected to the load bearing floor structure. On the other hand, a completely rigid CLT frame could be a functional choice when using elastically connected lining structures. Having a rigid load bearing frame is beneficial for example for the bracing of a building.

5. CONCLUSIONS

The horizontal sound insulation in a CLT framed building was investigated with sound insulation predictions using the ISO 12354 method. The airborne and impact sound insulation of the individual building elements were determined using both the finite element method as well as parametric methods. The calculated sound insulation of the building elements was compared to field measurements with good agreement. Larger discrepancies were found in the low frequency range, which could be due to differences between calculation assumptions and *in-situ* conditions as well as measurement uncertainties.

According to the calculation results the horizontal sound insulation between rooms can be significantly improved with elastically attached linings on room surfaces. Additionally, it was found that using an elastically mounted lightweight floor topping was a superior solution when compared to a cement screed floor.

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