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Application of elastic interlayers at junctions in massive timber buildings

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ABSTRACT

The application of elastic interlayers at junctions in massive timber buildings was investigated in a parametric study in the Laboratory for Acoustics at Empa. Flanking sound transmission across a junction of a floor with an exterior wall was investigated for different construction details with and without interlayers, as well as with rigid and decoupled connectors. The performance of the interlayers is discussed by comparing the apparent airborne and impact sound insulation between two rooms one on top of the other. The benefit of the elastic interlayers and connection variants is hereby gauged against other additional measures, for example wall linings, suspended ceilings, floating floors required to achieve equal sound insulation and to fulfill acoustic requirements.

Keywords: Sound Insulation, structure-borne sound transmission, flanking, connections, timber buildings

1. INTRODUCTION

With the worldwide trend for sustainable buildings the demand for multi-storey wooden buildings is increasing significantly. In many countries, including Switzerland, even high rise residential and office buildings are being designed and built out of wood. This was made possible due to massive timber floors and walls, like Cross-Laminated-Timber (CLT) or Glulam plates, that are able to carry high structural loads and provide sufficient fire safety (1). Besides these advantages, the sound insulation of the elements is limited due to their low mass in combination with a comparatively high bending stiffness. Therefore, for partitions between adjacent rooms in different units of the building additional measures, like for example floating floors, gypsum board wall linings and suspended ceilings, are required to fulfil sound insulation requirements for direct impact and/or airborne sound insulation (2). Some of these measures are also beneficial for improving flanking sound insulation. However, these additional measures are costly to install, reduce the room volume and also wooden surfaces of the structure are being covered and not visible anymore. In this paper solutions with resilient interlayers at the junction between the massive timber elements and visible surfaces are presented and their acoustical performance is gauged against wall linings. Further, consideration is given to the connection details between the elements that are required for structural integrity.

2. BUILDING PERFORMANCE

First, the methods for prediction of impact and airborne sound insulation in buildings using the methods of the EN 12354-series as well as the methods for the measurement of the necessary input

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data are briefly outlined. In the following only vertically adjacent rooms, with one room on top of the other, are considered. For this situation, besides the direct sound transmission path, at each building junction at the four floor edges additional three airborne and one impact flanking paths exists, where structure-borne sound is transmitted from one element to the other.

2.1 Prediction according to EN 12354

The airborne and impact sound insulation performance of massive wood buildings can be predicted with the methods of EN ISO 12354-1:2017 and EN ISO 12354-2:2017 respectively. As input data the sound insulation of the elements and the attenuation of structure-borne sound at the junction are required. The flanking sound reduction index R_{ij} can be calculated with equation 1 and the normalized flanking sound pressure level $L_{n,ij}$ with equation 2 respectively for each flanking path ij.

$$R_{ij} = \frac{R_{i,situ} + R_{j,situ}}{2} + \Delta R_{i,situ} + \Delta R_{j,situ} + \overline{D_{v,ij,situ}} + 10lg\frac{S_S}{\sqrt{S_i S_j}} \tag{1}$$

$$L_{n,ij} = L_{n,i,situ} - \Delta L_{situ} + \frac{R_{i,situ} - R_{j,situ}}{2} - \Delta R_{j,situ} - \overline{D_{v,ij,situ}} - 10lg\frac{S_i}{S_j} \tag{2}$$

For the two coupled elements i and j, the direct sound reduction index R and the normalized impact sound pressure level L_n, the improvement due to additional layers ΔR and ΔL_n for airborne and impact sound, the direction averaged velocity level difference $\overline{D_{v,ij}}$ and the area S of the flanking elements S_i and S_j as well as of the partition S_s have to be known for the considered building situation *situ*. The transfer of measurement data for massive timber elements from the lab to the building situation *situ* is discussed in detail in reference (3).

2.2 Junction transmission

The transmission of structure-borne sound at junctions of Type A elements according to EN ISO 12354-1:2017 is expressed in terms of the so-called vibration reduction index K_{ij}. The structural reverberation time of Type A elements in a building is governed by the structural transmission to adjoining elements, in essence this is true for homogenous building elements with a relatively low internal damping, like for the CLT and Glulam elements with fully glued wooden lamellas considered in this study. The K_{ij} is determined from the measured direction averaged velocity level difference of the two elements using equation 3.

$$K_{ij} = \overline{D_{v,ij,lab}} + 10\,\mathrm{lg}\frac{l_{ij,lab}}{\sqrt{a_{i,lab} a_{j,lab}}} \tag{3}$$

To determine $\overline{D_{v,ij,lab}}$ one of the two coupled elements i and j is excited mechanically and the difference between the spatial average surface velocity level on the excited and on the receiving element is measured. The the test is repeated with excitation of the second element and the results for both directions are arithmetically averaged afterwards. $\overline{D_{v,ij,lab}}$ is normalized with so-called absorption lengths a_i and a_j, that depend on the structural reverberation times T_s and surface area S of the coupled elements, and with the junction length l_{ij}.

$$a_{i,situ} = \frac{2.2\pi^2 S_i}{c_0 T_{s,i,situ}}\sqrt{\frac{f_{ref}}{f}}, \text{ and } \; a_{j,situ} = \frac{2.2\pi^2 S_j}{c_0 T_{s,j,situ}}\sqrt{\frac{f_{ref}}{f}} \text{ respectively} \tag{4}$$

For the prediction of the sound insulation in a building situation *situ*, the procedure for the normalization in equation 3 is inversed. $\overline{D_{v,ij,situ}}$ is obtained from K_{ij}, the structural reverberation times and the geometry of the building situation.

3. Measurement Setup

Experiments for this study were carried out in Empa's Laboratory for Acoustics and Noise Control. The structure-borne sound transmission at a T-junction of CLT walls and a Gluelam floor was investigated for different connection details with and without elastic interlayers. The investigated T-junction is a common solution for connecting a floor with exterior walls or with interior double walls, when the floor is not continuous across this junction.

3.1 Test Object

3.1.1 Junction

The measurement setup consists of a T-junction installed in the flanking facility of Empa's Lightweight Construction Laboratory, where building sections with a maximum of four rooms with two on each floor can be installed. In the current study only two rooms were installed as shown in Figure 1 separated by a 220 mm thick Glulam floor with a weight of 102 kg/m^2. The floor had a size of 4.20 m width by 5.60 m length consisted of seven approximately 60 cm wide planks. The planks had tongue and groove joints along their length side and were joined together with diagonally driven screws. The floor rested with the smaller edge on a 100 mm thick and 2.90 m high 3-ply CLT wall (48.4 kg/m^2) and on the opposite side on the permanent concrete structure of the facility. On the upper side of the junction a second100 mm thick and 2.90 m high 3-ply wall was on top of the Glulam floor. The remaining two opposite edges of the floor were free and only sealed to prevent sound leaks.

Two walls in each room as well as the floor in the lower room were part of a permanent concrete structure that gave the mock-up its structural integrity. The remaining two walls and the upper room's ceiling were movable massive wooden elements. Further, the heavy ceiling rested on the upper wall of the test junction to load it like in a real building. At all permanent walls of the facility, as well as the movable walls measures were taken, like additional linings, elastic mountings or structural breaks, to provide a high flanking sound insulation.

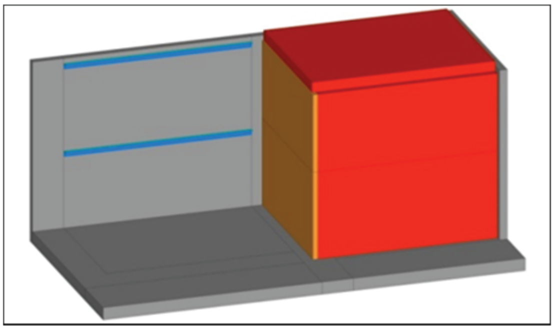


Figure 1 – Drawing of the test setup in the Empa Flanking Facility with the concrete backbone (grey), test specimen (orange) and movable walls (red)

3.1.2 Connection details

In this article four of the investigated connection methods between the upper wall and floor are discussed. For all these junctions the floor was always connected rigidly to the lower wall with 14 screws, 2 at each floor element, that were driven from the top through the Glulam-floor. The connection of the upper wall was modified as follows:

- Reference case:
  No elastic interlayers were installed, the upper wall was connected with 3 metal angles spaced 1.80 m at the inside of the junction.
  This case is the most common rigid connection method for the walls and floors considered.
- Limit of interlayer:
  The upper wall was put on an elastic PUR-foam strip (design frequency $f_0 \approx 20$ Hz) without any additional connectors.
  This is not a realistic solution, but is used to identify the maximum achievable structure-borne sound reduction of the interlayers.
- Interlayer with decoupled angles:
  The elastically supported upper wall was connected with 3 decoupled angles spaced 1.80 m.
  This is one recommended acoustically optimized connection method that fulfils also common structural requirements.
- Interlayer with rigid angles:
  The elastically supported upper wall was connected with 3 common rigid angles, like in the reference situation, at a spacing of 1.80 m.
  This method is not recommended from an acoustical point of view, nevertheless often applied due to structural reasons.

3.1.3 Additional Linings

For the prediction of the building situation an additional floor topping and wall lining are considered. The floor topping consists of a 70 mm thick concrete screed (147 kg/m^2) floating on a 30 mm impact sound insulation (glass fibre, dynamic stiffness ≤ 6 MN/m^3) and a 30 mm expanded polystyrene foam (EPS; elastified) as installation layer. Underneath a 90 mm thick gravel layer (126 kg/m^2) was placed on the bare floor as additional ballast.

The wall lining for the CLT walls is an additional layer of 15 mm gypsum fibre board that is directly attached to 40 mm thick wooden battens. The wooden battens are screwed to the CLT wall with a spacing of 62.5 cm. The cavity between the battens is filled with 40 mm lightweight glass fibre insulation with a flow resistivity > 5 kPa s/m^2.

3.2 Measurement methods

All input data for the prediction in this study is based on measured data obtained as follows.

3.2.1 Vibration Reduction Index K_{ij}

The vibration reduction index is measured according to EN ISO 10848-3:2017. Each element was excited with an electro-dynamical shaker (B&K, Type 4809) driven by white noise at 3 positions for 30 seconds. The velocity levels were measured with 6 accelerometers (B&K, Type 4513B-002) on each element simultaneously that were connected to a multi-channel analyser PAK MKII from VAS Müller BBM. On each element and for each excitation position the levels were measured at 12 positions and corrected for background noise, if necessary. For each excitation position the velocity levels were spatially averaged for each surface and the velocity level differences were calculated. The velocity level differences then were averaged for each excited surface and finally direction averaged for opposite transmission directions.

The structural reverberation times were measured with the same sensors and exciter, but connected to a second 4-channel analyser Apollo box and the software SAMURAI from Sinus Messtechnik GmbH at all 12 receiver positions on each element. A sine sweep signal was used for excitation and the impulse responses were band filtered and backward integrated to determine the structural reverberation times from the decay curves.

From both the velocity level differences and the structural reverberation times of the elements K_{ij} was calculated as described in section 2.2.

3.2.2 Performance of elements and additional layers

The direct airborne and impact sound insulation measurements of the elements and additional layers were conducted in two different facilities using both times the methods of EN ISO 10140-2:2008 and EN ISO 10140-3:2010.

The floors were installed in the flanking facility described in section 3.1. To suppress flanking transmission through the investigated junction additional shielding consisting of a double layer of gypsum board on 20 cm cavity insulation, was installed without structural connections in front of the flanking CLT walls. The sound insulation performance of the walls was measured at a nominally identical test specimen that was installed in Empa's wall facility with structurally separated rooms.

For airborne tests one room was excited with white noise for 60 s, the floors sequentially at two fixed loudspeaker positions and for walls with a moving loudspeaker. The sound pressure in the both rooms was measured simultaneously with two microphones on rotating booms. The sound pressure levels are corrected for background noise. The reverberation times were measured in the receiving room at six fixed microphone positions for two fixed loudspeaker positions using the interrupted noise method in the flanking facility and the MLS-method in the wall facility. At Empa the sound reduction index is usually measured twice in opposite directions and the reported result is the energetically average index of both tests.

For impact tests the floor is excited with a standard tapping machine for 60s sequentially at 6 positions and the sound pressure level is measured with a microphone on a rotating microphone boom. The measured levels are corrected for background noise and normalized with the reverberation time and room volume to obtain the normalized impact sound level.

The improvement of airborne and impact sound insulation is the difference of the one third octave band results for the bare reference specimen and of a second test with the wall lining or the floor topping installed.

4. Results

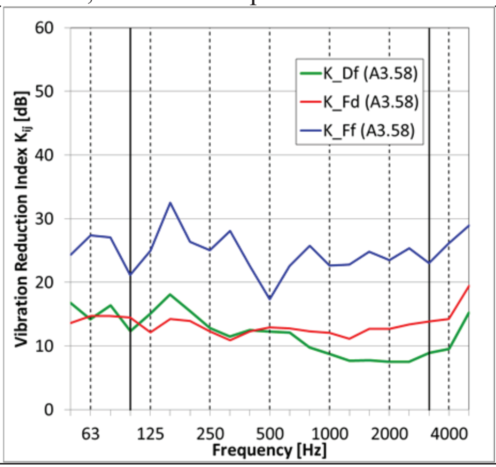
First, the results for K_{ij} for the junctions and the effects due to the connection method are presented. Then the sound insulation is predicted for three building situations showing the effect of elastic interlayers.

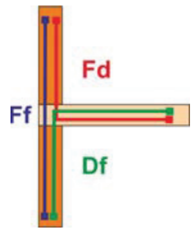
4.1 Vibration reduction index K_{ij} for connection methods

For the junction without interlayer the measured K_{ij} and for the junctions with interlayer the improvement ΔK_{ij} relative to this reference situation are shown for the three transmission paths Ff, Fd and Df, which are depicted in the Figures 2-4 in the middle. For K_{ij} higher values indicate a better sound insulation and for ΔK_{ij} positive values indicate an improvement relative to the reference situation. Besides the one third octave band data also single number ratings evaluated according to EN ISO 10848-1 as the arithmetic average of K_{ij} from 200 Hz to 1.25 kHz are presented.

4.1.1 Reference – rigid connection

For the reference case with the rigid connection and no interlayer K_{ij} are shown in Figure 2. The values are almost constant over frequency and the Ff-path (wall-wall) has with a single number value of about 24 dB the highest insulation. The Fd-path (upper wall-floor) and Df-path (floor-lower wall) are both about 12 dB lower and below 1 kHz equal, but above 1 kHz the angles at the upper wall transmitted slightly less sound than the screws at the lower wall. The higher K_{ij} of the Ff path is plausible as structure-borne sound has to be transmitted twice from the wall to the floor and to the other wall, whereas for path Fd and Df transmission occurs only between the floor and wall.





K_{ij} (200 Hz – 1.25 kHz):		
Ff	23.7	dB
Fd	12.3	dB
Df	11.4	dB

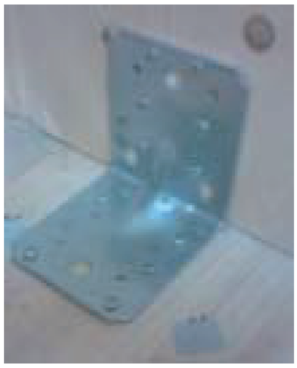


Figure 2 – Vibration reduction index K_{ij} of path Ff, Fd and Df for the rigid connection with 3 steel angles - Left: K_{ij}-Spectrum, middle: Single number rating K_{ij}, left: Connection details

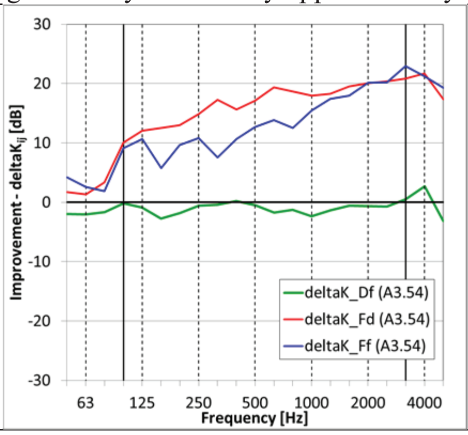
4.1.2 Elastic interlayer – no connection

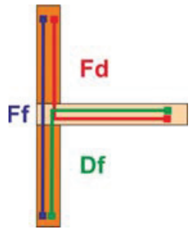
For this “ideal” case with only the elastic interlayer the maximum structural decoupling is obtained. ΔK_{ij} increases with frequency up to 20 dB for the Ff- and Fd-path that cross the elastic interlayer. Below 100 Hz the interlayer gives only 3-4 dB improvement, however, flanking transmission is not very important in this frequency range as it is shown in the predictions.

Between 200 Hz and 1 kHz the improvement for Ff is smaller than for Fd. Here the measurement setup reaches its limits as very high K_{ij} are measured for the Ff path. To obtain their absolute values ΔK_{ij} has to be added to the K_{ij} in Figure 2, where K_{Ff} is already much bigger than K_{Fd}. The single number K_{Ff} is 36 dB in comparison to K_{Fd} with 29.2 dB. Likely airborne sound transmission occurs between the upper to the lower wall. Both have their coincidence frequency in this range and radiate and receive very well sound waves travelling parallel to their surface. As expected for path Df ΔK_{ij} is approximately zero since the interlayer does not affect this path.

4.1.3 Elastic interlayer – 3 decoupled angles

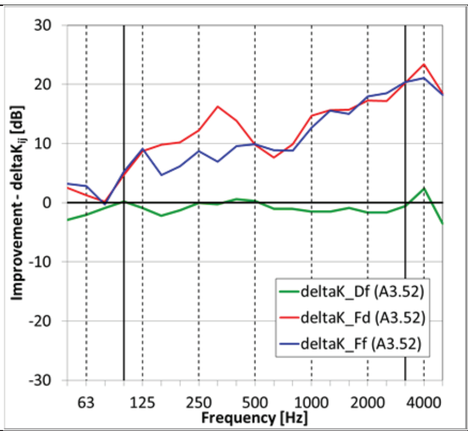
As next step 3 decoupled angles are added to provide the necessary structural stability to the junction. ΔK_{ij} in Figure 4 show a similar trend as without connectors in Figure 3. Ff- path is still limited due to airborne sound insulation between 125 Hz and 500 Hz. Therefore only the Fd-path is discussed in detail and ΔK_{ij} from 100 Hz to 2 kHz is except of a dip at around 800 Hz only 3 dB less than for the ideal case before. The dip is likely caused by a resonance, e.g. between the different steel plates and interlayers of the connecting angle, but needs further investigation. The single number ratings are only reduced by approximately 3 dB and 5 dB for the Ff-path and Fd-path respectively.

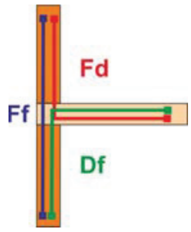




K_{ij} (200 Hz – 1.25 kHz):		
Ff	36.0	dB
Fd	29.2	dB
Df	10.4	dB

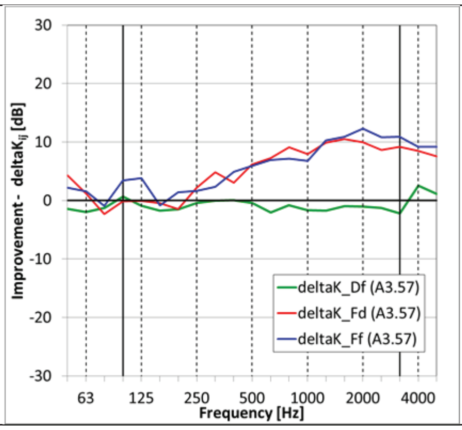
Figure 3 – Improvement of vibration reduction index ΔK_{ij} of path Ff, Fd and Df for elastic interlayer without connectors - Left: ΔK_{ij} -spectrum, middle: Single number K_{ij}, left: Connection details

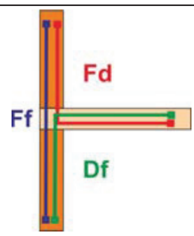




K_{ij} (200 Hz – 1.25 kHz):		
Ff	33.4	dB
Fd	24.5	dB
Df	10.8	dB

Figure 4 – Improvement of vibration reduction index ΔK_{ij} of path Ff, Fd and Df for elastic interlayer with 3 decoupled angles - Left: ΔK_{ij}-Spectrum, middle: Single number K_{ij}, left: Connection details





K_{ij} (200 Hz – 1.25 kHz):		
Ff	29.0	dB
Fd	17.8	dB
Df	10.5	dB

Figure 5 – Improvement of vibration reduction index ΔK_{ij} of path Ff, Fd and Df for elastic interlayer with 3 rigid angles - Left: ΔK_{ij} -spectrum, middle: Single number K_{ij}, left: Connection detail

4.1.4 Elastic interlayer – 3 rigid angles

Finally, ΔK_{ij} is shown in Figure 5 for three common rigid steel angles that connect the upper elastically supported wall. Often this is a compromise with structural requirements. The obtained ΔK_{ij} for both paths Ff and Fd are now equal and much smaller than with decoupled angles. Below 250 Hz results are even equal to the case without elastic interlayer. Above ΔK_{ij} is increasing to a maximum of 10 dB above 1 kHz. Also the single number K_{ij} of path Ff and path Fd give only a small improvement of about 5 dB in comparison without interlayer.

4.2 Prediction of sound insulation in buildings

To underpin the benefit of elastic interlayers in massive timber buildings, the in-situ airborne and impact sound insulation performance between two vertically adjoining rooms, that are separated by a 3 m by 4 m Glulam-floor as described in Section 3.1, is predicted based on measured input data. For all scenarios the floor topping of section 3.2.2 is considered. This is necessary to achieve an acceptable direct sound insulation. Along the 4 m long edges of the floor load bearing T-junctions with 100 mm CLT walls are assumed. The remaining two junctions are considered to be cross-junctions with non-loadbearing lightweight frame walls that do not contribute to flanking transmission and therefore are neglected in the following. The sound insulation of the single flanking paths are predicted with equation (1) and (2) using K_{ij} from section 4.1 as input data. For the matter of simplicity the in-situ structural reverberation times used for the transfer of K_{ij}, R and L_n are assumed to be equal to the Empa flanking test facility. Hereby slightly conservative results were obtained for all situations, as the used reverberation times are slightly longer than in real buildings.

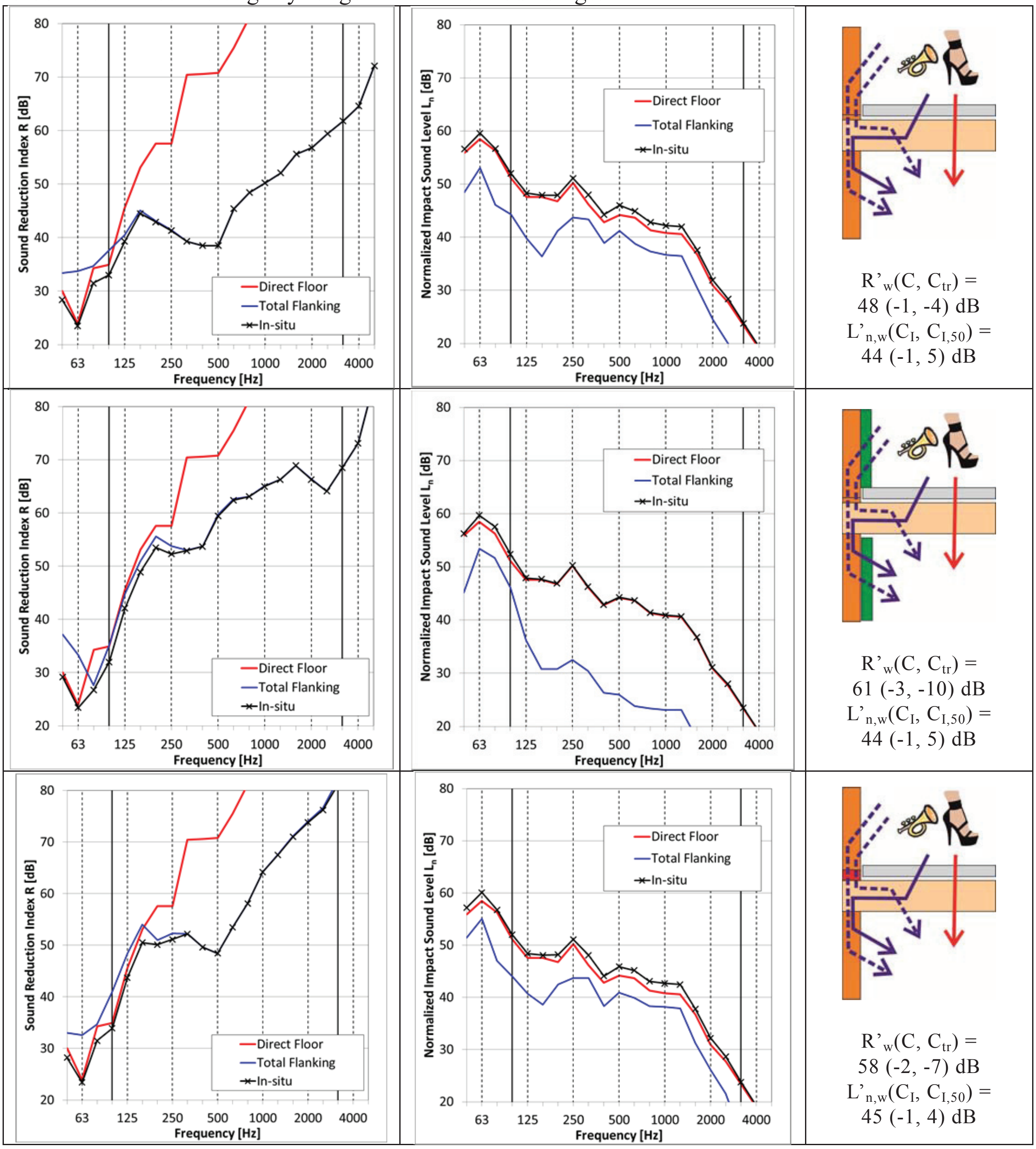


Figure 6 – Predicted airborne (left) and impact (middle) sound insulation performance with single number ratings (right) between two vertically adjacent rooms for three situations; top: without any measures at flanking walls, middle: with wall linings, and bottom: with elastic interlayer and isolated steel angles

For the first situation the walls at the junctions are assumed rigidly connected as for the reference situation. The CLT walls and ceiling are not equipped with additional linings. The results are presented in Figure 6 in the top row. The results are given for direct transmission through the floor (red), the resultant for all flanking paths (blue) as well as the overall transmission for the building situation (black). On the left the sound reduction index is presented and it is obvious that, except for the frequency range below 100 Hz, flanking is dominating due to the two dashed blue paths in the right drawing (Ff and Fd) that are not reduced by the floor topping. For the normalized impact sound pressure level in the middle, direct transmission (red) is dominating in the whole frequency range, as the Df-path (solid blue in the right drawing) is reduced well by the floor topping. Looking at the in-situ single number ratings in the right column of Figure 6 the $L'_{n,w}$-values for impact sound insulation likely fulfil building requirements, whereas the R'_w does not.

The improved results with the additional wall linings of Section 3.1 at the flanking walls are presented in Figure 6 in the middle row. The in-situ sound reduction index on the left is increasing, as flanking transmission is further reduced and $R'_w = 61$ dB is achieved. The in-situ impact sound insulation does not change, as direct transmission is not affected and flanking not relevant.

In the bottom row of Figure 6 the results are shown when the additional linings are substituted by the elastic interlayer and decoupled steel angles of section 4.1.3. Hereby, similar in-situ sound insulation performance with less effort for installation of additional wall linings is obtained.

5. CONCLUSIONS

Results of a study on the performance of elastic interlayers for reducing flanking transmission at a wall floor T-junction in massive timber construction are presented and the influence of typical connectors necessary for the structural stability of the building is investigated. For vertical sound transmission at the T-junction the most critical flanking paths are from upper wall to the lower wall and from the upper wall to the floor as the remaining floor-wall flanking path is usually sufficiently suppressed by a floor topping that is necessary to provide sufficient direct impact sound insulation. These two paths can be sufficiently improved by using an elastic interlayer between the upper wall and floor and provide a very effective alternative to the installation of wall linings at the flanking walls.

However, the type of used connectors at the decoupled wall, that are necessary for structural integrity, play a crucial role for the achievable sound insulation. Therefore, the performance of the connectors is gauged against the maximum performance of the interlayer without any connectors. Common decoupled steel angles achieve a structure-borne sound insulation that is only about 5 dB less than the maximum performance without connectors. Further optimization of the connectors is limited, as only a maximum of 2-3 dB further improvement can realistically be expected. Every connector will add additional rigidity to the ideal and increase structure-borne sound transmission respectively. The use of common rigid steel angles for the connection of the elastically mounted wall cannot be recommended, as only flanking sound reduction is improved only above 250 Hz and the single number vibration reduction index was only 5 dB better than the rigid connection without interlayer. This usually is not sufficient to replace additional wall linings.

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