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SOUND INSULATION IN CROSS LAMINATED TIMBER BUILDINGS AND THE EFFECT OF JUNCTIONS AND FASTENERS

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ABSTRACT: Sound insulation in cross laminated timber buildings can be challenging and is difficult to predict due to lack of reliable predicting models. Details in either the construction itself or in mounting may cause measurement results to vary significantly. Solutions vary notably between projects. Pre-accepted solutions are sparse and in high demand. Residential buildings are especially challenging and commonly need complementary floors, suspended ceilings and wall linings due to high sound insulation requirements. Clients and consumers in Norway often want the timber to be exposed, which make the flanking sound control essential.

Sound tests on a full scale CLT model have been conducted to identify efficient solutions. Flanking sound paths were tested using various resilient interlayers and fasteners in the junctions, and the vibration level difference across the junctions was measured between rooms. Elastically decoupled angle brackets performed better than ordinary angle brackets and screws that penetrate the vibration protection. Additionally, sound insulation measurements are reported on for various slab constructions, including both light and heavy weight complementary floors.

KEYWORDS: Cross Laminated Timber, junction damping, sound insulation

1 INTRODUCTION

Use of cross laminated timber (CLT) in building constructions has increased rapidly in recent years due to its environmentally sustainable and light weight capacities, rapid and efficient assembly, and other desirable physical parameters as summarized by Di Bella et al. [1]. Consequently, the interest from architects, developers, engineers, and politicians has increased notably. Studies on sustainability such as the overview of life-cycle assessment (LCA) by employing CLT in building constructions presented by Younis et al. [2], finding a possible reduction in greenhouse gas emissions of around 40 % is likely to further enhance the interest in CLT.

Espinoza et al. [3] estimated a growth in annual global CLT production from 2010 to 2015 of 250 %, with most of the growth occurring in new production countries outside Europe. Brandner et al. [4] similarly predicted an accelerated rise in the global production volume towards 2025, and particularly in countries such as Canada, United States and Japan, which is accordance with Plackner [5], who projects a possible annual global production of 3 million m^3 by 2025. Muszyński et al. [6] summarized the above and gives an interesting overview of the global CLT manufacturing plants per 2016. Sandoli et al. [7] reported an increase in CLT production in Europe alone from 650,000 m^3 in 2015 to 1,2 million m^3 in 2020. As the use of CLT has surged, the need for standardization and regulative processes for product, testing, mounting, and requirements of a solid timber construction system with CLT quickly became imminent [4], and is now a continuous ongoing process.

National guidelines and documentation of CLT floor and wall constructions published over the last couple of decades [8,9] give good starting points for dimensioning, where the latter presently is being revised as reported by Mahn et al. [10]. Such guidelines are supplemented by investigations of airborne and impact sound insulation for various floor assemblies and resilient layers with CLT constructions, as done by Verdaxis et al. [11], while Homb et al. [12] collected and compared impact sound insulation for typical floor assemblies in different European countries (and laboratories).

In Norway, CLT constructions in buildings with sound requirements are typically mounted with extensive use of screws, commonly also going through the strategically placed elastic layers, reducing their effect [13]. The dimensions of the CLT slabs and walls vary, but due to airborne and impact sound requirements heavy floating floors, addition of mass directly onto slabs, suspended ceilings and separate wall linings are common measures to ensure sufficient sound insulation quality. The extent of these measures is governed not only by the sound insulation requirements themselves, but in many cases

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just as much by which margin the constructors and designers are comfortable with. Experience with directly comparable constructions best enable reduction of such measures, but due to the detailing, vulnerability of construction errors, and variations in junction assembly and in the constructions themselves, such experience is often somewhat limited. Accordingly, Simmons [14] argued that specific experience with the same construction allows for reduced calculation margins with CLT, especially if junctions and lining types are known, while a provisional margin of at least 8 dB is needed for relatively unknown constructions. Such variations are not uncommon when a certain number of presumably identical rooms are included in measurement programs in larger measurement documentation setups, to the authors experience either. When such variations occur, they are usually due to specific construction errors, and not systematic design errors. Systematic deviations from project requirements may also be of such magnitude with limited control of junction design or linings.

CLT is presently considered in buildings with high sound insulation requirements, such as dwellings, cultural centres, and theatres, despite the increased challenges in prediction of sound insulation and vibration compared with heavier materials and constructions. Malo et al. [15] reported on structural design issues with a 14-storey CLT in 2016, and since then even more acoustically complex and higher buildings have been built or are planned in Scandinavia [16].

Additionally, clients and consumers in Norway often want the CLT to be exposed to a large extent, which makes control of flanking sound and junctions essential. Measurements of vibration reduction indices using various elastic interlayers and fasteners have been done by Morandi et. al. [17], who compared junction damping and sound insulation between floors and rooms for a selection of available products with elastic interlayers. Increased knowledge of junction damping and design are essential if wall linings and suspended ceilings should be omitted, the extent of floating floors reduced, and visible timber increased. However, available research results are not always easy to apply in an actual building project.

This paper reports on measurements of flanking sound paths using various resilient interlayers and fasteners in the junctions, and the vibration level difference across the junctions between rooms. Airborne and impact sound insulation measurements are done for various slab constructions, including both light and heavy weight complementary floors. The possible removal of wall linings and suspended ceilings with good junction design is also addressed.

2 THE TEST SETUP

A full-scale CLT mock-up construction was built in an industrial warehouse, with two rooms on the ground floor and one room on the top floor, as shown in Figure 1. The top floor could be lifted from the ground floor by hydraulic jacks, which allows repetitive testing of various resilient interlayers (RI), fasteners, angle brackets or screws commonly used as vibration protection in buildings with sound requirements. The different RI types were applied in the junctions vertically between floors or horizontally between adjacent rooms. These mounting methods were changed and repeated as the rooms were fitted with combinations of suspended ceilings, light or heavy floating floors and wall linings to assess how the mounting method affected the sound insulation and flanking sound transmission.

Figure 1: *Test room set-up.*

A schematic layout of the mock-up is shown in Figure 2, where the room dimensions and thicknesses of the CLT walls and floors are given. Vertical CLT panels were 3-ply of 100 mm thickness throughout. The ground floor and top roof were 3-ply 120 mm thick CLT panels, while the horizontal slabs between the floors and roof of the one-story high part were 5-ply 160 mm CLT. The test rig was delivered from Splitkon AS, element strength classes T15 and T22. The density of the wood is 460 kg/m^3.

Tests of airborne and impact sound insulation were done according to ISO 16283-1 and -2 [18,19], respectively. Variations in damping across building elements were assessed by measurements of velocity level difference across building elements. The velocity level difference is described in ISO 10848-1 [20].

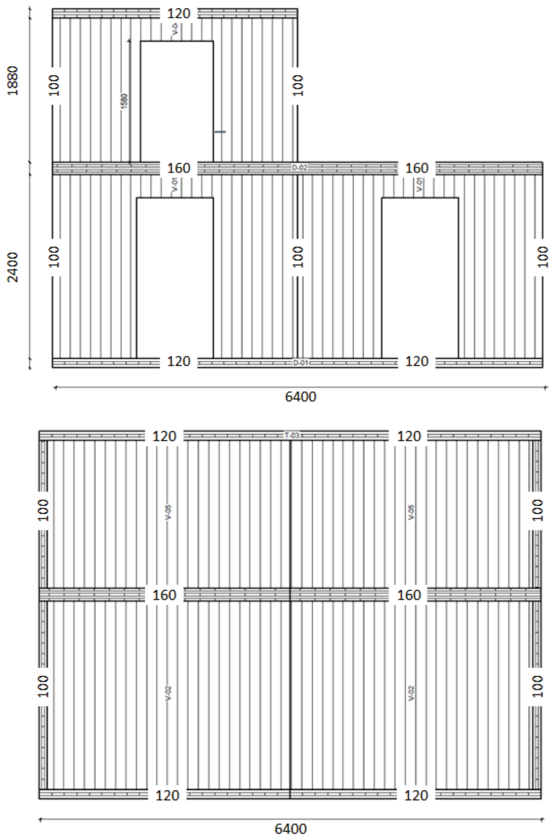

Figure 2: *Vertical section drawings of the test mock-up; a) length section and b) width section. All dimensions are given in mm.*

Four measurement positions were employed on each panel/building element to measure the velocity level difference, as Figure 3 shows. Tests were carried out using three different sound sources; pink noise fed through a loudspeaker, a tapping machine and hammer excitation. The results from hammer excitations have been left out since the excitation proved difficult to control. Results from junction damping shown in this paper have been conducted using a loudspeaker placed on sylomer pads as excitation, with two source positions for each measurement.

Velocity level differences show averaged values of two sets of sensor positions mounted on two corresponding walls, except for horizontal measurements and measurements with the floating floor, where only one set is included. Alltogether eight positions on the slab in the receiving room were used for horizontal measurements of junction damping.

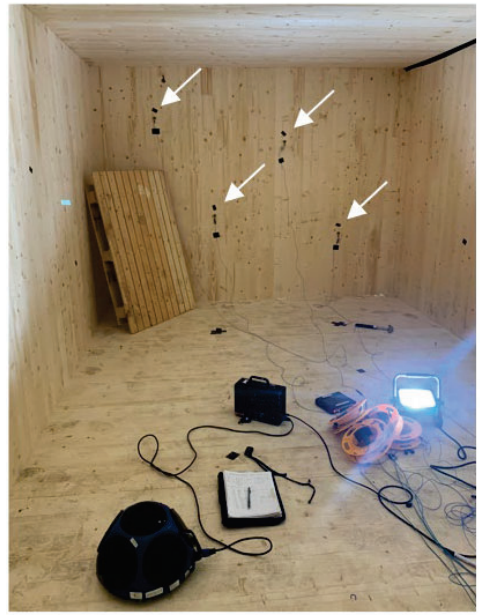

Figure 3: *Photo of sensor setup inside of the test rooms. Sensor positions indicated with white arrows.*

3 MEASUREMENTS RESULTS

3.1 VERTICAL JUNCTION DAMPING

Figure 4 shows the principle vertical junction between floors. The drawing displays a configuration with a RI between the upper wall and the slab and screws connecting the slabs to both the upper and lower wall.

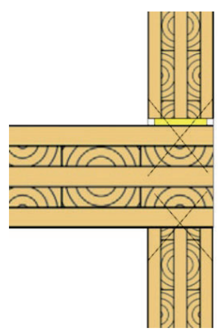

Figure 4: *Drawing of the vertical junction with resilient interlayer and screw fasteners indicated.*

Measurements of velocity level difference between floors using various RI fitted between the floors are shown in Figure 5. The lines show the arithmetic middle value from measurements with each RI type. One measurement (black line) was conducted without using any fastener in the junction between floors.

Measurements using screws and regular angle brackets as fastener resulted in similar results. Angle brackets placed on a RI resulted in marginally better damping above 400 Hz, while elastically decoupled angle brackets gave significantly higher damping.

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These tests showed that the type of fastener has a paramount effect on the junction damping between floors.

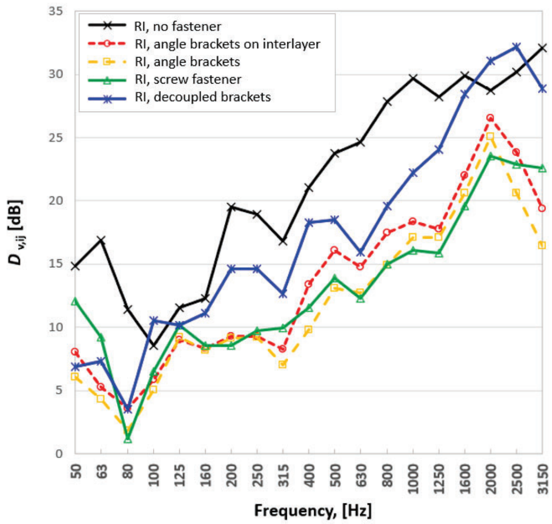

Figure 5: *Measurement results with RI between floors and various fasteners. Blue line shows damping obtained with elastically decoupled angle brackets, red line angle brackets with elastic interlayer between the bracket and the CLT, beige line regular angle brackets, green line screw fasteners and black line without fastener.*

A series of tests were conducted using screws of various thicknesses and centre distance. Both partially threaded (PT) screws, and fully threaded (FT) screws were tested. All screws were mounted diagonally in pairs through the wall-floor junctions between floors. While changing the type of fasteners made an impact on the result, the screw configurations resulted in little variation in junction damping.

An interesting finding is that RI between the floors did not improve the damping around the middle frequencies when screws were inserted through the junction, which corresponds well to results reported by Morandi et al. [17]. This is shown in Figure 6 where a measurement using no RI (black line) is compared to tests conducted with different RIs. This indicates that screws that penetrate the resilient interlayer ruin the effect of the RI and gives limited vibration protection.

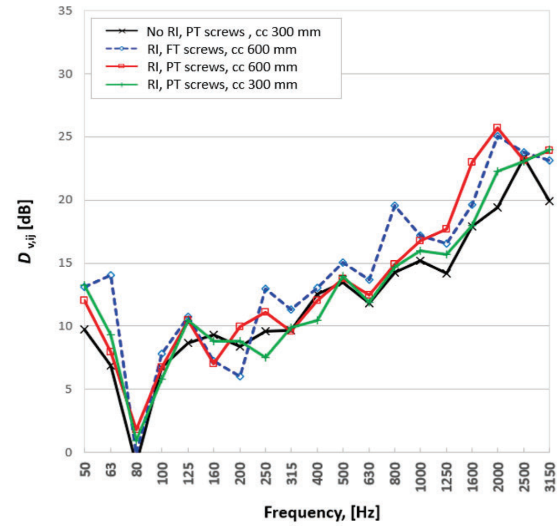

Figure 6: *Measurement results of vertical damping with screw fasteners of various types and spacing. Blue line shows damping obtained with FT screws cc 600 mm, red line PT screws cc 600 mm, green line PT screws cc 300 mm and black PT screws cc 300 mm and no elastic interlayer between the floors.*

3.2 HORIZONTAL JUNCTION DAMPING

Measurements on horizontal junction damping were also conducted. The top floor of the mock-up was removed and the roof slab and connection walls were cut in half, as shown schematically in Figure 7. A floating floor and wall linings were applied in the sending room to control the flanking paths.

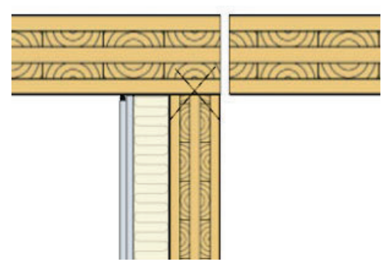

Figure 7: *Drawing of vertical cross section displaying the junction between horizontally adjacent rooms.*

Various fasteners were inserted across the cut between the horizontally adjacent rooms. Sensors were mounted on the roof slab on both sides of the parting wall.

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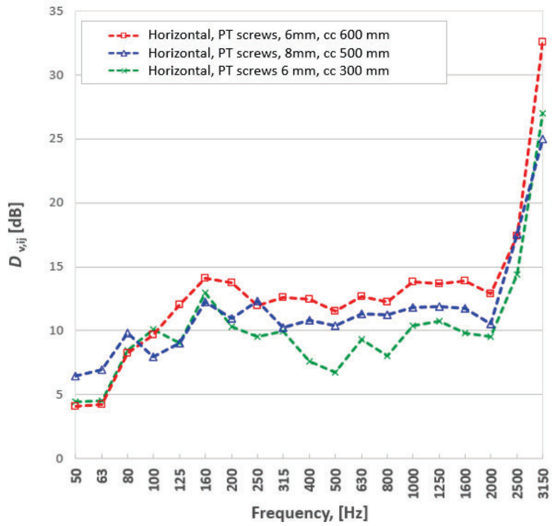

Figure 8: *Measurement results of horizontal damping with screw fasteners.*

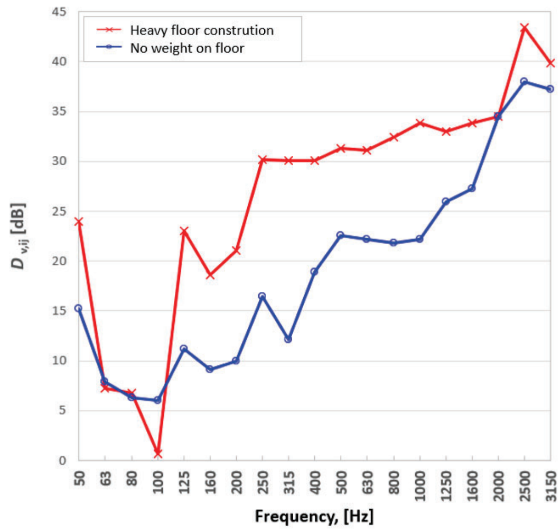

Figure 9: *Measurement results with (red line) and without (blue line) heavy floor construction.*

Figure 6 and Figure 8 illustrate that screw fasteners measured across horizontal and vertical junctions result in similar damping, around 10 dB, in the middle frequencies. The horizontal damping is higher than in the vertical direction in the low frequencies, while vertical damping is better in the high frequencies.

The results from the horizontal measurements also show improved damping with increased centre distance between screws, as opposed to vertically where the results are the same, as the red and green line in Figure 6 show. Morandi et al. [17] points out that the weight of the overlying structure could cause a connection between the elements that reduces the effect of the type of fastener used.

3.3 VERTICAL JUNCTION DAMPING WITH AND WITHOUT HEAVY FLOOR CONSTRUCTIONS

To add mass to the CLT slab 100 mm gravel was laid directly onto the CLT floor, with a floating floor consisting of 40 mm mineral wool with 70 mm concrete on top.

Measured velocity level differences with and without heavy floating floor are shown in Figure 9. Sylomer is used as elastic interlayer in both measurements, and decoupled angle brackets, GePi 240, as fastener.

Adding the floating floor increased the velocity level difference more than 15 dB from 125-1000 Hz.

3.4 SOUND INSULATION WITH FLOATING FLOORS

Airborne and structural sound insulation was measured with different floors constructions, ceilings and linings. Vertical measurements shown below are conducted with various floors as described in Table 1, but without a suspended ceiling to keep the wood exposed in the bottom room. Linings were used to reduce the flanking sound, making the sound travelling directly through the slab would dominant.

Table 1: *Description of floating floor constructions. Exposed CLT ceiling in receiving room.*

Floor type	Floating floor (top to bottom)
A	2x22 mm chipboard, 40 mm mineral wool
B	2x22 mm chipboard, 135 mm joists on 25 mm Sylodyn. Insulated cavity
C	2x22 mm chipboard, 135 mm joists on 25 mm Sylodyn. Insulated cavity. Concrete slabs in cavity covering the majority of the floor area.
D	2x22 mm chip board, 40 mm mineral wool, 100 mm gravel
E	70 mm concrete cast, 40 mm mineral wool, 100 mm gravel

Results for airborne and impact sound insulation with the various floor types described in Table 1 are shown in Figure 10 and summarized in Table 2. As expected, adding weight to the light weight CLT floor construction improves the sound insulation noticeably in the lower frequencies. Gravel added directly to the CLT floor gave considerable improvement, especially for impact sound insulation, as the results with floor types D and E show. The results indicate that the type of the floating floor is not crucial if weight is added directly to the CLT floor.

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Measurements C, D and E comply with the current Norwegian minimum requirements for sound insulation between dwellings of $R'_w \geq 55$ dB and $L'_{n,w} \leq 53$ dB.

Table 2: *Results from measurements of airborne and impact sound insulation on various floating floor constructions.*

Floor type	R'_w ($C_{50-5000}$) [dB]	$L'_{n,w}$ ($C_{I,50-2500}$) [dB]
A	53 (-2)	57 (6)
B	54 (-2)	55 (5)
C	58 (-1)	52 (3)
D	63 (-3)	44 (9)
E	61 (-2)	43 (7)

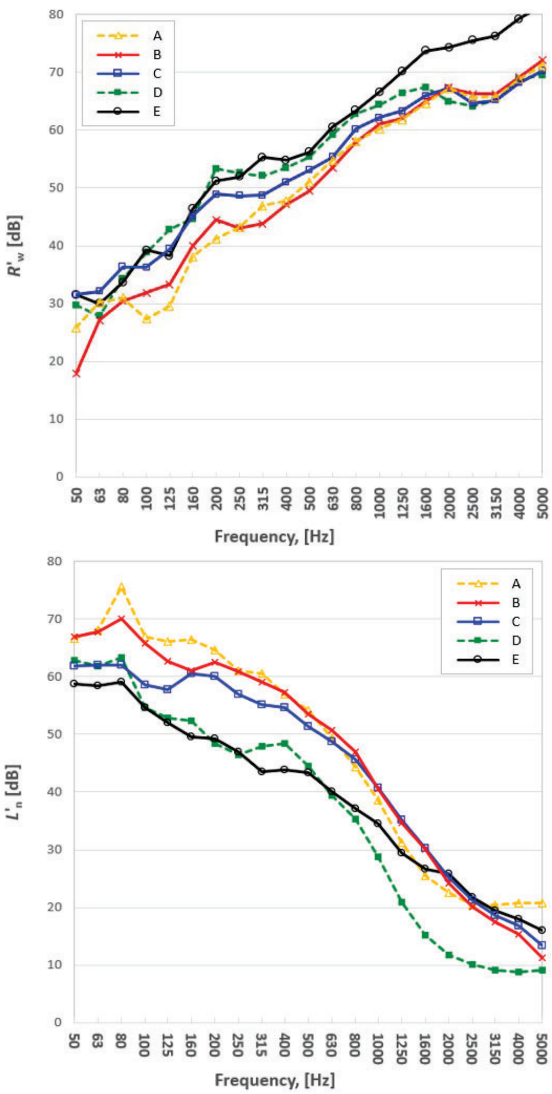

Figure 10: *Vertical airborne (upper) and impact (lower) sound insulation measured between floors with various floor constructions. Slab element was kept exposed in the bottom room, i.e. no suspended ceiling.*

3.5 EFFECTS OF HEAVY FLOOR CONSTRUCTIONS ON SOUND INSULATION WITH EXPOSED CLT

Measurements were performed vertically on a heavy floating floor construction equal to construction E described in Table 1. Elastically decoupled angle brackets were used as fastener in the junction between the floors.

Repetitive tests were done exposing various parts of the CLT construction in the bottom room. All walls and ceiling on the top floor were kept visible throughout the measurements. Results are shown in Figure 11 and summarized in Table 3.

These tests indicate that part of the CLT can be kept visible when using a sufficiently good fastener and applying weight to the floor and still fulfil quite high sound insulation requirements, including the Norwegian minimum requirements for dwellings. Impact sound insulation increased by 6 dB when the suspended ceiling was added. An improvement in the low frequency region from 80-125 Hz can be seen for impact sound insulation with a suspended ceiling, which is especially important to subjective annoyance [21]. Still, the spectrum adaptation terms were equal and smaller without the suspended ceiling for airborne and impact sound insulation, respectively.

The other tests show a up to 3 dB decrease in sound insulation from exposing the wood construction. All three measurements fulfil the minimum sound regulations in Norway between dwellings.

Table 3: *Result table of measurements of airborne and impact sound insulation on heavy top floor and various degree of visible CLT in bottom room.*

Meas. no.	Description	R'_w (+ $C_{50-5000}$) [dB]	$L'_{n,w}$ ($C_{I,50-2500}$) [dB]
E	Exposed CLT in ceiling. Linings in bottom room.	61(-2)	43(7)
F	Sound insulated ceiling, exposed wall in bottom room.	62(-2)	39(8)
G	Sound insulated ceiling. Linings in bottom room.	64(-3)	37(10)

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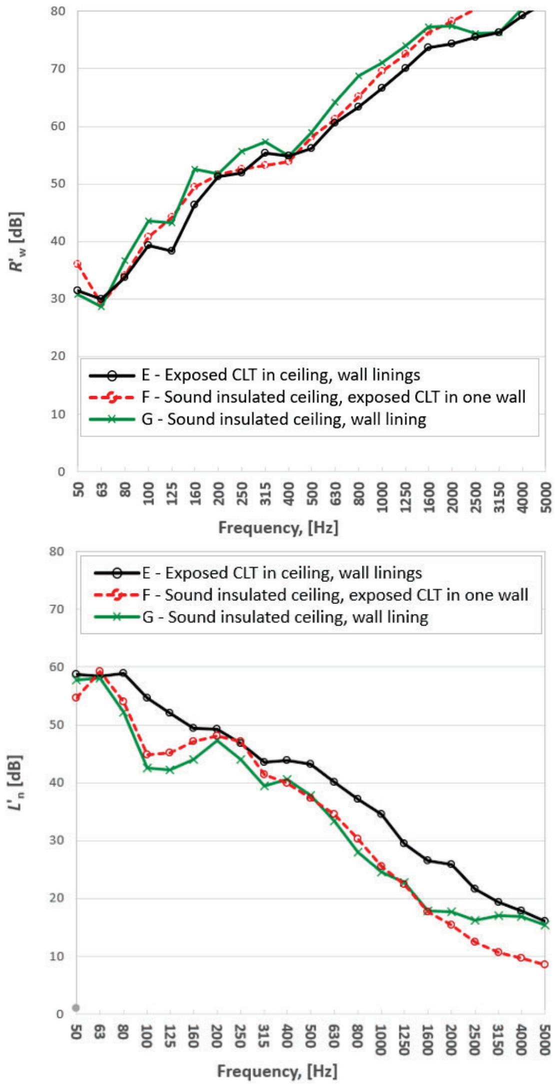

Figure 11: *Vertical airborne (upper) and impact (lower) sound insulation between floors showing effects of visible wall/slab elements.*

4 CONCLUSIONS

The variation in damping between various configurations of elastic interlayers and fasteners in junctions has been assessed by measuring the velocity level difference on a full scale CLT mock-up. Measurements of sound insulation were done in parallel to the measurements of velocity level differences.

Results show that the type of fastener is crucial to the junction damping. The use of elastically decoupled angle brackets proved to increase the damping compared to regular angle brackets and traditional screw fasteners.

Tests conducted on various screw fasteners show low damping effect and little change between various configurations regardless of elastic interlayer. Measurements of horizontal damping proved more sensitive to various configurations of screw fasteners than vertical measurements. As a whole, the test results suggest that the choice of fastener has greater impact on the damping than the type and use of vibration protection.

Heavy floating floors added onto the CLT floor significantly increased the velocity level differences between rooms, as various upper floor constructions were tested. Weight applied directly on to the CLT floor showed a significant increase in low frequency sound insulation.

Three floor constructions using a heavy floor construction were in accordance with the minimum regulations for sound insulation between dwellings in Norway, one of which was measured with exposed CLT in the ceiling. Thus, the measurements of sound insulation reveal that part of the wood can be kept visible when using a favourable fastener and applying weight to the floor.

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