DEVELOPMENT AND TESTING OF NOISE & VIBRATION ISOLATION SOLUTIONS FOR CROSS LAMINATED TIMBER (CLT) CONSTRUCTIONS

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1 INTRODUCTION

Mass timber solutions, including cross-laminated timber (CLT), can be an excellent substitute for traditional, very stiff, heavy building materials when some of their inherent properties aren't required. The use of these mass timber products allows for the reduction of the carbon footprint of the built environment.
While CLT has many advantages as a sustainable building material, it can also pose some rather unique challenges in terms of acoustics.
Following the regulations in Europe, most of the regulatory main requirements are showing $D_{nT,w} \geq 55$ dB and $L'_{nT,w} < 52$ dB. These increasingly stringent requirements are becoming more and more challenging for traditional building materials, but unfortunately, due to its high structural stiffness and low mass density, cross-laminated timber is even less effective acoustically, resulting in lower airborne and impact sound isolation compared to the traditional materials. In CLT constructions, vibrational energy is also easily transmitted from one building part towards another through their common junction, resulting in increased flanking sound transmission compared to traditional construction techniques. CLT panels are also an ideal building material for modular constructions, however, transferring vertical and horizontal forces between stacked structures can compromise acoustic requirements.
CDM Stravitec has developed solutions to increase airborne and impact sound isolation for CLT structural floors, to elastically decouple building parts and to stack modular construction without compromising the acoustic decoupling of the modules.
Section 2 will describe the test campaign executed in the laboratory of Buildwise, Belgium, to define the airborne and impact sound isolation of various types of floating floors installed on CLT structural slabs. Section 3 describes an in-situ experiment done to define the efficiency of a resilient polyurethane strip in combination with an angle bracket with acoustic decoupling features. Section 4 finally discusses the influence of angle brackets with acoustic decoupling features on the sound transmission between 2 modular units..

2 AIRBORNE AND IMPACT SOUND ISOLATION OF CLT STRUCTURAL FLOORS

2.1 Test setup

Tests were carried out on a bare 5-layer cross-laminated timber (CLT) slab, 180 mm thick, over a surface of 260 cm x 442 cm. Each test element was mounted according to the NBN EN ISO 10140-3 standard, in a similar manner to the actual construction, and tests were carried out on each system described in this paper.

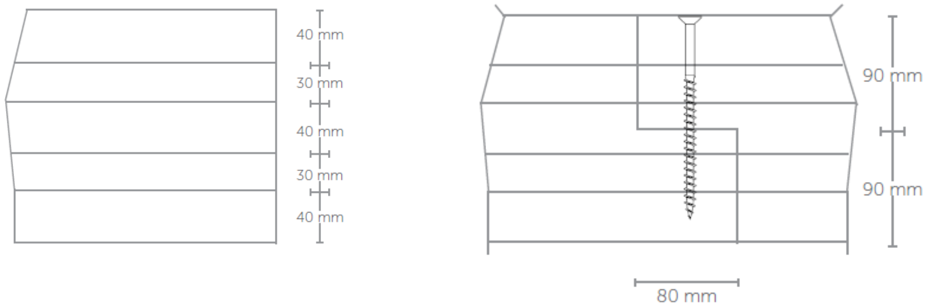

Figure 1 - Layer structure of CLT 180 L5s and joint/screw detail of the slab

The test floor is sandwiched between 2 heavy concrete ceiling elements by mineral wool compressed to 5 cm. The test floor bears in its longitudinal direction and is laid on its short sides on the load-bearing walls of the test cell on an intermediate strip of mineral wool. The mobile room “M” is then installed on top of the floor, but without making direct contact with the underlying receiving room. Within this source room, a metal frame adjustable in height and with underlying mineral wool filling shields the edges of the test floor and thus defines the test area [10 m²]. This test area corresponds to the unshielded ceiling area in the receiving room below, as visible in the cross section below. The remaining space between the mobile source room and the test elements is filled with compressed sound-absorbing wool to avoid sound leaks.

Figure 2 – Details of mobile source room installation above the test floor (details without showing absorbing wool filling) and CLT slab installed between the rooms.

2.2 Test Results

In f the different tested setups is presented. The presence of a dropped ceiling is shown together with the elastic supports and board materials of the tested assembly. All tests are performed on dry, panelized, floating floor systems except setup G in which a gypsum topping of 50 mm thickness is installed on top of the structural CLT slab.

Setup	Dropped Ceiling	Elastic Support	Floating floor	Build-up Height(1)
BS	n.a.	n.a.	n.a.	n.a.
A	n.a.	Stravifloor Mat-W8a	HydroFlam® 18 mm + Damping Layer 5 mm + OSB/3 18 mm	49 mm
B	Yes(2)	Stravifloor Mat-W8a	HydroFlam® 18 mm + Damping Layer 5 mm + OSB/3 18 mm	49 mm
C	Yes(2)	Stravifloor Mat-W8a	HydroFlam® 18 mm + OSB/3 18 mm	44 mm
D	n.a.	Stravifloor Mat-W25	Plywood 19 mm +	75.5 mm

			Fermacell® Powerboard H20 12,5 mm + Plywood 19 mm	
E	n.a.	Stravifloor Mat-W25 strips [o.c. 610 mm]	Plywood 19 mm + Fermacell® Powerboard H20 12,5 mm + Plywood 19 mm	75.5 mm
F	n.a.	Stravifloor Mat-W25 strips [o.c. 610 mm]	Plywood 19 mm + Plywood 19 mm	63 mm
G	n.a.	Stravifloor Mat-W25	Gypsum topping 50 mm	75 mm
H	n.a.	Isolated Channel-M30 [Pad-M30 [30 mm]] (o.c. 610 mm)	HydroFlam® 18 mm + Fermacell® Powerboard H20 12,5 mm + OSB/3 18 mm	78.5 mm
I	n.a.	Isolated Channel-M30 [Pad-M30 [30 mm]](o.c. 610 mm)	HydroFlam® 18 mm + OSB/3 18 mm	66 mm
J	n.a.	Isolated Channel-M30 [Pad-M30 [30 mm]] (o.c. 610 mm)	Plywood 19 mm + Plywood 19 mm	68 mm
K	n.a.	Isolated Channel-M50 [Pad-M50 [50 mm]] (o.c. 610 mm)	Plywood 19 mm + Damping layer 5 mm + Plywood 19 mm	93 mm
L	n.a.	Isolated Channel-M50 [Pad-M50 [50 mm]] (o.c. 406 mm)	Plywood 19 mm + Damping layer 5 mm + Plywood 19 mm	93 mm
M	n.a.	Isolated Channel-M50 [Pad-M50 [50 mm]] (o.c. 406 mm)	Plywood 19 mm + Plywood 19 mm	88 mm
N	n.a.	Isolated Channel-M50 [Pad-M50 [50 mm]] (o.c. 406 mm)	Plywood 15 mm + Fermacell® Powerboard H20 12,5mm + Plywood 15 mm	100.5 mm
O	n.a.	Isolated Channel-M50 [Pad-M50 [50 mm]] w/ 30 mm overheight (o.c. 406 mm)	3x Fermacell® Powerboard H20 12,5 mm + Plywood 19 mm	136.5 mm
P	n.a.	Isolated Channel-M50 [Pad-M50 [50 mm]] w/ 30 mm overheight (o.c. 406 mm)	Plywood 19 mm + Plywood 19 mm	118 mm

(1) Not including bare slab or dropped ceiling if applicable.
(2) 2 layers 12.5 mm gypsum hung on metal grillage 150 mm.

Table 1 a description of the different tested setups is presented. The presence of a dropped ceiling is shown together with the elastic supports and board materials of the tested assembly. All tests are performed on dry, panelized, floating floor systems except setup G in which a gypsum topping of 50 mm thickness is installed on top of the structural CLT slab.

Setup	Dropped Ceiling	Elastic Support	Floating floor	Build-up Height(1)
BS	n.a.	n.a.	n.a.	n.a.
A	n.a.	Stravifloor Mat-W8$_a$	HydroFlam® 18 mm + Damping Layer 5 mm + OSB/3 18 mm	49 mm
B	Yes(2)	Stravifloor Mat-W8$_a$	HydroFlam® 18 mm + Damping Layer 5 mm + OSB/3 18 mm	49 mm
C	Yes(2)	Stravifloor Mat-W8$_a$	HydroFlam® 18 mm + OSB/3 18 mm	44 mm
D	n.a.	Stravifloor Mat-W25	Plywood 19 mm + Fermacell® Powerboard H20 12,5 mm + Plywood 19 mm	75.5 mm
E	n.a.	Stravifloor Mat-W25 strips [o.c. 610 mm]	Plywood 19 mm + Fermacell® Powerboard H20 12,5 mm + Plywood 19 mm	75.5 mm
F	n.a.	Stravifloor Mat-W25 strips [o.c. 610 mm]	Plywood 19 mm + Plywood 19 mm	63 mm
G	n.a.	Stravifloor Mat-W25	Gypsum topping 50 mm	75 mm
H	n.a.	Isolated Channel-M30 [Pad-M30 [30 mm]] (o.c. 610 mm)	HydroFlam® 18 mm + Fermacell® Powerboard H20 12,5 mm + OSB/3 18 mm	78.5 mm
I	n.a.	Isolated Channel-M30 [Pad-M30 [30 mm]](o.c. 610 mm)	HydroFlam® 18 mm + OSB/3 18 mm	66 mm
J	n.a.	Isolated Channel-M30 [Pad-M30 [30 mm]] (o.c. 610 mm)	Plywood 19 mm + Plywood 19 mm	68 mm
K	n.a.	Isolated Channel-M50 [Pad-M50 [50 mm]] (o.c. 610 mm)	Plywood 19 mm + Damping layer 5 mm + Plywood 19 mm	93 mm
L	n.a.	Isolated Channel-M50 [Pad-M50 [50 mm]] (o.c. 406 mm)	Plywood 19 mm + Damping layer 5 mm + Plywood 19 mm	93 mm
M	n.a.	Isolated Channel-M50	Plywood 19 mm + Plywood 19 mm	88 mm

		[Pad-M50 [50 mm]] (o.c. 406 mm)		
N	n.a.	Isolated Channel-M50 [Pad-M50 [50 mm]] (o.c. 406 mm)	Plywood 15 mm + Fermacell® Powerboard H20 12,5mm + Plywood 15 mm	100.5 mm
O	n.a.	Isolated Channel-M50 [Pad-M50 [50 mm]] w/ 30 mm overheight (o.c. 406 mm)	3x Fermacell® Powerboard H20 12,5 mm + Plywood 19 mm	136.5 mm
P	n.a.	Isolated Channel-M50 [Pad-M50 [50 mm]] w/ 30 mm overheight (o.c. 406 mm)	Plywood 19 mm + Plywood 19 mm	118 mm

(1) Not including bare slab or dropped ceiling if applicable.
(2) 2 layers 12.5 mm gypsum hung on metal grillage 150 mm.

Table 1 - Section of tested setups

In Table 2 the overview of the global ratings for all different setups is given. In section 2.3 conclusions that can be deducted from the test campaign are given.

Setup	Dry Screed Load [kg/m²]	$L_{n,w}$ (C_i) [dB]	ΔL_w ($C_{i,\Delta}$) [dB]	R_w (C;C_{tr}) [dB]
BS	n.a.	87 (-5)	n.a.	39 (-1;-4)
A	26	67 (0)	23 (0)	50 (-1;-6)
B	26	53 (0)	35 (3)	64 (-2;-8)
C	22	53 (1)	34 (2)	63 (-2;-8)
D	46	61 (0)	27 (0)	53 (-1;-6)
E	36	56 (0)	32 (5)	59 (-3;-9)
F	23	60 (0)	28 (5)	55 (-2;-9)
G	92	65 (0)	21 (0)	56 (-1;-7)
H	35	54 (0)	34 (4)	62 (-2;-8)
I	26	57 (0)	31 (4)	60 (-3;-9)
J	23	57 (1)	30 (4)	59 (-3;-9)
K	28	55 (-1)	34 (2)	64 (-2;-8)
L	28	55 (-1)	35 (3)	63 (-2;-8)
M	23	55 (0)	34 (4)	62 (-3;-9)
N	32	54 (0)	35 (2)	63 (-2;-8)
O	52	47 (0)	42 (1)	67 (-2;-7)
P	23	53 (0)	36 (2)	65 (-2;-7)

Table 2 – Results overview (global ratings)

2.3 Conclusions

There is an improvement on both airborne and impact sound insulation of around 14 dB due to the installation of a suspending ceiling. The improvement is across all frequencies above 80 Hz. For low frequencies, we see a negative effect of the dropped ceiling. However, it is important to mention that the dropped ceiling installed isn't using resilient hangers or insulation material in the void, not being an acoustical dropped ceiling. The little negative effect of the dropped ceiling at low frequencies can be easily solved by adding insulation material in the void to avoid standing waves and using resilient hangers rather than stiff ones. Ceilings might not always be visually appealing, especially when you can expose a timber structure instead, but they have several acoustic design functions that can lead to important cost savings, such us to control not only airborne and impact sound insulation but flanking sound (above partitions, via building services and structural penetrations or via structural elements), sound reverberation and noise of building services hung from the soffits.
There is a significant improvement in both, airborne and impact sound insulation (around 3 dB) when using strips of 100 mm Stravifloor Mat-W25 spaced of 610 mm versus full surface support with the same resilient material.

Full surface wet systems tested can perform up to 3 dB better in airborne noise insulation but have lower performance (up to 4 dB) in terms of impact noise insulation, with the most significant differences at frequencies above 160 Hz. The dry solutions have the added benefit of being thinner and quicker to install.

When comparing setups using discrete bearings with setups using mats as resilient support, there are improvements on airborne sound insulation up to 10 dB and 5-7 dB on impact sound insulation, those improvements are visible across the complete frequency spectrum. The use of discrete bearings as resilient support of lightweight floor systems in combination with well-designed dry screed results in another step up in terms of acoustic isolation, especially at lower frequencies.

The implementation of Fermacell® Powerboard H20, 12.5 mm thick and with a surface density of 13.5 kg/m², leads to an increase in both airborne and impact sound insulation by approximately 3 dB.

In the current study, three types of wooden boards were used for testing, namely HydroFlam®, OSB/3, and plywood. HydroFlam® is a P5 chipboard that exhibits moisture resistance, fire retardancy (standard performance of B-s1, d0), and structural integrity, with 89% of its materials being renewable and 95% being recycled wood. OSB/3 is a versatile panel with good mechanical strength, stiffness, and durability under temporary humid conditions, and standard fire reaction performance of D-s2, d0. Plywood, on the other hand, is a wood-based material composed of multiple thin layers of wood veneers glued crosswise to normalize material properties such as shrinkage and swelling behavior. Comparing the results obtained in this study, we observed no significant differences in acoustic performance among the test setups that differed only in the type of wooden board used. This finding can be attributed to the similarity in thickness and density of the boards, even when changing the board typology (OBS combined with HydroFlam® vs. plywood).

In this study, the acoustic performance of test setups with channel spacing of 406 mm and 610 mm between bearings, while maintaining a constant distance of 500 mm between bearings in the other direction, was investigated. Results showed that there was no significant difference in acoustic performance for frequencies starting from 50 Hz.

In the context of lightweight acoustic floor systems, the distribution of loads towards the supporting structural floor is ensured using lightweight panels, which provides bending stiffness to the floor system. Wood-based panels are preferred due to their optimal ductility/strength ratio and low radiation efficiency. However, these panels exhibit dips in transmission loss in the resonance and coincidence-controlled regions. This issue can be addressed by using constrained layer damping (CLD) techniques with high damping viscoelastic acoustic membranes, known as damping layers. The added damping layer works by converting mechanical energy into heat, thus reducing noise and vibration radiation under impact loads. In this study, it was found that there was no significant difference between results of test setups with and without damping layer, except for slightly better results at the lowest end of available data (< 50 Hz) and higher transmittance above 800 Hz. This is because the impact generated by the standardized tapping machine used in the tests was not sufficient to generate high shear loads in the damping layer. Therefore, no significant energy was lost in this layer during the tests. However, it is expected that for higher loads, the panels and damping materials will be more compressed, resulting in higher deformation and shear deformation and a more pronounced benefit of the use of constrained layer damping.

Comparing the setups using 30 mm bearings with those using 50 mm bearings, it is observed that there is a 2-3 dB improvement in airborne sound insulation as well as in impact sound insulation. It is noteworthy that the improvements are predominantly observed in the low frequency range due to the overall stiffness of the system and the increase in void resulting in reduced impact of stiffness of the entrapped air.

Increasing the air void between the floating floor system and the supporting structural floor from 50 mm to 80 mm results in a noticeable enhancement in both airborne and impact noise insulation. The shift of the R_w curve towards the left at lower frequencies confirms this observation. This can be attributed to the reduction in air spring stiffness, as the air void becomes larger.

A system can be designed with a total build-up height (excluding structural slab) of 136.5 mm by combining an acceptable number of boards to achieve a high surface load of 52 kg/m² with an overheight of 30 mm and pads of 50 mm. This system can achieve global values of $L_{n.w}$ = 47 dB and R_w = 67 dB.

Comparing setups using 2 plywood boards and dry screed (setup P) with setups using a plywood board combined with 3 layers of Fermacell (O), an influence can be observed on sound insulation at low frequencies due to the added surface mass.
Overall, the test campaign proves that by combining discrete pads with selected panels, very high performances can be achieved for airborne as well as impact sound isolation, even using a structural floor in CLT.

3 IMPROVING FLANKING SOUND TRANSMISSION IN CLT CONSTRUCTIONS

To learn more about the influence of elastic interlayers and acoustic brackets on the flanking sound transmission, an in-situ test campaign was carried out on a T-junction. The campaign was executed on a construction site situated in Lier, Belgium. The construction is a residential multi-storey building with structural elements at all levels above ground made of CLT panels. At the time of measurements, only the structure was present without any finishing. Almost all walls are supported on an elastic layer. Goal of the test campaign is the determination of K_{ij} for the different transmission paths.

In Figure 3 one can find the geometry of the measured T-junction. The geometry and material properties of each of the components in the T-junction is known.

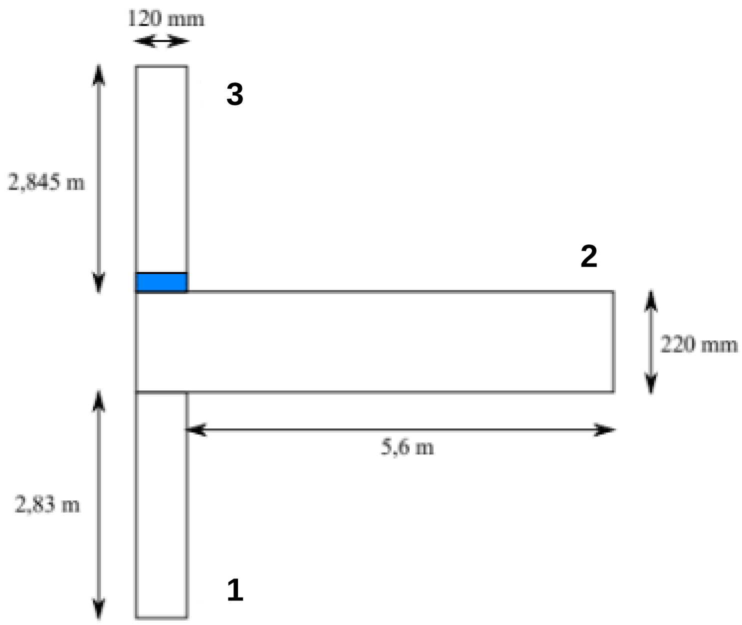

Figure 3 - Geometry of measured T-junction
Taken from "Voorspelling van flankerende geluidtransmissie in lichtgewichtconstructies"[1]

Experiments to define K_{ij} for each of the transmission paths is done for 3 different connection types:

1. Straviwood WallBreak-S (Elastic strip, 12.5 mm)
2. Straviwood WallBreak-S (Elastic strip, 12.5 mm) + metal L-bracket (rigid connection)
3. Straviwood WallBreak-S (Elastic strip, 12.5 mm) + Straviwood WallBracket (see Figure 4)

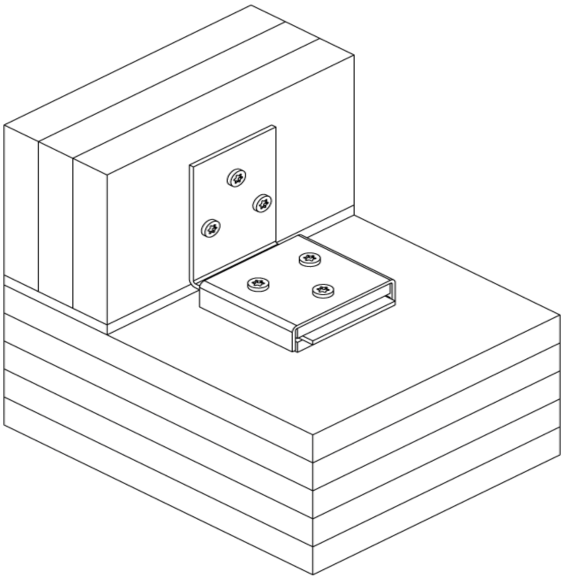

Figure 4 - Schematic drawing of Straviwood WallBracket

Measurements are done following international norm ISO 10848-1[2]. The positioning scheme of accelerometers and impact generation as well as the method of processing of measurement data can be found in "Voorspelling van flankerende geluidtransmissie in lichtgewichtconstructies"[1].
In the below graphs, measurements of K_{ij} and results from the empirical formula in Annex F of ISO 12354[3] are shown for the different transmission paths in the T-junction.
Figure 5 - Vibration reduction index K23 shows the vibration reduction index of path 2 to 3, the path from upper wall to floor through the elastic layer. One can see that all measurements result in a higher vibration reduction index than the empirical formula of ISO 12354, showing that the elastic layer has a positive effect.
The measurement without any fixation shows the highest values. The measurements with angle brackets show lower values of K_{ij} compared to the setup with just the elastic layer. Acoustically decoupled angle brackets (Straviwood WallBracket – see Figure 4) can mitigate the additional transmission over the junction, but still result in lower values of K_{ij} compared to connections without brackets.

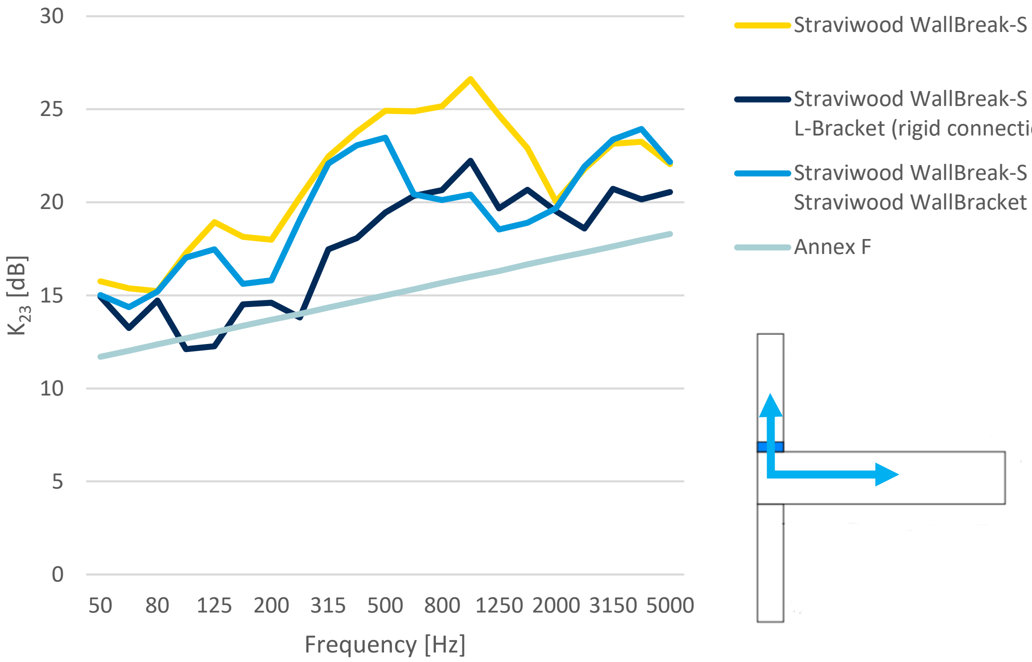

Figure 5 - Vibration reduction index K_{23}

Figure 6 shows K_{ij} for path 1 to 3, the path from the upper wall to the lower wall. One can clearly see the same happening with the highest values for the setup without angle brackets and lowest measurements values for the setup with fixed angle brackets. The empirical formulas of ISO 12354 result in values that are too low compared to the measurements.

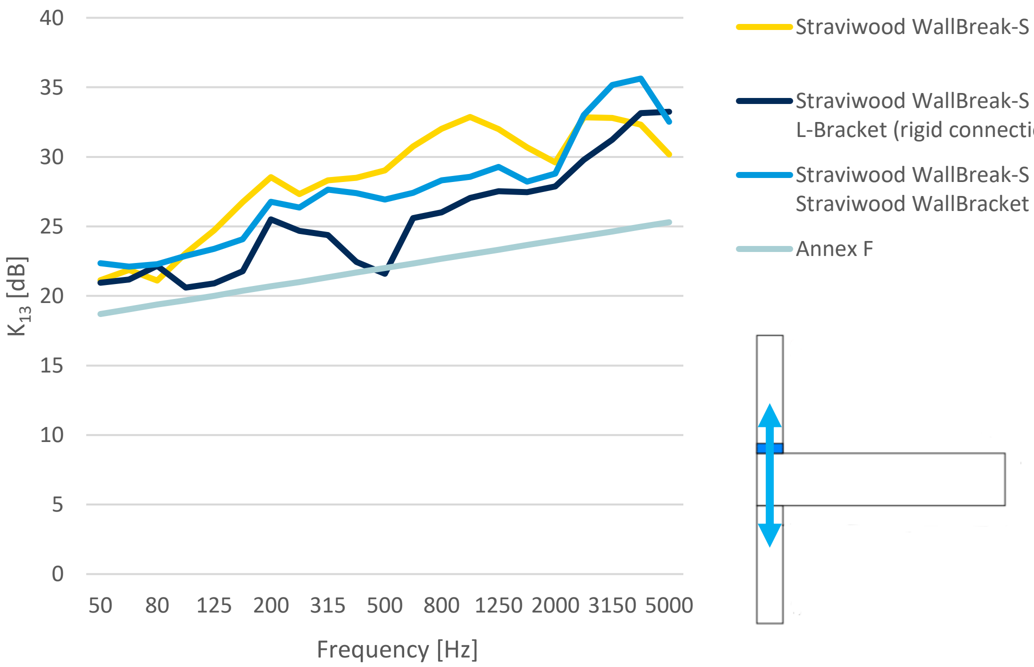

Figure 6 - Vibration reduction index K_{13}

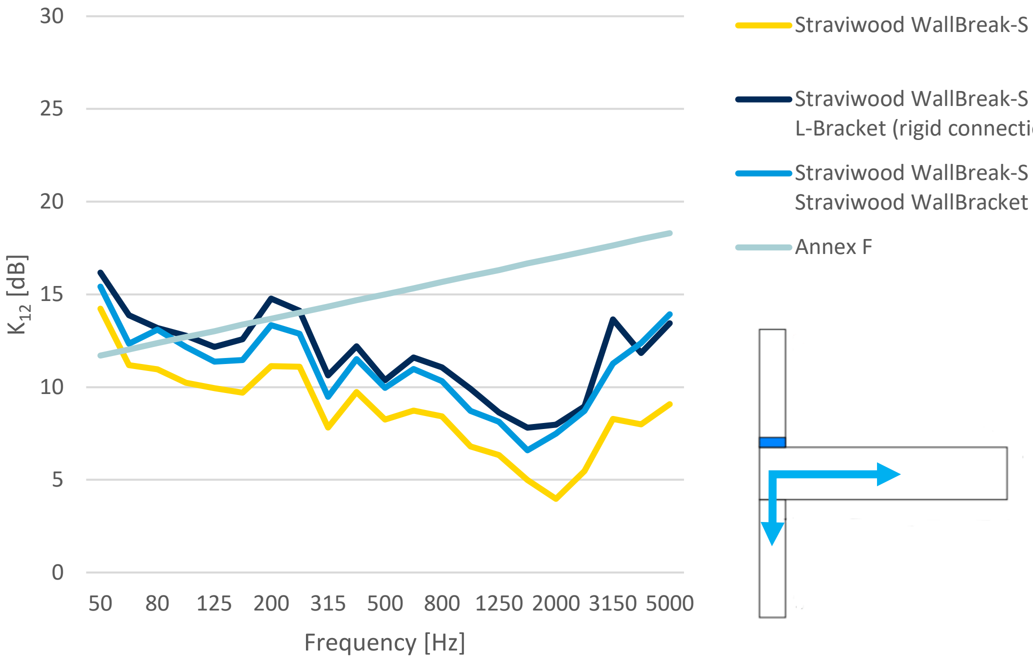

Figure 7 shows the vibration reduction index for the floor – lower wall path. In this graph one sees that the vibration reduction index measurements show lower values than the empirical formula. This might be a result of the presence of the elastic layer between the floor panel and upper wall. Due to the presence of the layer, the vibrations are directed to the non-isolated building element, resulting in a lower vibration reduction index from element 1 to element 2 and vice versa.

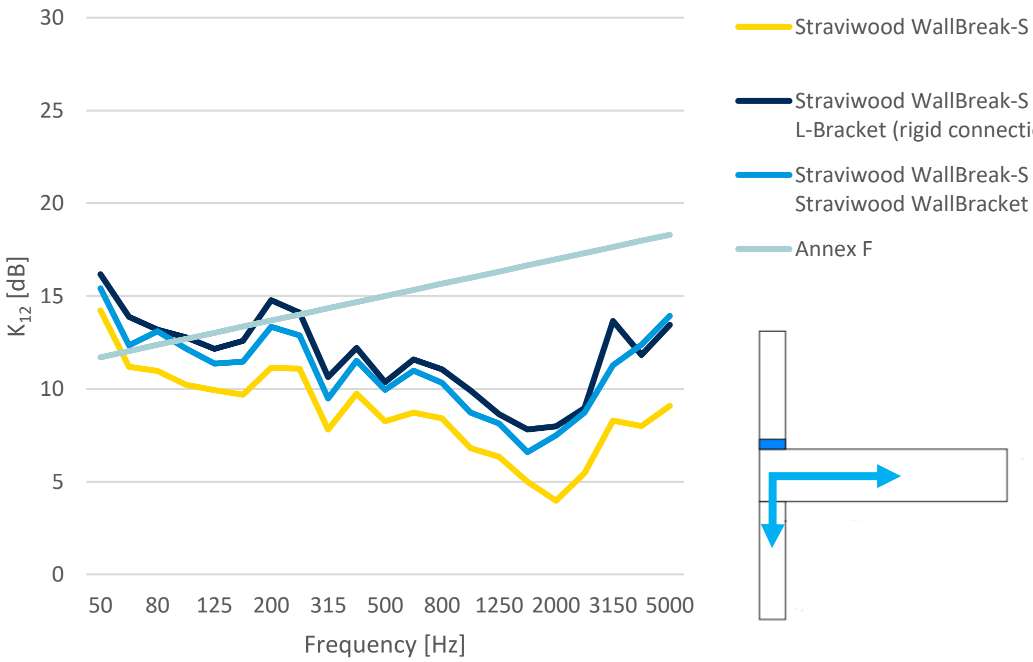

Figure 7 - Vibration reduction index K_{12}

4 IMPROVING FLANKING SOUND TRANSMISSION IN CLT MODULAR CONSTRUCTIONS

As modular timber structures in cross-laminated timber grow larger and higher, the modules need, from a structural point of view, to be more solidly connected to each other in the horizontal direction. This, unfortunately, results in acoustic contact bridges. In The Netherlands a test arrangement was made with two modules in cross-laminated timber to test them with various ways of interconnection. The connections were ranging from full dilatation (without any connection), rigid metal connections to 3 variants of Straviwood ModuLink with different stiffnesses. Apart from these, no other connections were made in between the 2 modules.

The study was carried out on two used Finch Buildings modules, each measuring approximately 4 x 8.5 m. To minimize noise transmission through the supporting structure, each module was installed on 6 isolation pads in CDM-104 material with dimensions of 300 x 140 x 12.5 mm, supplied by CDM Stravitec. The space between the floors of the modules and the supporting structure was filled with rockwool. The modules were horizontally connected at roof level with 4 anchors with a horizontal spacing of 2.25 m.

A schematic view of the setup can be found in Figure 8 and Figure 9.

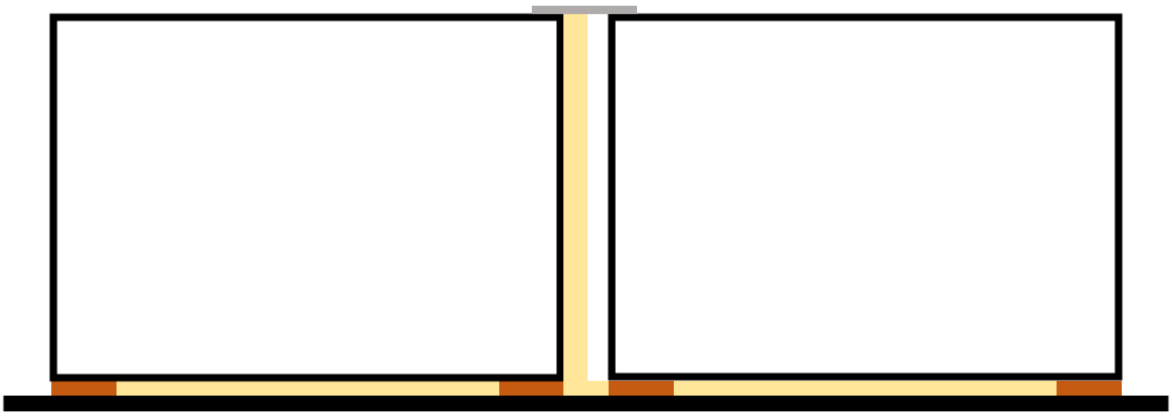

Figure 8 - Front view of the test setup

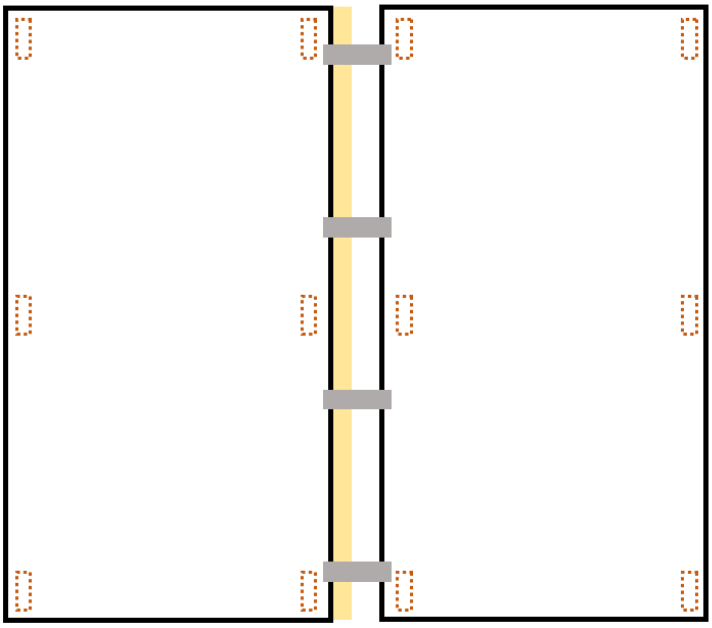

Figure 9 - Top view of the test setup

The images below show the test arrangement on site.

Different connection methods were made and tested. Below the relevant specifications that influence the acoustic behavior of the setup are listed.
Separating wall: 140 mm CLT5S – cavity of 100 mm filled with 50 mm glass wool – 140 mm CLT5S
Acoustic anchors – type Straviwood ModuLink (by CDM Stravitec):

- Type C1: Straviwood ModuLink 0.8 kN SLS – consists of 2 x CDM-102 isolation pads with dimensions of 140 x 45 x 25 mm + 2 elastomeric sleeves M12. The resonance frequency of the solution is approximately 15 Hz.
- Type C2: Straviwood ModuLink 6.7 kN SLS – consists of 2 x CDM-105 isolation pads with dimensions of 140 x 45 x 25 mm + 2 elastomeric sleeves M12. The resonance frequency of the solution is approximately 15 Hz.
- Type C3: Straviwood ModuLink 17 kN SLS – consists of 2 x CDM-106 isolation pads with dimensions of 140 x 45 x 25 mm + 2 elastomeric sleeves M12. The resonance frequency of the solution is approximately 15 Hz.

Tests were performed following norm NEN-EN-ISO 717-1:2013[4] and normative references herein. In total 5 variants with different connection methods were tested, ranging from fully dilatated (C0 - no connection at roof level), over 3 acoustic anchors – type Straviwood ModuLink by CDM Stravitec (C1, C2 and C3) and hard connections with stiff metal anchors (C4). Figure 10 shows the results of the test campaign.

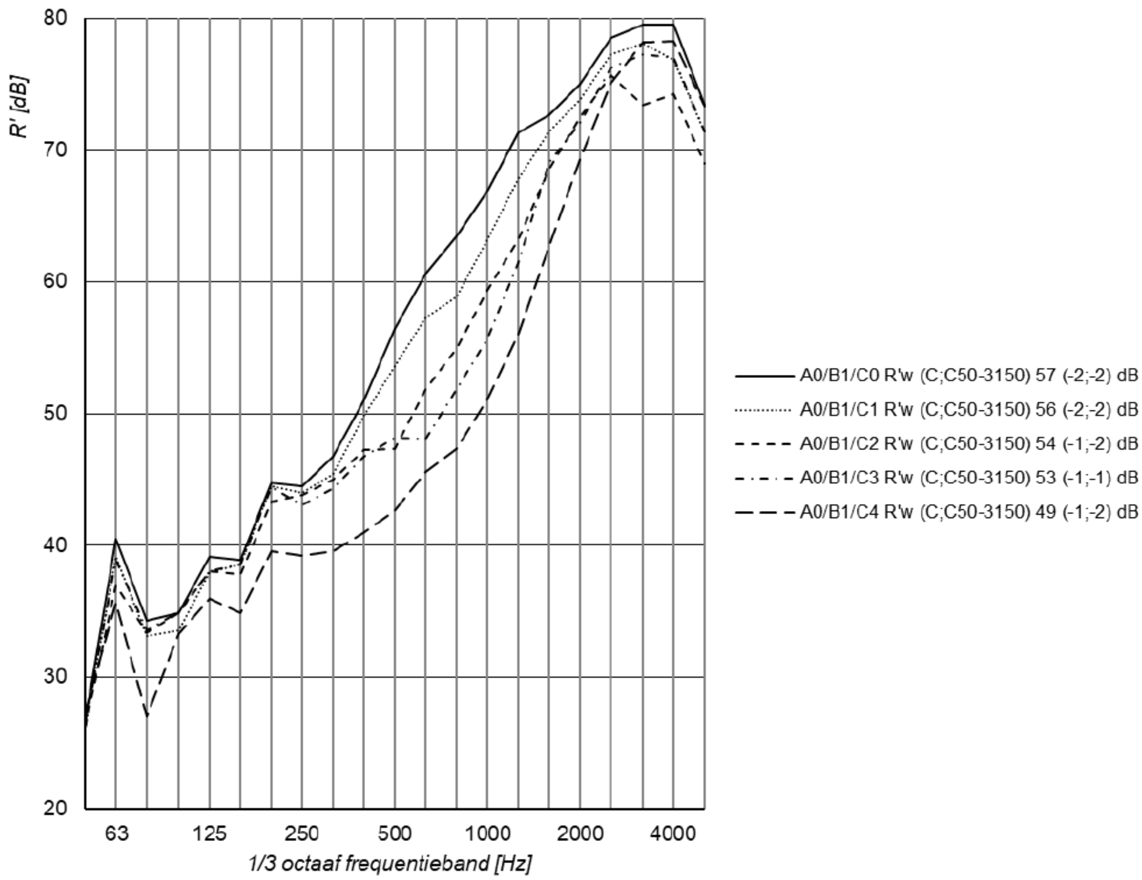

Figure 10 – Airborne sound isolation results of different test setups

The measurement results show clearly that connections at roof level influence the overall sound insulation between modules. In the case of rigid steel couplings, this effect occurs over almost the entire frequency range. This leads to a decrease in airborne sound insulation R'_w of 8 dB. When Straviwood ModuLink anchors are used, the effect is limited to 1 to 4 dB, depending on the stiffness/load capacity of the anchor.

One can analyze based on these results the change in vibration reduction index ΔK compared to a fixed connection (Setup C4 in the discussed test campaign). This calculation can be done based on formulas 18 and 20 in ISO 12354-1[3]. From the below formula one can deduce per situation the direct part ($R_{D,w}$) and the flanking part ($R_{F,w}$).

$$R'_w = -\left(10\log\left(10^{-R_{D,w}/10} + 10^{-R_{F,w}/10}\right)\right) dB$$

The formula of the flanking path can be written as:

$$R_{F,w} = R_{F,w,C0} + \Delta K$$

With ΔK the improvement of the vibration reduction index compared to the fixed connection results.

Connection type	R'_w (dB)	$R_{D,w}$ (dB)	$R_{F,w}$ (dB)	ΔK (dB)
C0	57	57	>57	>17
C1	56	57	63	13

C2	54	57	57	7
C3	53	57	55	5
C4	49	57	50	-

Table 3 - Measurement results for different connection types

The vibration reduction index ranges from 5 dB to 13 dB for the different brackets, with the one using the isolators with the lowest stiffness having the highest vibration reduction index.

The performance obtained in practical situations may deviate slightly from the results in the test setup. This is caused partly by a different geometry of rooms and partly by a different spacing in between the structural Straviwood ModuLink anchors. From this study can be concluded that high-quality acoustic connectors have an important contribution to achieving the limit and target values for sound insulation in a project.

5 REFERENCES

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