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Acoustic behaviour of CLT structures: influence of decoupling bearing stripes, floor assembly and connectors under storey-like loads

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ABSTRACT

Timber buildings do not have a high acoustic performance regarding vibration transmission through the structure. To find out the peculiarity of timber sound conduction, an acoustic lab test with CLT was set up. Several measurement configurations were built and airborne sound measurements according to EN ISO 16283-1 and impact sound measurements according to EN ISO 16283-2 were carried out. The test results were set in relation to reference measurements on the bare CLT slab and on a floor assembly, with and without decoupling bearing stripes and with and without connectors. In addition to the standard sound measurements, the sound transmissions through the ceiling element and through the flank components (walls) were also measured with accelerometers. The results showed in an experimental evaluation method a reduction of the apparent sound reduction index R' *and normalized impact sound pressure level* L'_{n}*. All tests were carried out with the same load of 17 kN/m on the decoupling bearing stripes and the ceiling element. The load was applied by means of threaded rods and secured by strain gauges. The influence of decoupling bearings stripes, types of fastening systems and floor structures on sound transmission through the flanking components on a real scale mock-up could therefore be investigated.*

1. INTRODUCTION

The measurement of airborne and impact sound insulation of building ceilings is an indispensable component and cannot yet be determined exclusively by simulation calculations. This applies in particular to the evaluation and further development of innovative timber ceilings (lightweight construction) that take into account sound transmission via sound bypasses in its form as the weighted apparent sound reduction index R'_{w} and as the weighted standardized impact sound pressure level $L'_{nT,w}$ according to OIB RL5 in Austria. The current research is of scientific interest with regard to the competitiveness of lightweight timber construction, which can be seen as the building material of the future due to its sustainability and resource efficiency. In terms of building technology, the scientific challenge is to generate innovative and economical ceiling structures. In addition to the

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optimal sound insulation quality (airborne and impact sound), the possibilities of heat supply with combined floor/ceiling heating also need to be included. In timber construction (lightweight construction), in addition to the combinations of the layers of the ceiling structure, the sound bypasses (flank transmissions) must also be taken into account, especially with regard to the proper choice of materials and design. In this publication, special attention is paid to this area and fundamental investigations are carried out concerning this matter.

1.1. Definitions of terms

- Apparent sound reduction index R'

  Ten times the common logarithm of the ratio of the sound power, W_1, which is incident on a test element to the total sound power radiated into the receiving room if, in addition to the sound power, W_2, radiated by the test element, the sound power, W_3, radiated by flanking elements, is significant. R' is expressed in decibels.

$$R' = 10 * \log (W_1 / (W_2 + W_3))$$

- Standardized impact sound pressure level L'_{nT}

  Energy-average impact sound pressure level, L_i, reduced by a correction term that is given in decibels, being ten times the common logarithm of the ratio of the measured reverberation time, T, to the reference reverberation time, $T_0 = 0.5$ s, when the impact source is the tapping machine. L'_{nT} is expressed in decibels.

$$L'_{nT} = L_i - 10 * \log (T / T_0)$$

- Normalized impact sound pressure level L'_n

  Energy-average impact sound pressure level, L_i, increased by a correction term that is given in decibels, being ten times the common logarithm of the ratio between the measured equivalent absorption area, A, of the receiving room and the reference equivalent absorption area, $A_0 = 10$ m², when the impact source is the tapping machine. L'_n is expressed in decibels.

$$L'_n = L_i + 10 * \log (A / A_0)$$

1.2. Acoustic Test Lab

For the planned investigations, a ceiling test stand was set up based on a standard test stand, in which the flank transmission via the component connections can also be measured.

The ceiling test stand consists of a transmitter room, a receiver room and a small measuring room. The transmitter room, the raw ceiling (separating component) as well as the upper part of the receiver room (1.0 m high) consist of cross laminated timber elements. Due to the existing situation, the height of the cross laminated timber walls is only 1.0 m, instead of 2.5 m required in EN ISO 10848-1. This ceiling test stand is therefore a research test stand that is used to gain new knowledge. The height of 1.0 m of the cross-laminated timber element (upper part of the receiving room) was chosen in order to be able to absorb at least a quarter of the wavelength at 100 Hz (the wavelength at 100 Hz is 3.40 m). Low frequencies can so only be partially detected. It is therefore an experimental evaluation. The lower part of the receiver room consists of lime-cement bricks and reinforced concrete with a mass per unit area of 500 kg/m² (complies with the standard requirements for a sound test stand). For the installation of decoupling bearings, the upper floor (transmitter room) can be raised up to 30 cm with and without a ceiling element using hydraulic cylinders. A staircase connects the measuring rooms. A special feature that is indispensable for this type of investigation is the possibility of preloading the wall-ceiling-wall connection by means of threaded rods. The amount of prestressing can be adjusted by means of strain gauges installed on the threaded rods. This makes it possible to simulate different loads (e.g. several storeys) with regard to the effect of decoupling strips.

The measuring rooms (transmitter room, receiver room) have a floor area of 21.5 m² (5.24 m long; 4.10 m wide). The volume of the transmitter room is 53.5 m³ and of the receiver room 75.5 m³. For standard measurements (standard test stand), the 1.0 m high wooden frame can be removed, in which case the room volume is 54.0 m³. The standard cross laminated timber ceiling used has a height of 16 cm. For the replacement of the raw ceiling, the entire upper floor (transmitter room) can be lifted off with a truck-mounted crane. This design of the sound test stand makes it possible to carry out the tests according to ÖNORM EN ISO 16283-1 and ÖNORM EN ISO 16283-2, i.e. like in situ measurements. This way, practice-relevant results are achieved. In addition to the standard measurements for airborne and impact sound insulation, the sound bypasses (flank transmissions) are measured with accelerometers.

Ceiling test stand, outside

Transmitting and receiving room, inside

Lifting system

Figure 1: Acoustic ceiling test stand and detail images

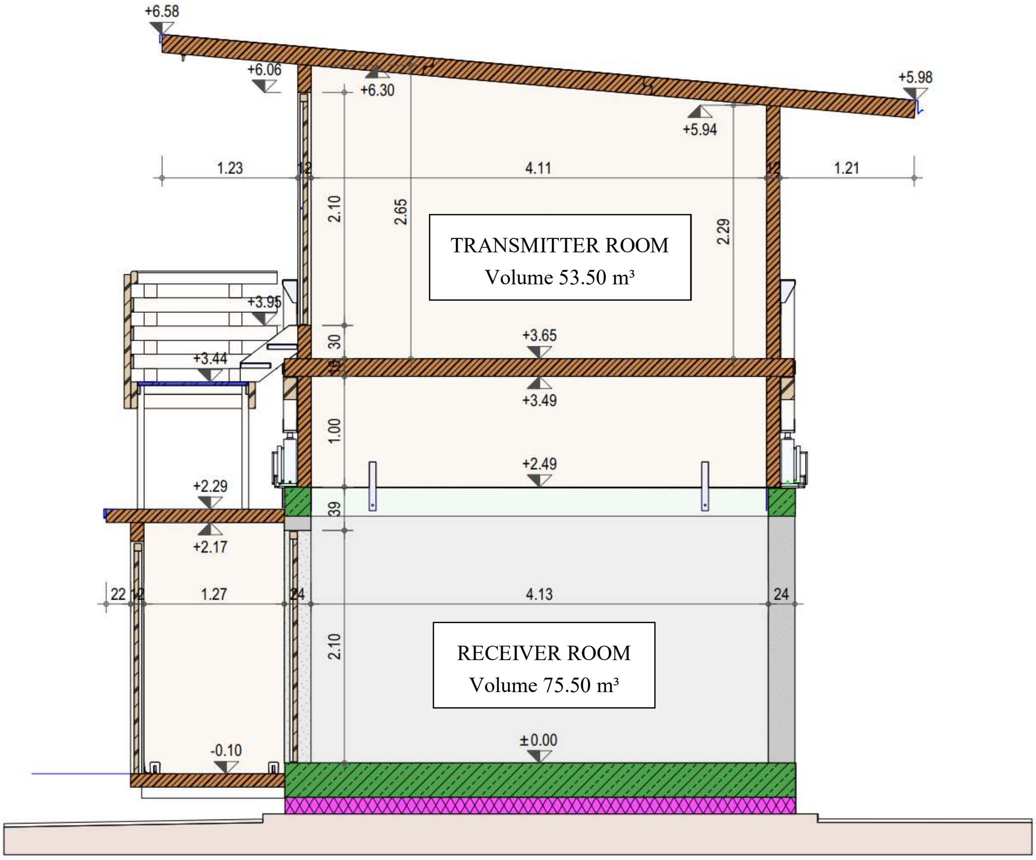


Figure 2: Section 1-1 - Acoustic ceiling test stand

1.3. Measuring devices

The following measuring instruments are used for the sound tests in the acoustic ceiling test stand.

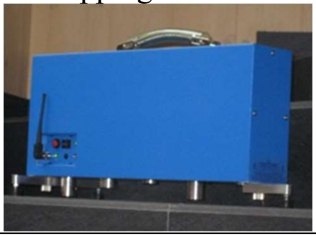
Soundbook MK2	Tapping machine	Dodekaeder	Microphone	Accelormeter
				

Figure 3: Measuring devices used

2. Project Description

The research focus is on the acoustic investigations concerning the effectiveness of decoupling bearings. Based on the reference measurements (160 mm cross laminated timber ceiling and 120 mm cross laminated timber wall), without decoupling bearings and without bolting or fixing brackets, 8 measurement configurations are carried out in the first part as airborne sound measurements according to ÖNORM EN ISO 16283-1 and impact sound measurements according to ÖNORM EN ISO 16283-2. When performing the measurements, the same load of 17 kN/m (approx. one storey) is always applied to the ceiling element and thus also to the decoupling bearings. This is ensured by means of pre-tensioning through threaded rods and by using strain gauges on the threaded rods. Since air tightness is also an essential parameter for a high and comparable sound quality, a blower door test is carried out for every test modification before the sound measurement. This ensures that leaks have no influence on the measurement results. In the measurement configurations of the first test series (A), in addition to the standard airborne and impact sound measurements, the separating component S(0) (ceiling element) and flank side 2 (south side of the ceiling test stand) are also measured. In the second test series (B), with the floor structure, all four flank components (walls) are examined acoustically with accelerometers in addition to the separating component (ceiling). On the one hand, it is examined whether the flank transmission is the same on all sides and, on the other hand, how large the sound reduction index or the normalized impact sound pressure level is over the flank components. This shows the influence of the longitudinal sound transmission on the overall measurement, i.e. on the single number value of the standard measurement.

For fixing the cross laminated timber ceiling to the underlying cross laminated timber wall, HBS 6x240 mm screws, spaced 300 mm apart, are used. For the fastening of the wall elements resting on the ceiling element, angles of the type Titan TTN240 with LBS screws 5x70 mm, from the company Rothoblaas, are used (figure 4). A total of 10 angles with 72 screws each are used for this fastening. The positioning of the brackets is shown in figure 5.

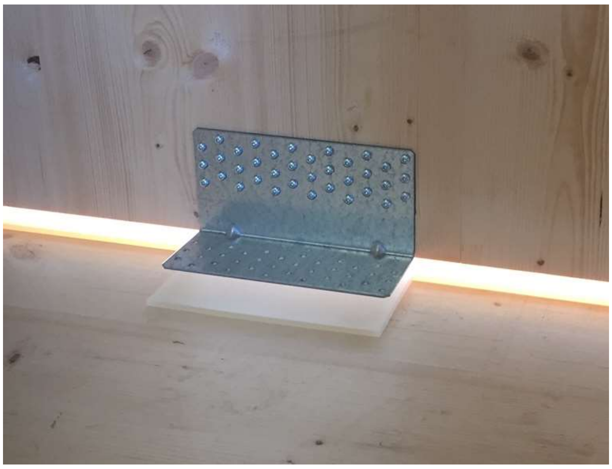


Figure 4: Titan TTN240

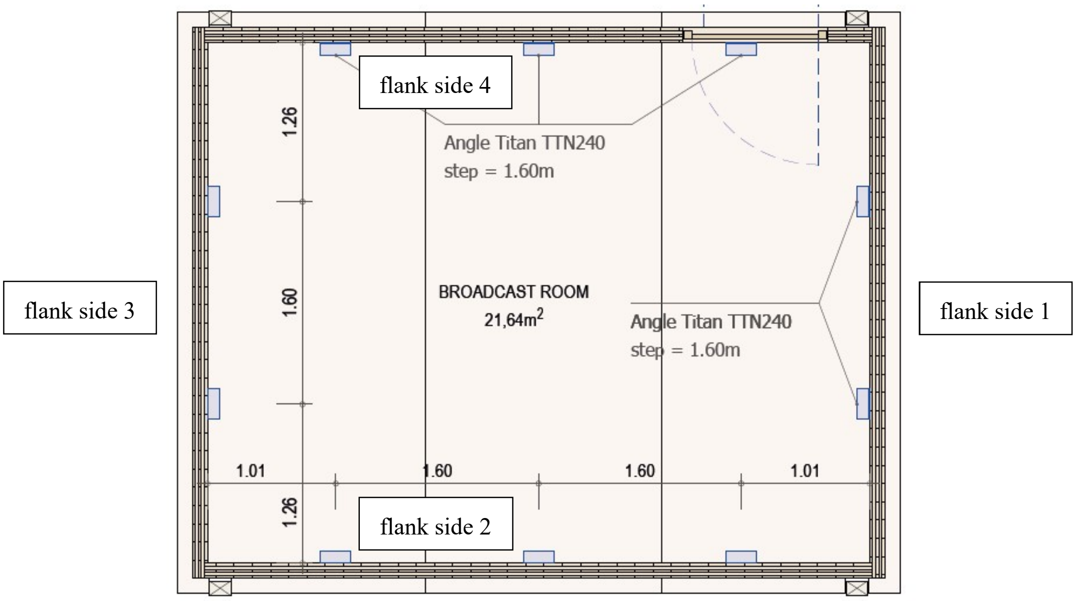


Figure 5: Floor plan - Ceiling test stand - Angle mounting arrangement - Titan TTN240

2.1. Eight test configurations without ceiling construction - test series 1 (A)

- 1A: Both sides without 6 mm Xylofon35; ceiling screwed; wall fixed with angle bracket
- 2A: Ceiling above - 6 mm Xylofon35; ceiling screwed; without angle fastening
- 3A: Ceiling above - 6 mm Xylofon35; ceiling screwed; wall fixed with angle bracket
- 4A: Ceiling above - 6 mm Xylofon35; ceiling not screwed; wall fixed with angle bracket
- 5A: Ceiling below - 6 mm Xylofon35; ceiling not screwed; wall fixed with angle bracket
- 6A: Ceiling below - 6 mm Xylofon35; ceiling screwed; wall fixed with angle bracket
- 7A: Both sides - 6 mm Xylofon35; ceiling screwed; wall fixed with angle bracket
- 8A: Both sides - 6 mm Xylofon35; ceiling not screwed; without angle fastening

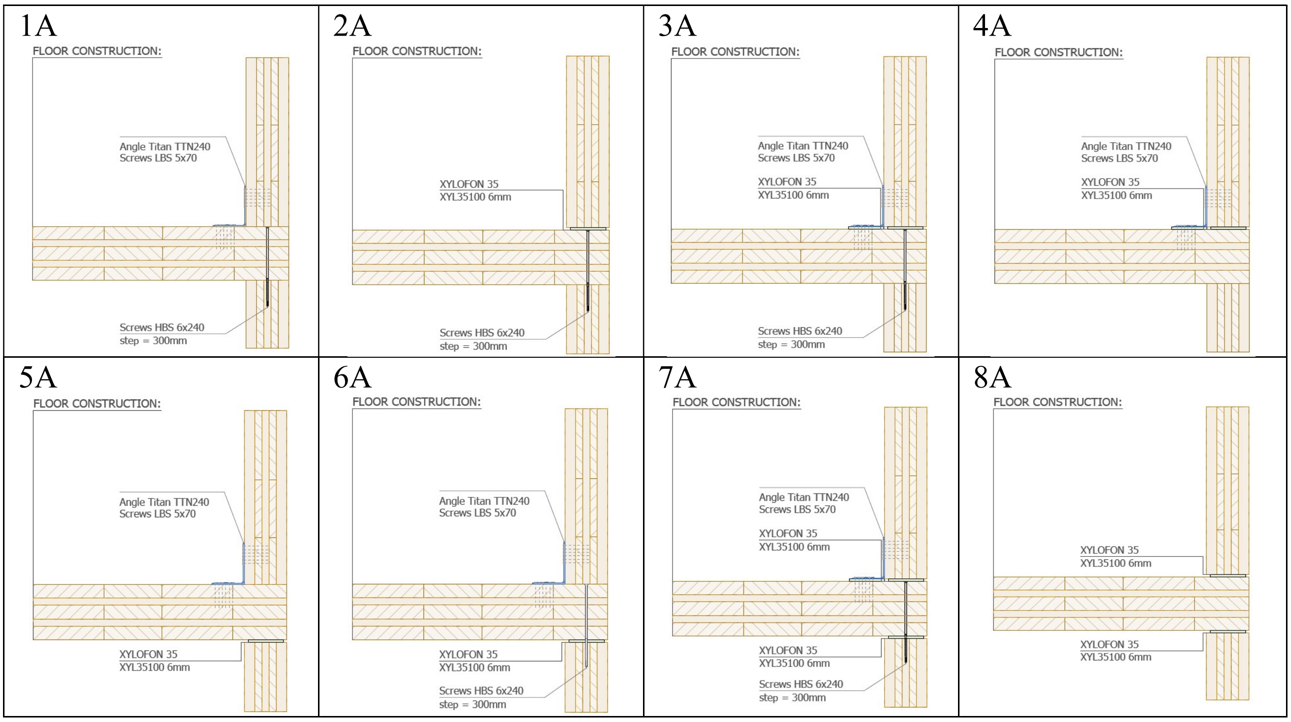


Figure 6: Test configurations - first series of measurements (A)

Of the 8 measurement configurations, 5 of the most suitable configurations for the comparison and reduction of the flank transmission are tested a second time with a previously determined floor construction. The sound quality of the floor construction is chosen in such a way that the influence of the flank transmission via the separating component (ceiling) is significantly reduced. This allows to better determine the sound decoupling effect of the XYLOFON35 XYL35100 insert strips with a thickness of 6 mm via the longitudinal sound transmission of the wall.

2.2. Ceiling construction:

- 32 mm GIFAfloor FHB 32
- 30 mm Silencium Gold 31
- 10 mm Silent Floor Evo
- 160 mm Cross laminated timber (CLT)

2.3. Five test configurations with ceiling construction - test series 2 (B)

- 1B: Both sides without 6 mm Xylofon35; ceiling screwed; wall fixed with angle bracket
- 3B: Ceiling above - 6 mm Xylofon35; ceiling screwed; wall fixed with angle bracket
- 4B: Ceiling above - 6 mm Xylofon35; ceiling not screwed; wall fixed with angle bracket
- 6B: Ceiling below - 6 mm Xylofon35; ceiling screwed; wall fixed with angle bracket
- 7B: Both sides - 6 mm Xylofon35; ceiling screwed; wall fixed with angle bracket

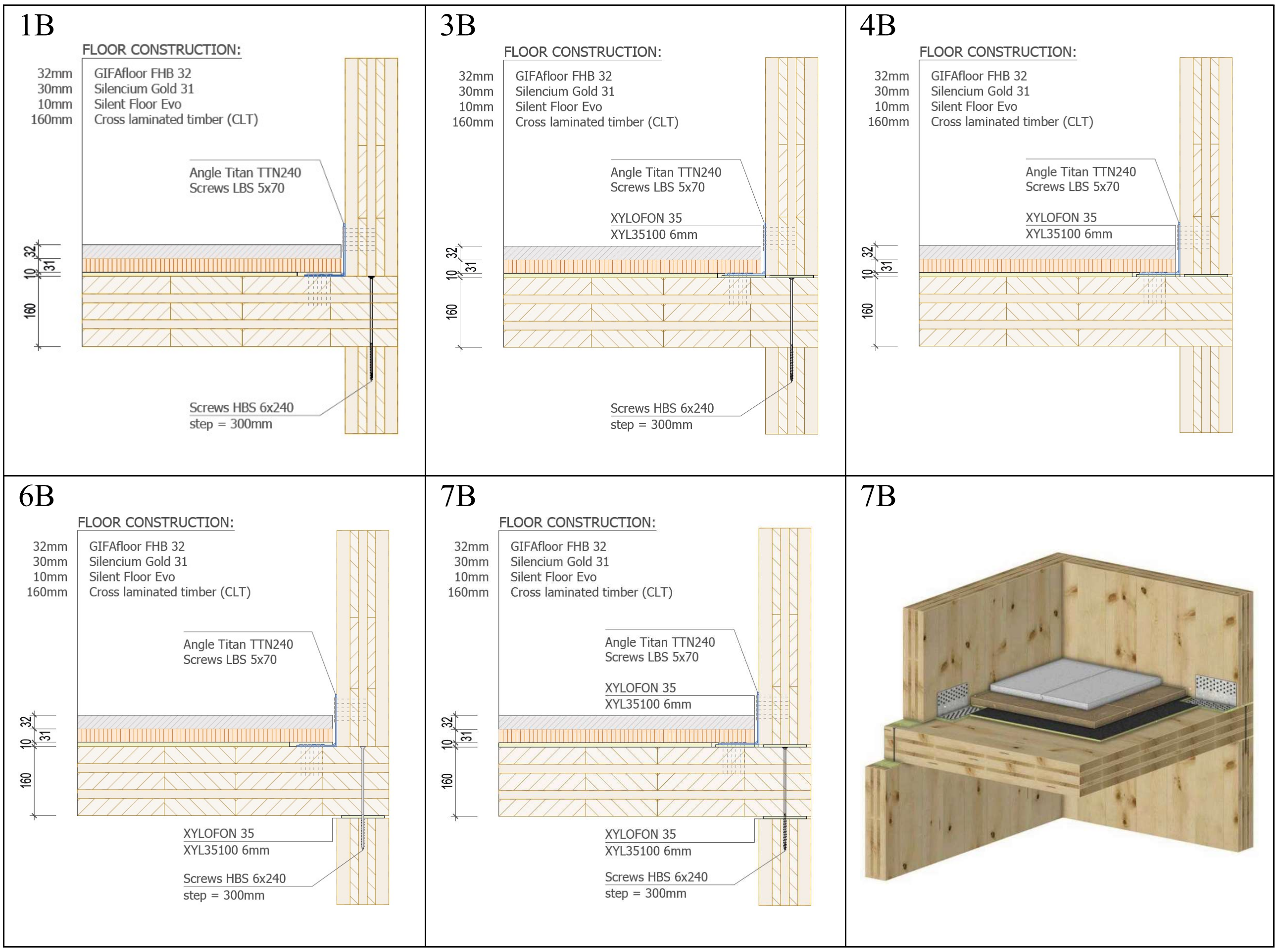


Figure 7: 5 Test configurations - second series of measurements (B)

2.4. Positions of the measuring devices

For the airborne sound measurement, two positions are used for the dodekaeder and the microphone no.1 in the transmitter room. Position 1 (Pos.1) is shown in figure 8. For this position six measuring positions for microphone no.2 in the receiver room are used. Then, the positions of the dodekaeder and the microphone no.1 in the transmitter room are swapped and again six measurements are made.

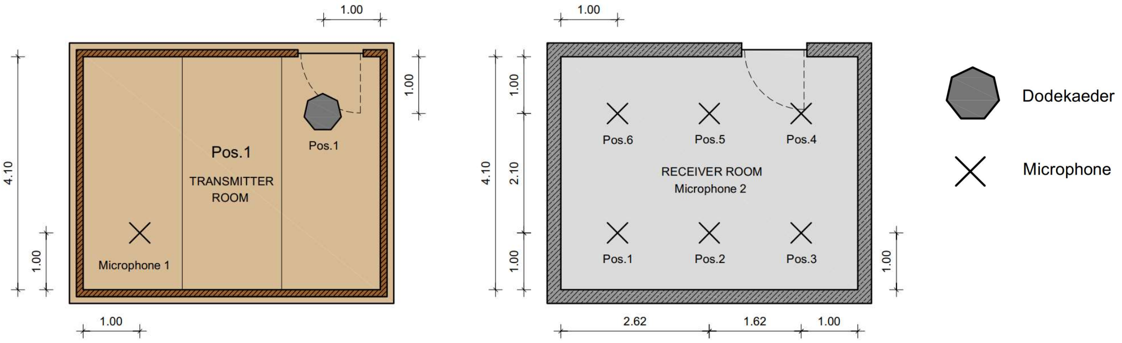


Figure 8: Airborne sound measurement

For the impact sound measurement, three positions are used for the tapping machine in the transmitter room. Each of these positions with two measuring positions for the microphones in the receiver room.

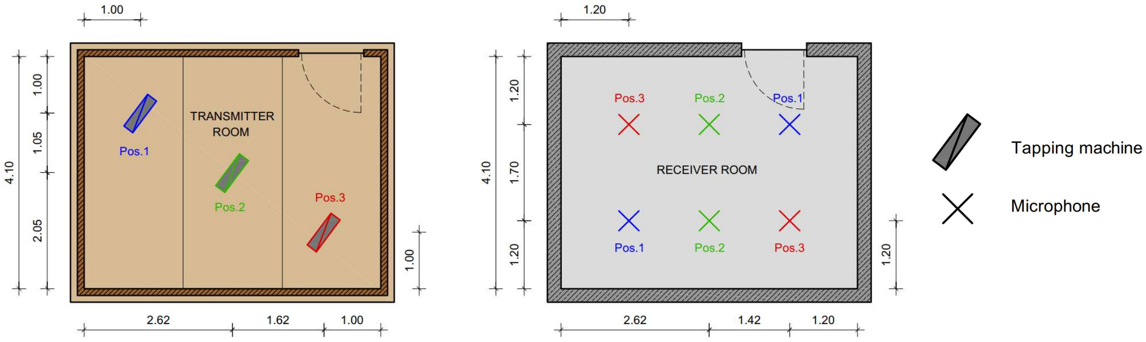


Figure 9: Impact sound measurement

2.5. Accelerometer placements

According to EN ISO 10848-1, the accelerometer positions must be randomly distributed over the surface of the element. For comparability of all measurements, the positions of the accelerometers were always chosen to be the same.

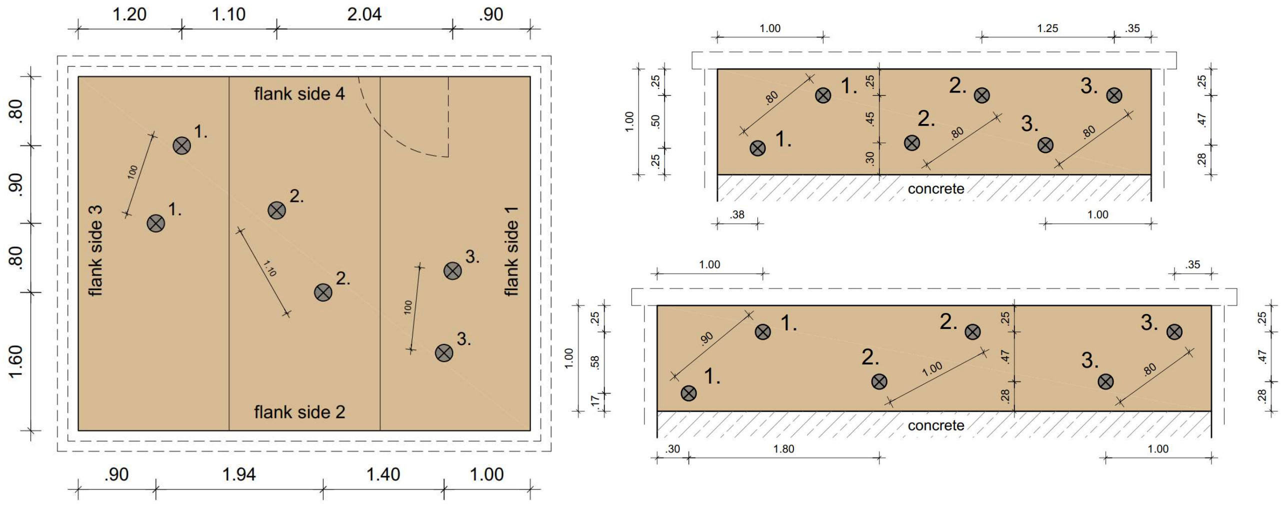


Figure 10: Accelerometer placements on the separating component S(0) and on the flanks

3. Results

The results of the airborne and impact sound measurements are determined according to the standard procedures ÖNORM EN ISO 16283-1 and ÖNORM EN ISO 16283-2 and are therefore not described separately.

3.1. Evaluation of the measurements with the accelerometers

The measurement of the flank transmission and evaluation as a sound reduction index or level measure used here is not yet declared in the standards and is therefore described in this publication as an experimental investigation.

Formula for R S(0) e.g. separating component:

$$R\ S(0) = LS\ (f) - Lb\ (f) - K56 + 20 * \log\ (f \text{ in Hz}) - 10 * \log \sigma \tag{1}$$

R S (0) = Sound reduction index of the separating component [dB]
LS (f) = Sound level in the transmission room as a function of frequency [dB]
Lb (f) = Sound level flanks as a function of frequency for separation area 0 [dB]
K56 = Calibration values accelerometer [dB]
f = Frequency [Hz]
$10 * \log \sigma$ = Radiation index as a function of frequency for separation area 0

Formula for R SF(1) e.g. flank side 1:

$$R\ SF(1) = LS\ (f) - Lb\ (f) - K56 + 20 * \log\ (f \text{ in Hz}) + 10 * \log\ ((A\ S(0)/A\ SF(1))) - 10 * \log \sigma \tag{2}$$

R SF (N) = Sound reduction index of the flank SF (1, 2, 3 or 4) [dB]
LS (f) = Sound level in the transmission room as a function of frequency [dB]
Lb (f,N) = Sound level flanks as a function of frequency and flank number N [dB]
K56 = Calibration values accelerometer [dB]
f = Frequency [Hz]
A S(0) = Area separating component S [m^2]
A SF = Area flank SF (1, 2, 3 or 4) [m^2]
$10 * \log \sigma$ = Radiation index as a function of frequency and flank side

Formula for K56 - Calibration of the accelerometers:

$$a_0 = A_{cal} * 10\hat{\ }(-L_{cal} / 20) = 10 * 10\hat{\ }(10 / 20) = 31{,}62 \text{ V / m/s}^2 \tag{3}$$

$$K56 = 10 * \log\ (\rho_c * a_0^2 / W_0 / \pi^2) = 10 * \log\ (400 * 31{,}62^2 / 10^{-12} / \pi^2) = 166{,}1 \text{ dB} \tag{4}$$

a_0 = Sensitivity value
K56 = Calibration value accelerometer
$A_{cal} = 10\ m/s^2$ = Calibration acceleration
$L_{cal} = -10$ dB = Calibration level
$\rho_c = 400\ kg/m^3 * m/s$ = acoustic impedance of air
$W_0 = 1*10^{-12}\ W/m^2$ = lower limit of the sound intensity range
$\pi = 3{,}142$ = Pi

In this experimental investigation, the sound reduction index R and the normalized impact sound pressure level L_n from the separating component and the flanks are determined. The sound reduction index R and the normalized impact sound pressure level L_n are widely used in practice and suitable for evaluation and comparison. The demand from users for values for R and L_n is high.

The two formulas shown (1+2) are used to determine the sound reduction index and level measure from the separating component and the flanking transmission. The particular challenge here is to determine the correct radiation index of the materials. The correctness of the input of the radiation values can be checked by adding the results of the flank components SF(1-4) and the separation component S(0) (ceiling element) measurements. If the input of the radiation values is correct, the result of the addition of the flanks and the separating component should correspond to that of the standard measurement (apparent sound reduction index, normalized impact sound pressure level), within the range of the measurement accuracy (one to two dB).
The results for airborne sound agree very well with the standard measurements. For the impact sound measurements the agreement is also good.

3.2. Results of the investigations carried out

The results of test series (A) show that a significant reduction of the longitudinal sound conduction can be achieved by using decoupling bearings below or above or on both sides of the ceiling element. However, it also shows that the single number value for the measurement with the raw ceiling and the raw walls (cross laminated timber) is reduced to the weakest part of the structure. I.e. the results of the eight measurement configurations without additional floor construction show on the one hand that the single number values hardly change and on the other hand that the decoupling strips bring about an acoustic improvement. The installation of the floor construction improves the airborne and impact sound quality of the ceiling construction. As a result, the longitudinal sound conduction over the flanks becomes the weak point in terms of sound technology. This enables a better evaluation or assessment of the acoustic effect of the XYLOFON decoupling bearings.
The following tables show 4 measurements each from the first (A) and second (B) series of measurements that can be compared with each other. For example, measurement no. N of the first series (A) is given the index M0N-A.

Table 1: Summary of the measurement results, configurations without ceiling construction

Measure	**R'_w (dB)**	R_w S(0) (dB)	R_w SF(2) (dB)	**$L'_{n,w}$ (dB)**	$L_{n,w}$ S(0) (dB)	$L_{n,w}$ SF(2) (dB)
M01-A	**38**	38	53	**85**	87	71
M03-A	**39**	39	53	**85**	87	71
M06-A	**40**	39	58	**84**	84	64
M07-A	**39**	39	60	**84**	86	63

Both, the single-number values of the weighted apparent sound reduction index R'_w as well as for the weighted normalized impact sound pressure level $L'_{n,w}$ the deviations are a maximum of 2 dB. These deviations can essentially be attributed to the measurement accuracy. Due to the modification, e.g. lifting the wall elements of the ceiling element from the test stand, reinserting the decoupling bearings and screwing them back in, a deviation in the range of 2 dB is to be regarded as standard. I.e. with the raw elements (cross laminated timber - wall, ceiling) the sound quality does not change due to the decoupling, related to the single number values. This can be explained by the fact that in this case the ceiling element is the weakest component in terms of sound and thus determines the sound value. The values shown R_w S(0) - partitioning component ceiling - with the same sound values confirm this statement. When considering the flank transmission R_w SF(2), only the flank side 2 (south wall) was examined in these tests, clear differences are evident. In the comparison of M01-A (without decoupling) and M07-A (with decoupling on both sides), there is an improvement in the apparent sound reduction index R_{w} over the flanks of 7 dB. In the impact sound measurements, the improvement (normalized impact sound pressure level $L_{n,\mathrm{w}}$) is even 8 dB for the same comparison. In the measurements with the raw elements (without ceiling construction), it should be mentioned that a higher airborne and impact sound is achieved via the flank components when the decoupling bearing is inserted below the ceiling element.

Table 2: Summary of measurement results, configurations with ceiling construction – airborne sound

Measure	**R'_{w} (dB)**	R_{w} S(0) (dB)	R_{w} SF(1) (dB)	R_{w} SF(2) (dB)	R_{w} SF(3) (dB)	R_{w} SF(4) (dB)	R_{w} S(0) + SF (1-4) (dB)
M01-B	**47**	50	57	57	57	57	47
M03-B	**50**	52	62	62	60	62	50
M06-B	**48**	50	63	63	62	63	49
M07-B	**51**	51	66	67	65	66	50

In the second series of tests (B), a floor construction is chosen, as already described, which has only a small sound improvement measure. The airborne and impact sound measurements are considered separately in this test series, since all four flank sides were measured in this series compared to the first. There are clear improvements in the single number values of the airborne sound measurement due to the floor construction. The single number value improves by 4 dB in comparison without decoupling bearings and with decoupling bearings (top and bottom). The value of the apparent sound reduction index of the flank measurements is 10 dB or more than 10 dB better than the single number value for all four measurement configurations compared to the standard measurement. Thus, the sound quality of the ceiling construction is decisive for the single number value. With a difference of 10 dB or more, the flanking components no longer have any influence on the result of the single number value. The improvement of the apparent sound reduction index via the flank components between non-decoupled (M01-B) and decoupled on both sides (M07-B) lies in the range of 8 dB and 10 dB. The single number values of the flank measurements are comparable over all four flank sides and lie within the measurement accuracy range of 2 dB. The possible reasons for the deviation of the single number values have already been described for measurement series (A). In addition, when measuring wood surfaces with accelerometers, deviations in the measured values can also occur due to knots, cracks and different hardnesses on the surface.

Due to the floor construction, the decoupling bearings above the ceiling element have a higher influence on the sound quality than the decoupling strips below the ceiling element. Based on further investigations, it can be said that the higher the quality (acoustically assessed) of the floor construction, the lower the influence of the decoupling strips below the ceiling element. The investigations also show that with decoupling strips inserted on both sides, the airborne sound insulation is usually improved by 1 to 3 dB. Therefore, it must be decided on a situation-by-situation basis whether acoustic decoupling is needed on both sides.

Table 3: Summary of measurement results, configurations with ceiling construction – impact sound

Measure	**$L'_{n,w}$ (dB)**	$L_{n,w}$ S(0) (dB)	$L_{n,w}$ SF(1) (dB)	$L_{n,w}$ SF(2) (dB)	$L_{n,w}$ SF(3) (dB)	$L_{n,w}$ SF(4) (dB)	$L_{n,w}$ S(0) + SF(1-4) (dB)
M01-B	**62**	64	45	44	44	46	64
M03-B	**62**	64	45	44	42	45	64
M06-B	**62**	67	40	40	37	41	67
M07-B	**62**	67	39	40	37	40	67

The single-number value of the impact sound insulation improves with the selected floor structure and independently of the decoupling by $L'_{n,w}$ = 22 dB to 23 dB. The floor construction also reduces the longitudinal sound conduction via the flank connections of $L_{n,w}$ SF(2) = 71 dB (M01-A) by 27 dB to $L_{n,w}$ SF(2) = 44 dB (M01-B) reduced. This means that the floor structure alone significantly reduces the flank transmission via the wall components. The normalized impact sound pressure level via the flank components is reduced by a further 4 dB to 7 dB with decoupling bearings inserted on both sides compared to without decoupling bearings.

In the four measurements shown, the normalized impact sound pressure level of the flanks is so low that the values no longer have a negative influence on the single number value $L'_{n,w}$. In this case, the better the acoustic design of the floor structure, the more the flanks contribute to the single number value. However, it can already be seen in these measurements (floor construction with low acoustic quality) that the flank transmission is improved by 4 to 7 dB by inserting decoupling stripes below the ceiling element or on both sides.

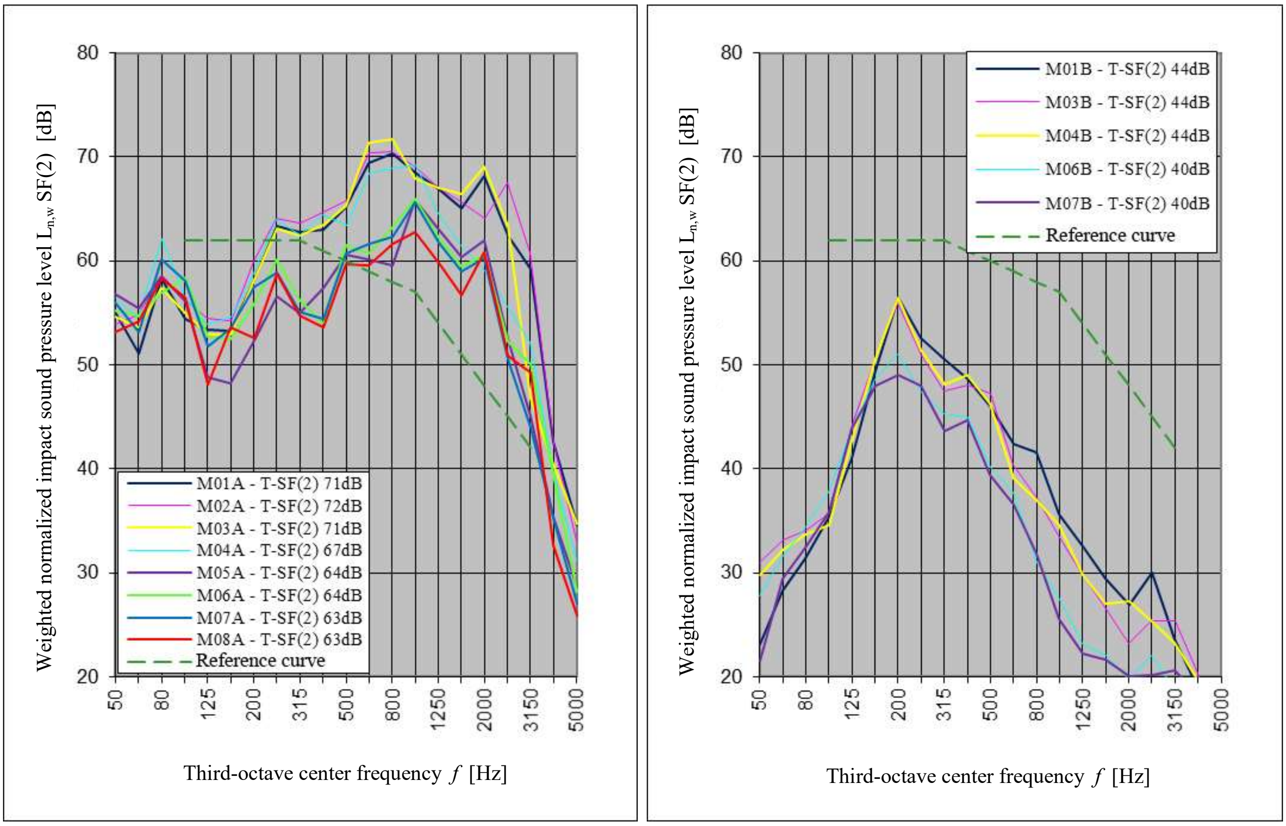


Figure 11: Summary - flanks measurements - normalized impact sound pressure level $L'_{n,w}$ series (A) and series (B)

4. CONCLUSIONS

The investigations for airborne sound and impact sound insulation of the solid wood elements (CLT) with and without floor superstructures and without facing shells show that the use of decoupling bearings (XYLOFON), with a thickness of 6 mm, bring about an effective sound improvement. The acoustic effect - above or below the ceiling - is strongly dependent on the chosen floor and wall constructions. The investigations show that for high acoustic requirements, the installation of decoupling bearings (above and below the ceiling element) is absolutely necessary. It should be mentioned again that a preload of 17 kN/m was applied to the ceiling element in all sound tests (test series A and B). The Titan TTN240 angles used were fastened with 36 screws per angle side. The large number of screws for the angles can be cited as one of the reasons why a functioning spring effect (decoupling of the angles) is no longer possible and thus no acoustic effectiveness is apparent. The results also show that the fastening materials (angles, screws) do not show any significant difference in comparison with or without fastening. The applied prestressing, which may be the reason for this, simulates the weight of approx. one storey. Due to the applied measurement methodology, the results of the acoustic measurements carried out correspond to a practical design.

5. ACKNOWLEDGEMENTS

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