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Evaluation of the acoustic performance of a CLT floor in a wide frequency range

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In countries having large forest resources like Sweden, there is an increasing interest for bio-based and renewable materials for more sustainable buildings. The use of massive Cross Laminated Timber (CLT) in various building elements, such as floors and walls, is becoming more and more popular, also thanks to its architectural benefits. However, the acoustic performance, especially at low frequencies, is a challenge. In this study, a 230 mm thick homogeneous CLT floor for an office building was tested in a laboratory in combination with various additional acoustic solutions. Because of restrictions on total construction depth the types and dimensions of the solutions were limited. While airborne sound insulation was measured down to 50 Hz, measurements of impact noise were conducted in an extended frequency range down to 20 Hz in order to evaluate the low frequency performance, which is recommended in the Swedish sound classification scheme for residential buildings in the higher sound classes. In addition, vibration measurements at different layers in the constructions and dynamic stiffness of the resilient layers in the floating floors are used to study resonance phenomena and as input to prediction models. Measured sound insulation and impact noise levels were used to auralize sound in a typical room, and to investigate the acoustic performance of the floor from realistic sources such as a TV-set or a chair pulled over the floor. The results show that the 230 mm thick CLT floor in combination with a floating floor may fulfil acoustic requirements for office buildings, while for residential buildings there is a need to improve the acoustic behaviour in order to be an acceptable solution. The possibilities to achieve acceptable solutions are significantly severed with more constraints of e.g. total construction depth.

1 Introduction

Cross Laminated Timber (CLT) has gained increasing attention as building material in last years and extensive research has been conducted in the area. Wood has many benefits from an environmental point of view and is in addition attractive for industrialised building processes. However, one of the challenges is to achieve sufficient acoustic quality mainly with respect to low frequency impact noise [1, 2, 3]. Airborne sound insulation in wooden building system may in many situations be as good as, or even superior to, heavy building systems thanks to the higher damping at higher frequencies. However, at low frequencies the mass per unit area is normally a critical parameter for homogeneous structures and hence light weight structures needs to be designed with extra care. Normally CLT plates do not fulfil acoustic requirements without additional layers or in combination with suspended ceilings. However, from architectural and esthetical reasons it is attractive for the CLT to be visible, which put restrictions on what type of acoustic measures that can be applied. Added layers and/or double wall constructions results in thicker constructions, which could be limited by the total building height.

Most research on light weight timber structures has focused on residential buildings, where the results show that low frequency impact noise may lead to annoyance. This paper presents selected results from an innovation project with the aim to develop a floor structure for an office building in Gothenburg. The office building is planned to be used as "A Working Lab" (AWL) where research and tests under realistic conditions with tenants could be performed. This paper will focus on the airborne and impact sound insulation of the floor assemblies that were tested in the frequency range down to 20 Hz for impact noise. Since the existing available research is based on residential buildings where correlation between subjective response and objective measures has been studied, this paper also includes evaluation of the construction's performance with respect to psychoacoustic measures to achieve some insight in the subjective response.

2 Floor assemblies

The load bearing floor structure was a 230 mm thick Cross Laminated Timbre (CLT) slab 3,0 x 4,0 m^2. The slab was made from two separate 1,5 m wide elements screwed together during installation in the lab. The floor plate was installed in the floor opening in the impact noise transmission lab at RISE, Research Institutes of Sweden. It was simply supported along the two shorter edges and the edges along the length of the slab were free. The installation should mimic the normal installation in the field situation as close as possible. On top of the load bearing floor various toppings and floor coverings were tested. The assemblies are described in Table 1, and Figure 1 shows a picture of the CLT floor element.

Table 1 Floor assemblies in the study

Case	*Assembly*	*Description*
1	Bare floor	230 mm CLT floor
2	30 mm screed	30 mm screed on 25 mm mineral wool floating floor + suspended ceiling
3	60 mm screed	60 mm screed on 25 mm mineral wool floating floor
4	40 mm screed	40 mm screed on 36 mm fibreboard floating floor
5	Access floor	Raised steel access floor system on elastomer with soft carpet on top
6	Wood	Multilayer wooden floor fulfilling Swedish sound insulation requirements for Class B in residential buildings
7	Concrete	Homogeneous concrete floor fulfilling Swedish sound insulation requirements for Class B in residential buildings

Assembly cases 1 to 5 were tested in laboratory, while the data for assembly 6 and 7 were collected from available filed measurements performed in the AkuLite project [1]. The field measurement data were included for comparison and reference only to compare with residential buildings.

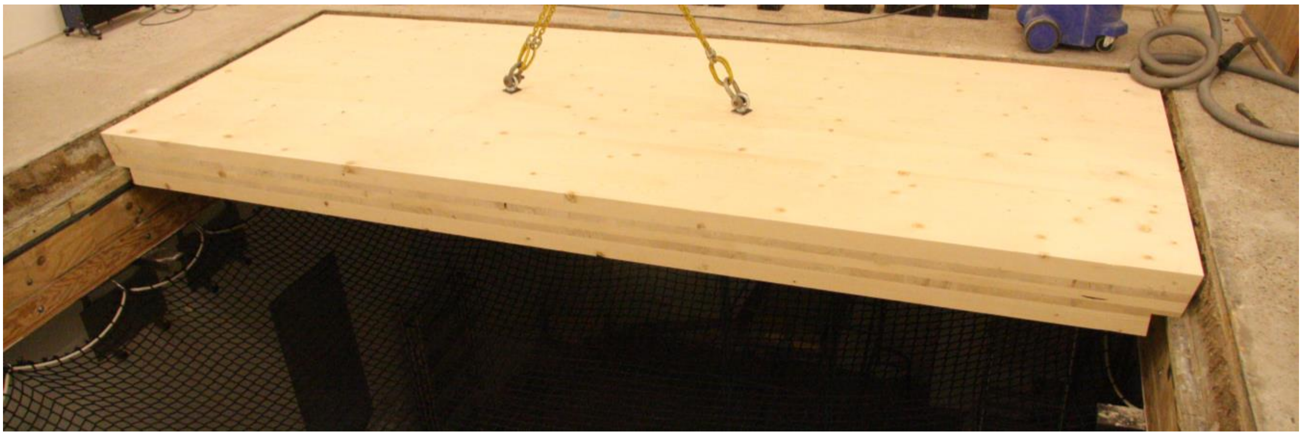

Figure 1 An element of the bare CLT floor (Case 1) during installation in the lab

3 Laboratory measurements

Laboratory measurements of impact and airborne sound insulation were carried out according to standards ISO 10140-1 in the extended frequency range down to 50 Hz. In addition, impact noise insulation measurements were carried out in the third octave bands 20 – 40 Hz in order to evaluate the low frequency impact noise behaviour according to the recommendation for light weight floors according to the Swedish sound classing system [4]. The measurement uncertainty and reproducibility at frequencies below 50 Hz is not known. However, the repeatability of the laboratory measurements is still considered to be sufficient to be able to compare and evaluate the floor assemblies in this extended frequency range under laboratory conditions.

3.1 Airborne sound insulation

The sound reduction indexes as function of frequency measured according to ISO 10140-1 are shown in Figure 2. The weighted single number ratings according to ISO 717-1 are given in Table 2.

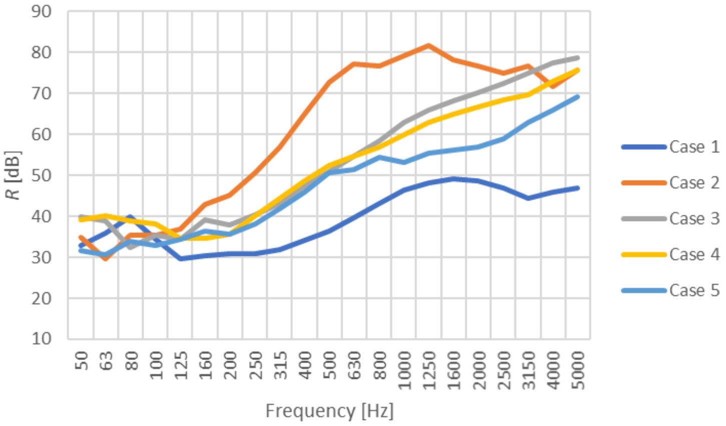

Figure 2 Airborne sound insulation from laboratory measurements

The results show that the bare CLT floor gives the lowest sound insulation while the combination of a floating floor and a suspended ceiling gives the highest performance, expect for the lowest frequencies below 100 Hz. The solutions without suspended ceiling are similar regarding the acoustic performance, where floor assembly 3 gives slightly better overall performance.

Table 2 Weighted airborne sound insulation from laboratory measurements

Case	R_w ($C_{50-3150}$)
1	42 (-1)
2	61 (-4)
3	53 (-1)
4	53 (-2)
5	51 (-2)

3.2 Impact noise levels

The standardized impact noise levels as function of frequency for the laboratory tested floor assemblies are shown in Figure 3 in the extended frequency range down to 20 Hz. For frequencies below 50 Hz no correction for the reverberation time was made. The impact noise levels were measured according to ISO 10140-1 using the tapping machine as impact source. The same source was used for the entire frequency range down to 20 Hz and 9 source positions were used. A rotating microphone was used in the receiving room and the average time was 64 s for each measurement. The weighted single number ratings according to ISO 717-2 are given in Table 4. Additionally, the spectrum adaptation term $C_{I,20\text{-}2500}$ as defined in the Swedish sound classing system [4] is given. The adaptation term is calculated according to equation 1.

$$C_{\mathrm{I},20-2500} = 10lg\left(\sum_i 10^{(L_{\mathrm{n}T,i}+X_i)/10}\right) - L_{\mathrm{n}T,w}, \qquad (1)$$

where X_{i} are given in Table 3 Table 3, and $L_{\mathrm{n}T,i}$ is the standardised impact noise level in third octave band i.

Table 3 Correction terms for the extended frequency range 20-2500 Hz

f [Hz]	*20*	*25*	*31,5*	*40*	*50-400*	*500*	*630*	*800*	*1k*	*1,25k*	*1,6k*	*2k*	*2,5k*
X_{i}	-7	-9	-11	-13	-15	-14	-13	-12	-11	-10	-9	-8	-7

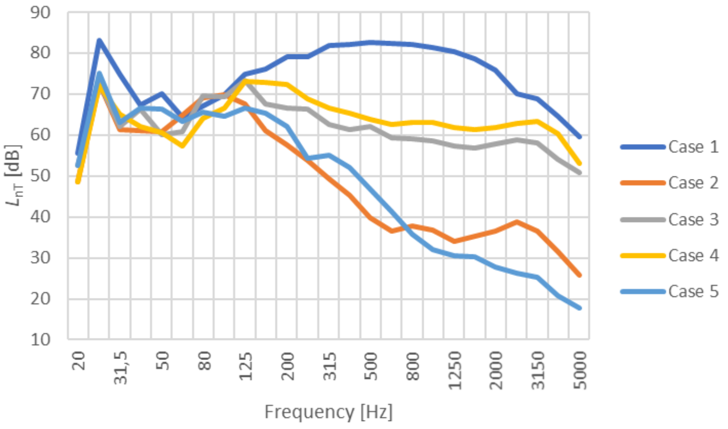

Figure 3 Standardized impact noise level from laboratory measurements. No correction for reverberation time has been made for frequencies below 50 Hz.

Table 4 Weighted impact noise levels from laboratory measurements

Case	$L_{\mathrm{n}T,\mathrm{w}}$ ($C_{\mathrm{I},50\text{-}2500}$; $C_{\mathrm{I},20\text{-}2500}$)
1	82 (-5 ; -2)
2	55 (5 ; 10)
3	66 (-3 ; 1)
4	70 (-5 ; -2)
5	55 (4 ; 12)

The results show that the bare CLT floor has the lowest acoustical performance, while the combination of floating floor and suspended ceiling and the installation floor gives the highest performance. The two floating floors without suspended ceiling perform in between with slightly better performance for the thicker screed on mineral wool (Case 3). However, taking frequencies below 100 Hz and especially below 50 Hz into account, the constructions giving the lowest $L_{\mathrm{n}T,\mathrm{w}}$ are the ones having the highest adaptation terms and hence are dominated by low frequency impact sound.

In addition to the laboratory measurements two field measurements of normalized impact noise level as function of frequency in residential buildings are shown in Figure 4. One (Case 6) is for a wooden building and the other (Case 7) is for a concrete building. The measurements are done in an extended frequency range down to 20 Hz, using the tapping machine as impact sound source. The weighted single number ratings are shown in Table 5. Both floors fulfil requirements for sound class B for residential buildings, and gives the same rating taking the adaptation term in the extended frequency range down to 50 Hz into account.

Table 5 Weighted impact noise levels from field measurements

Case	$L'_{n,w}$ ($C_{I,50\text{-}2500}$)
6	43 (7)
7	50 (0)

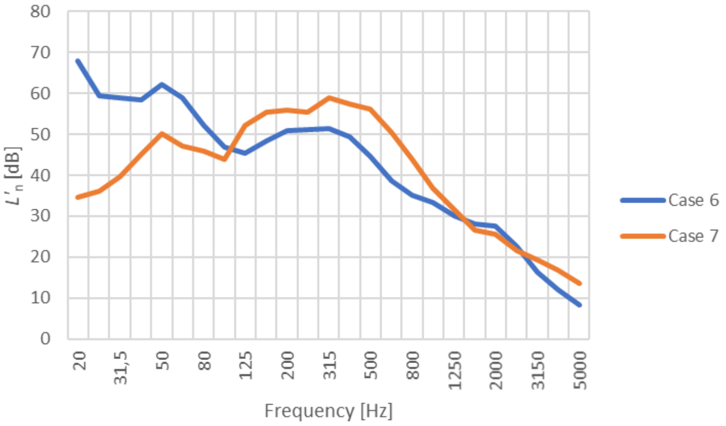

Figure 4 Impact noise level measurements from field measurements

4 Auralization

4.1 Method

To evaluate the performance of the floor assemblies with respect to various sources with different character, sound signals for airborne sounds as well as structure borne sound were auralized. Source signals based on recordings were used as input. The measured sound insulation and impact noise data were used to determine the coefficients of a third octave band filter. For airborne sources the source signals were filtered in the frequency range between 50 – 5000 Hz, while the structure borne sources were filtered in the frequency range 20 – 5000 Hz. As a start the same method was used for airborne and structure borne sources in this study because of lack of information about the input forces from the structure borne sources. The purpose of the evaluation is to compare the floor assemblies alone. The same reverberation time was simulated in the receiving room for all signals, and no further normalisation or standardization of the signals were applied.

4.2 Airborne sources

Two airborne sources were used to auralize the sound in the receiving room, a dog barking and a TV commercial. These sounds are considered to be rather familiar to most people and could be used as source signals for listening tests in the future, although they might be more relevant for residential buildings than for office buildings. The sounds used are described in the following.

Table 6 Source description for auralization

Sound example	*Source*	*Description*	$L_{A,eq}$ [dB]
1	Dog bark	Doberman-Pincher barking and growling, 14 s	82,4
2	TV	TV commercial, mixed music and female voice, 30 s	83,1

4.3 Structure-borne sources

Two structure borne sources were used to auralize the sound in the receiving room, footsteps and the pulling of a chair over a floor. Both these sounds are considered to be relevant for office buildings and rather familiar to most people. and could be used as source signals for listening tests in the future. The sounds used are described in the following.

Table 7 Source description for auralization of impact noise

Sound example	*Source*	*Description*	$L_{A,eq}$ [dB]
3	Footsteps	Walker with shoes, 10 steps on a wooden floor, 10 s	51,6
4	Chair pull	Chair pulled 10 times over a wooden floor creating scratching sound, 19 s	75,5

5 Evaluation of sound insulation and impact noise

The auralized signals were evaluated with respect to the A-weighted equivalent sound pressure levels in the receiving room as well as with respect to the psychoacoustic measures loudness level and sharpness. The evaluation is based on the methodology described in [5] where a loudness model for sound insulation was developed. However, in this study single number ratings are used, and the analysis has been extended to include sharpness as a measure. Additional measures could be studied in the future. The Head Acoustics Artemis software was used to calculate the psychoacoustic measures. The Zwicker loudness model according to DIN 45631 was used and diffuse field conditions were assumed. Sharpness was calculated according to DIN 45692.

5.1 Airborne sound

The Swedish sound classing system for premises [6] put acoustic requirements on office buildings. The minimum requirements for new buildings corresponds to class C, while higher acoustic requirements are given in class B, and class A. The minimum requirement for floors separating different tenants is $R'_w = 48$ dB for airborne sound insulation and for class B the requirement is $R'_w = 52$ dB. No requirements on low frequency noise below 100 Hz are considered. Comparing with the laboratory measurement results in Table 2, all floor constructions (except the bare CLT slab) fulfil the minimum requirements, not taking flanking sound transmission into account. In practice however, the flanking sound transmission could be substantial depending on the installation of the floor and flanking constructions in the specific building, which needs to be taken into account in each particular project.

The differences in A-weighted sound pressure level, loudness level and sharpness for the two airborne source signals are shown in Figure 5. The results show that the A-weighted sound level difference, loudness level difference and sharpness difference depend on the character of the source. The floor assembly 2 (floating floor and suspended ceiling) resulting in the largest measured weighted sound reduction index also results in the largest reduction of loudness level and sharpness. Interestingly, Case 2 reduce the sharpness of the two sounds approximately equal, while the other floors reduce the sharpness more for the TV sound compared to the Dog bark sound. However, the sharpness is generally low for both cases. The loudness level difference correlates well with the A-weighted sound pressure level difference.

Figure 6 shows the correlation between the psychoacoustic measures and the objective standard laboratory measurements. Both the A-weighted sound pressure level differences as well as loudness level differences correlate well with R_w for both sounds, while the correlation with sharpness is lower for the Dog bark sound. To add the adaptation term down to 50 Hz does not increase the correlation in these cases.

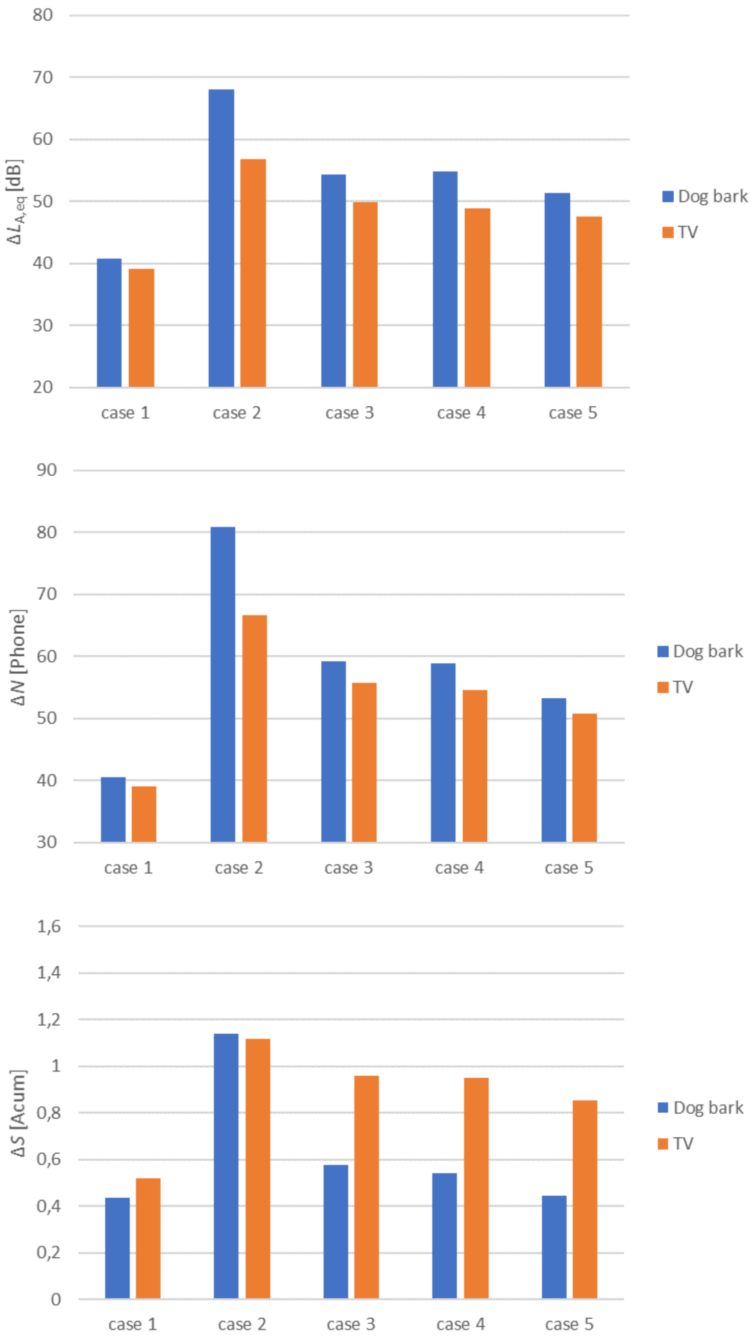

Figure 5 Differences in A-weighted sound pressure level (top), loudness level (mid) and sharpness (bottom) between sending room and receiver room for the different floor assemblies depending on source signal

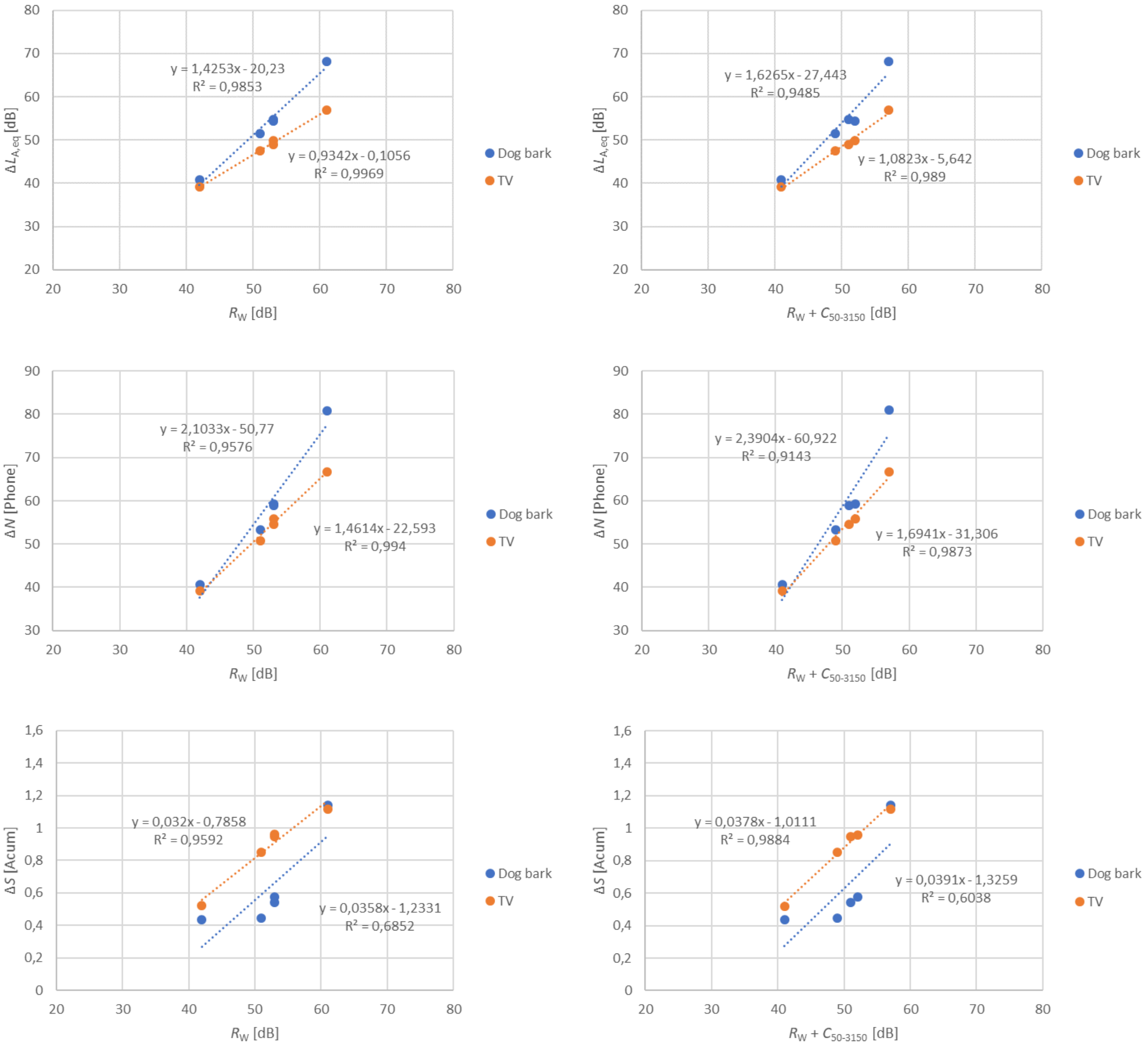

Figure 6 Correlation between laboratory airborne sound insulation measurements and psychoacoustic metrics of the auralized signals. Left column 100-3150 Hz, right column 50-3150 Hz.

5.2 Structure borne sound

As for airborne sound insulation the classing system [6] put demands on the impact noise level in offices. The impact noise should consider all structure borne sources, not only sound due to footsteps. The minimum requirements according to sound class C between offices with different tenants is $L'_{\mathrm{n,w}}$ = 68 dB, and according to sound class B $L'_{\mathrm{n,w}}$ = 60 dB. However, stricter requirements could be applicable e.g. between large conference rooms where $L'_{\mathrm{n}T\mathrm{,w}}$ = 56 dB is the minimum requirements. Comparing the measurement results in Table 4 with the requirements shows that the floor assemblies Case 2 and Case 5 might fulfil the minimum impact noise requirements for conference rooms, if flanking transmission is neglected. In practice the flanking transmission can be substantial for this kind of constructions.

The A-weighted sound pressure level, loudness level and sharpness for the floor assemblies and the two structure borne sound sources are shown in Figure 7. Also, the field measurements Case 6 and Case 7 are included for comparison. The A-weighted sound pressure level correlates well with the loudness level, and shows better performance for Case 2 and Case 5. The results from the field data shows that the concrete floor perform substantially better for the Footstep sound compared to the wooden floor, while for the Chair pull sound the wooden floor perform better than the concrete floor.

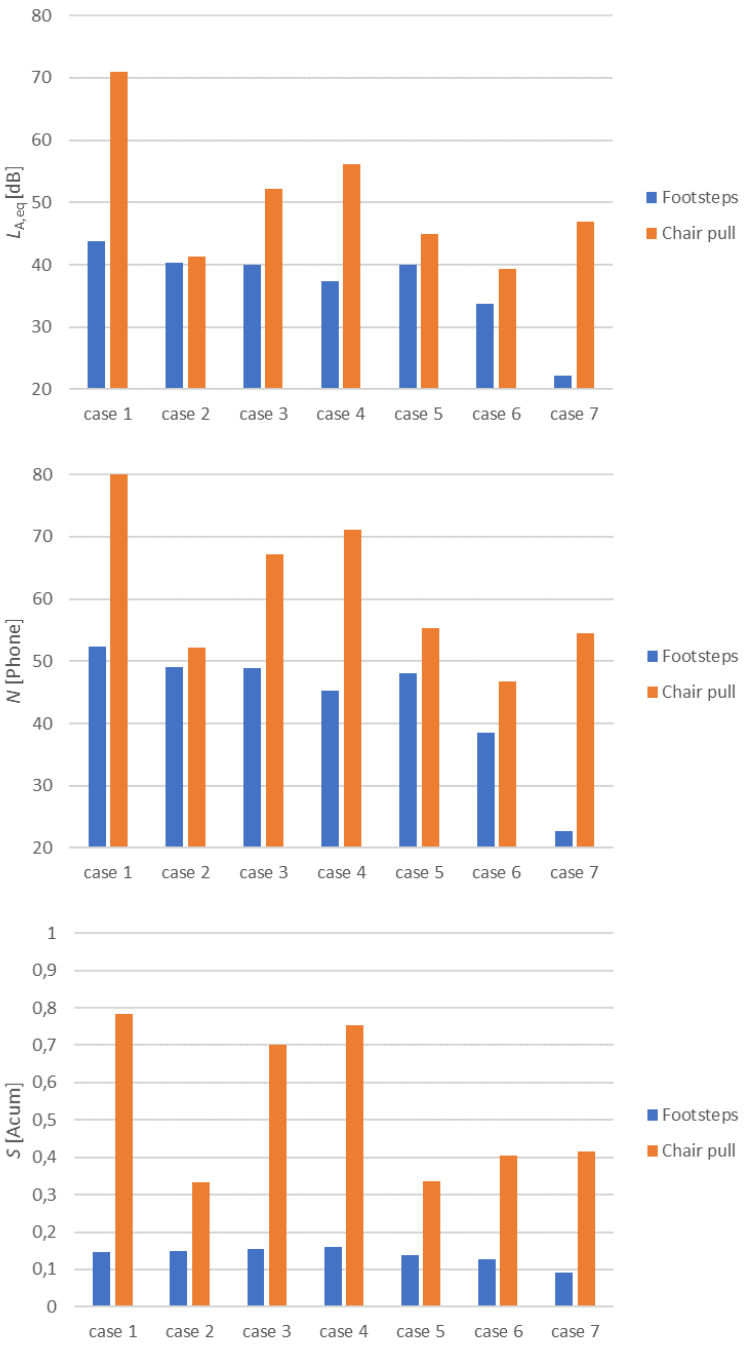

Figure 7 A-weighted sound pressure level (top), loudness level (mid) and sharpness (bottom) in the receiving room for the different floor assemblies depending on source signal

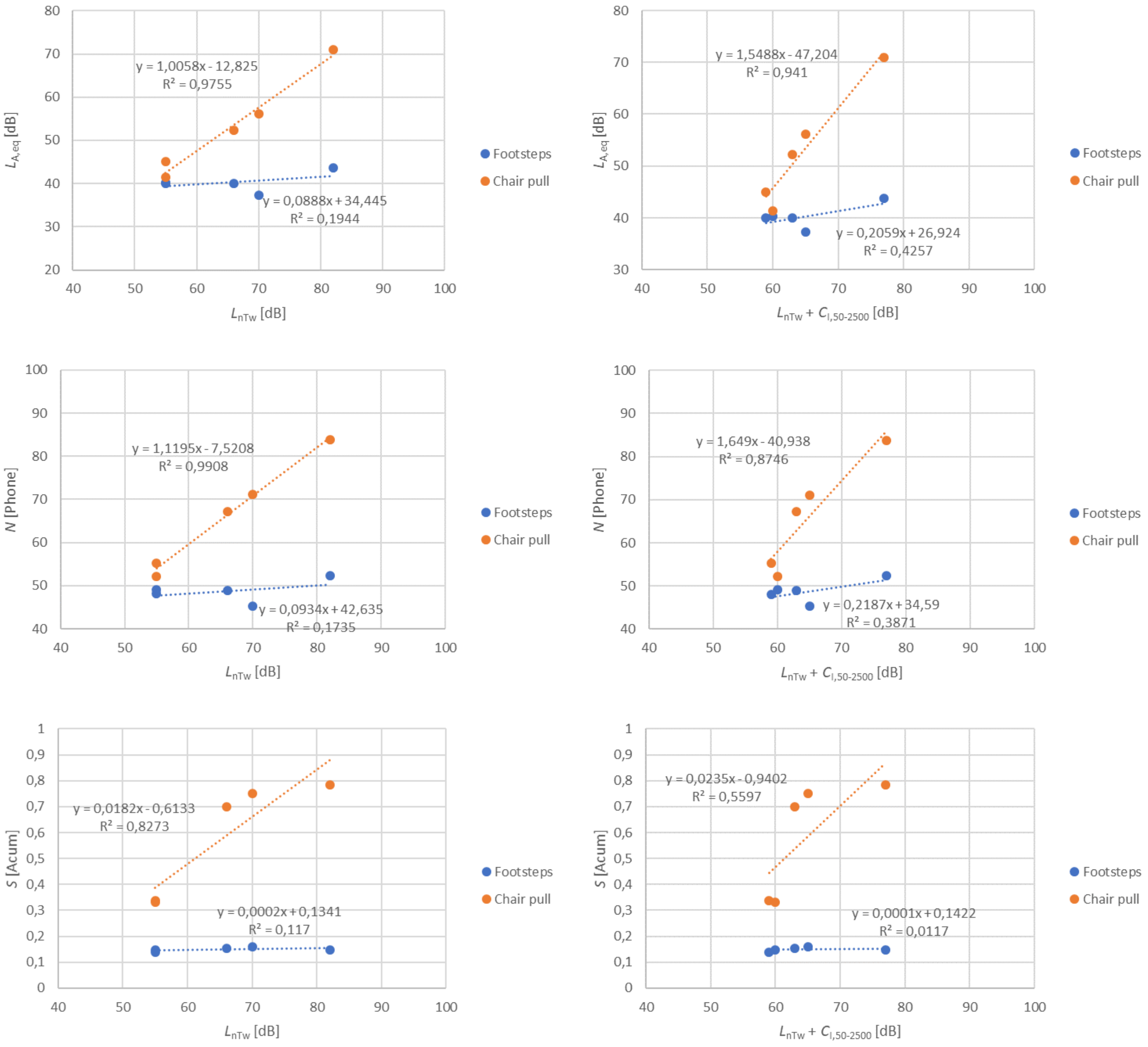

Figure 8 Correlation between laboratory airborne sound insulation measurements and psychoacoustic metrics of the auralized signals. Left column 100-2500 Hz, right column 50-2500 Hz.

Figure 8 shows the correlation between the objective laboratory measured weighted standardised impact noise levels and the calculated psychoacoustic measures used in this study. For the Chair pull sound the correlations between the A-weighted level and loudness level are high, while for the Footstep sound the correlation is weak. Adding the spectrum adaptation term down to 50 Hz improves the correlation for the Footstep sound, while reducing it for the Chair pull sound. Generally, the correlation between the sharpness and the impact noise level is lower, but also in this case the correlation is better for the Chair pull sound. The sharpness is generally very low for the Footstep sound which might influence the accuracy of the evaluation. Adding the low frequency adaptation term does not improve the correlation for sharpness evaluation.

Figure 9 shows the correlation between the laboratory measured weighted standardised impact noise levels and the calculated psychoacoustic measures when adding the spectrum adaptation term down to 20 Hz. Also, in this case the A-weighted sound pressure level and the loudness level show similar behaviour and shows higher correlation for the Chair pull sound than for the Footstep sound. The correlation for the Footstep sound is further improved by adding the adaptation term down to 20 Hz, while it is further reduced for the Chair pull sound as compared to adding the spectrum adaptation term down to 50 Hz.

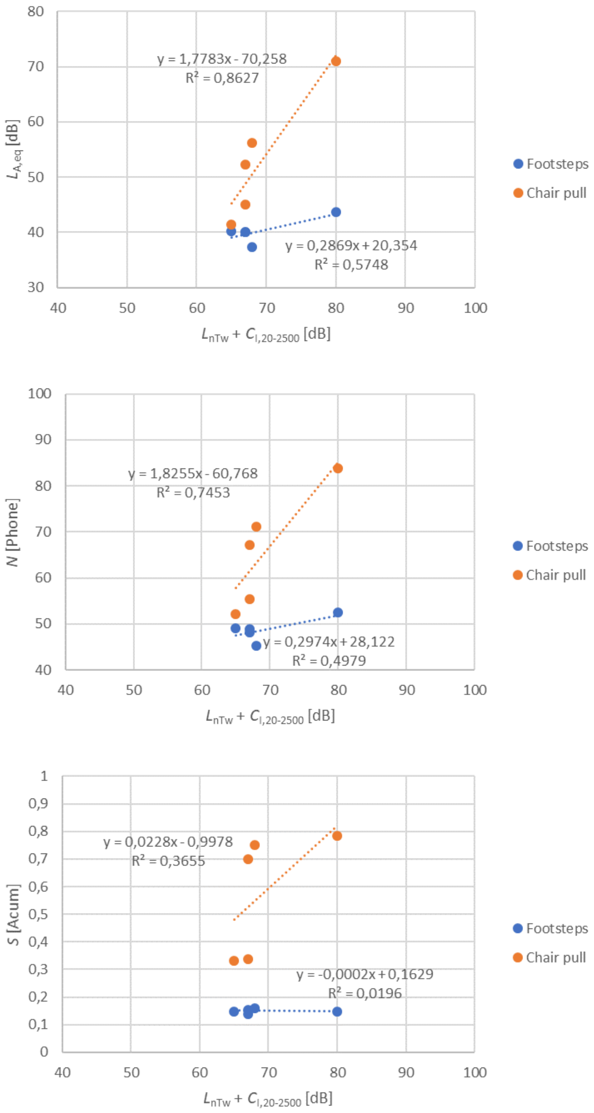

Figure 9 Correlation between laboratory airborne sound insulation measurements and psychoacoustic metrics of the auralized signals. Frequency range 20-2500 Hz

6 Summary, conclusions and future work

In this paper the acoustic properties of a 230 mm thick CLT floor slab in combination with various floating floors and suspended ceiling have been studied and evaluated in the laboratory. The results show that the CLT floor slab itself can not meet minimum requirements for office buildings but needs a treatment in the form of an added topping or/and a suspended ceiling to be used. In this case, a suspended ceiling could provide an acoustically good solution, but because of architectural and height requirements this solution might not be implemented in this project. However, the solution might be applicable in other projects where other requirements are set. An access floor could work as an effective solution to provide sufficient sound insulation, but at the same time it might be more expensive than a floating floor. The two floating floors that were tested without suspended ceiling in this extended frequency range down to 20 Hz perform approximately equal, but with somewhat better performance for the screed on mineral wool regarding the impact noise level.

Beside the standardised laboratory measurements, the floor assemblies were also evaluated with respect to psychoacoustic measures of auralized sound signals. The performance depends on the type of source due to differences in frequency content and time variations. For the two airborne sound sources tested in this study, the measured weighted reduction index correlate well with the differences in A-weighted equivalent sound pressure levels and loudness level, while for sharpness the correlation is weaker. Adding low frequency adaptation term did not improve the correlation. For the two structure borne sound sources the correlation between the laboratory measurement data correlates well with the source with a broader frequency range (Chair pull), while for Footstep sound the correlation is weak. Adding the low frequency adaptation terms improved the correlation for the Footstep sound, while lowering it for the Chair pull sound. The method for auralization and psychoacoustic evaluation of sound insulation and impact noise could be a way to get more insight in the acoustic behaviour of various building elements in the future and help in decision making at an early stage in the design process. However, the method needs to be developed further and validated in order to be implemented. Especially the use of single number ratings of the psychoacoustic measures, and the auralization of structure borne sound sources.

7 Acknowledgements

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