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Sound insulation performance of CLT prefabricated modules for high-rise buildings

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Abstract

The Energie Hotel is a 15-storey high energy-efficient building that will be developed near Ede, the Netherlands, using cross-laminated timber (CLT) prefabricated modules. The wooden columns form a full load-bearing column when the modules are stacked on top of each other and bound together by means of a steel connection attached to the floor slab. This system creates a double-leaf partition between two adjacent modules, both in the horizontal direction (wall-wall) and in the vertical direction (floor-ceiling), with the steel connection representing the only acoustic coupling. This allows to achieve good sound insulation with relatively small thickness of the partitions. Airborne and impact sound insulation measurements have been performed according to the ISO 16283 to determine which measures, in terms of type of floating floor, cavity size and insulation material, are necessary to provide the desired acoustic comfort. It is also discussed whether the current system can achieve the level of airborne and impact sound insulation required by the Dutch Building Decree (2012) for residential buildings.
Keywords: cross-laminated timber, high-rise, prefabricated modules, sound insulation, measurements.

1 Introduction

Cross-laminated timber (CLT) has seen a steady increase in popularity in recent years, both for residential and non-residential buildings [1]. Numerous examples of low- and mid-rise buildings are now scattered all over Europe, especially in the northern countries, as well as in the United States, Canada and Australia. CLT is a sustainable building material, lighter than concrete, which makes for easier production, transportation, and construction. Several factors have contributed for the growing application of CLT in high-rise buildings, such as the development of new building systems in combination with other construction materials, like steel [2,3] and concrete [4], and the growth of off-site prefabrication. The possibility of prefabricating modules is the key for making the construction of high-rise building viable, also from a financial point of view. The advantages are the increased safety and efficiency of the construction process, the ease and speed of assembly on site, the possibility to disassemble and reuse or recycle the modules, and the reduction of emission and, potentially, costs [1,5-7].

The use of CLT prefab modules is also seen as a sustainable and cost-effective approach to the increasing global housing demand. In The Netherlands, the aim of the government is to realize 845.000 new homes between now and 2030 [8], in compliance with the pledge to reduce CO emissions by 49% by the same year [9], placing high-rise CLT modular constructions in the front line. In order to be used in residential buildings, however, modular CLT constructions must meet the requirements imposed by the national building decrees, including those regarding sound insulation. In this sense, the industrialized methods used in prefabrication give an advantage, as variations in sound insulation are smaller compared to on-site production where construction is done in a less controlled environment [10].

Prefab wooden modules are already employed both in residential and non-residential buildings, of which the 45-meter high Treet Tower in Bergen [11] and the Jakarta Hotel in Amsterdam with its hybrid CLT-concrete modules [12] are two notable examples. More and more high-rise buildings will make their appearance in the next few years. One of these is the Energie Hotel, a 15-storey high energy-efficient building that will be developed near Ede, the Netherlands, consisting of CLT prefab modules assembled around a steel central core. Each module has a pair of massive wooden columns which form a full load-bearing column when the modules are stacked on top of each other. The columns of adjacent modules are bound together by means of a steel connection attached to the floor slab, which in turn is connected to the steel central core. This system creates a double-leaf partition between two adjacent modules, both in the horizontal direction (wall-wall) and in the vertical direction (floor-ceiling), with the steel connection representing the only acoustic coupling. This allows to achieve good sound insulation with relatively small thickness of the partitions.

This paper presents the results of the airborne and impact sound insulation measurements performed by the authors on a pair of prototype CLT modules. The aim is to determine which measures, in terms of type of floating floor, cavity size and insulation material, are necessary to provide the desired acoustic comfort. It is also discussed whether the current system can achieve the level of airborne and impact sound insulation required by the Dutch Building Decree [13] for residential buildings.

2 Description of the measurement setup

The sound insulation measurements have been performed in the factory facilities of Heko Spanten B.V. in Ede, The Netherlands, in January 2021. Two prototype CLT modules have been used for the test. The modules comprise of two load-bearing wooden columns at the façade side and a 240 mm 7-ply CLT floor, connected to each other by means of steel connections. The non-bearing walls consist of 80 mm 3-ply CLT panels, whereas a 60 mm 3-ply CLT panel is used for the ceiling. The temporary façade consists of a wooden frame with laminated double glass HR++ type GL33.1. All visible seams at the connections between the walls and the other construction elements have been closed with a wooden slat and made airtight with duct tape. A floating floor, with characteristics defined in Figure 1, is applied on top of the CLT floor, providing an additional mass of approximately 45 kg/m^2. A 3D representation of the module is given in Figure 2.

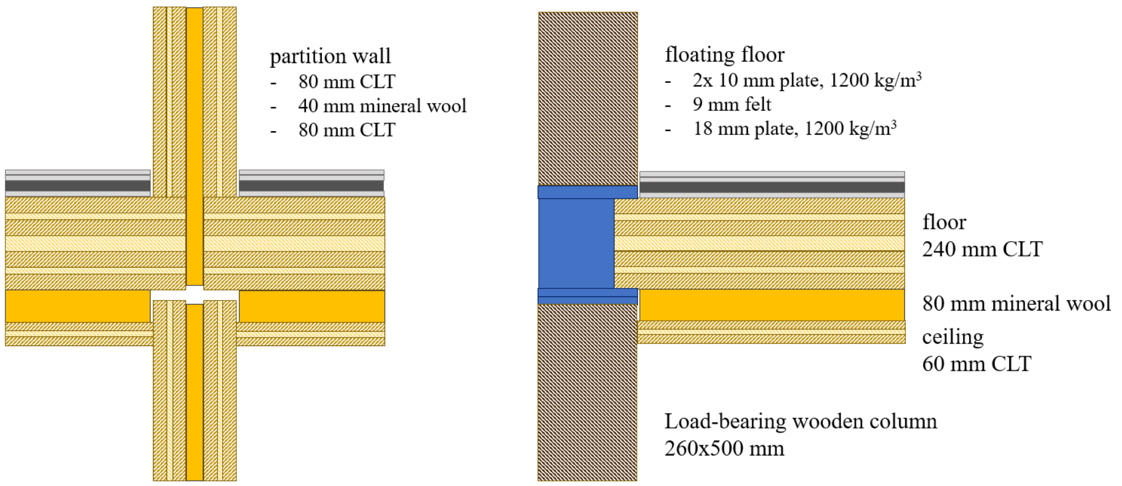

Figure 1. Wall, floor and ceiling constructions

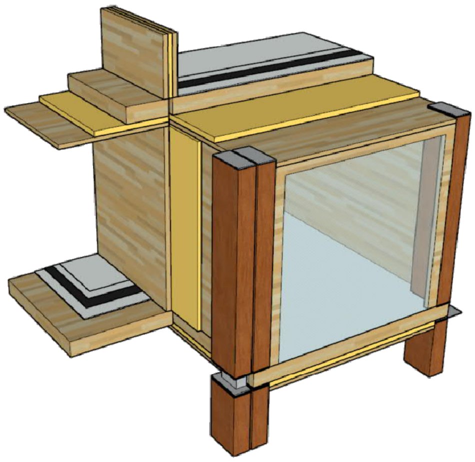

Figure 2. A 3D representation of the CLT prototype module (with adjacent elements)

The two prototype modules have been tested in the vertical arrangement as well as in the horizontal arrangement, as shown in Figure 3. In the vertical arrangement, the connection is made by placing the floor steel elements of the top module on the steel plates on top of the columns of the bottom module. The cavity of approximately 80 mm that is formed between the floor and the ceiling is filled with mineral wool, with the wool along the edges being more compressed than the insulation material in the center of the ceiling panel.
Two modules in the horizontal arrangement also form a cavity of approximately 40 mm, which is also filled with mineral wool. In this case, mineral wool mats have been attached to the outer side of the wall of one of the two modules. The connections between the adjacent modules is made by means of a steel plate. Figure 4 shows the floor steel element and the steel connection plates.

Figure 3. The CLT modules in the vertical arrangement (left) and in the horizontal arrangement (right).

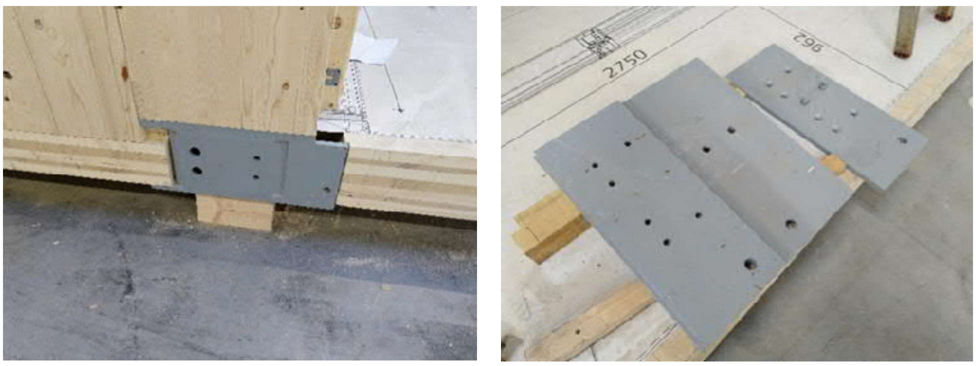

Figure 4. The floor steel element (left) and the steel connection plates (right).

The measuring equipment used for the measurements is reported in Table 1.

Table 1. Measurement equipment.

Device	**Manufacturer**	**Model**
Sound level meter (2 pieces)	Brüel & Kjær	2250 en 2260
Loudspeaker/power amplifier	Brüel & Kjær	4292-L/2734
Tapping Machine	Norsonic	Nor277

3 Measurement results

The measurements were carried out in one-third-octave bands in accordance with the ISO 16283 [14,15]. Use was also made of the ISO 717 [16,17] and the NEN 5077 [18] for the calculation of the single-number ratings. Reverberation time and background noise measurements were also carried out. The average reverberation time measured at 6 different positions inside the module is given in Figure 5, where a large variation can be noticed in the low frequencies below 100 Hz and, to a smaller extent, between 200 Hz and 500 Hz.

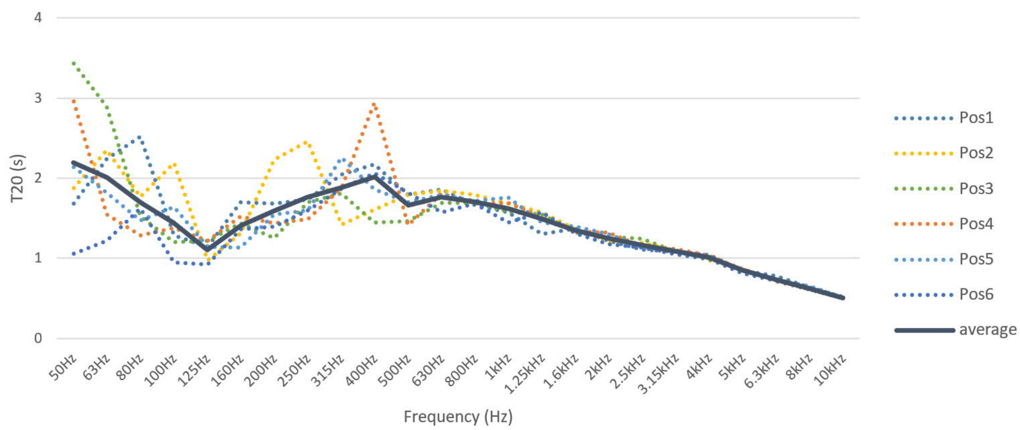

Figure 5. Reverberation time averaged from 6 source-receiver positions

The sound insulation measurements are assessed with the single-number ratings in use in the Dutch standards [18] and in the Dutch Building Decree [13]. For the airborne sound insulation, the following ratings are calculated, both for the standard range 100 Hz – 3.15 kHz and the extended range 50 Hz – 5kHz:

- the A-weighted airborne sound level difference $D_{nT;A}$ defined as the weighted standardized level difference $D_{nT;w} + C$, where C is the adaptation term from Spectrum No.1 in ISO 717-1 [16];
- the Characteristic weighted standardized level difference $D_{nT;A;k}$ defined in the NEN 5077 [18] as

$$D_{nT;A;k} = D_{nT;A} - 10 \log\left(\frac{0.16\,V}{T_0\,S}\right) \tag{1}$$

with V the volume of the receiving space (approx. 39 m^3), S the surface of the separating element (approx. 15 m^2 for both arrangements), and T_0 = 0.5 s the reference reverberation time. In these tests, the $D_{nT;A;k}$ is 1 dB higher than the A-weighted airborne sound level difference $D_{nT;A}$.

For the impact sound insulation, the following ratings are calculated for the range 100 Hz – 3.15 kHz:

- the weighted standardized impact sound pressure level $L_{nT;w}$ defined in ISO 717-2 [17].
- the A-weighted impact sound level $L_{nT;A}$ defined in the NEN 5077 [18] as

$$L_{nT;A} = 10 \log \sum_{i=1}^{N} 10^{L_{nT,i}/10} - 15 \tag{2}$$

with $L_{nT,i}$ the standardized impact sound pressure level at third-octave-band i and $N = 16$.

3.1 Measurement results for the vertical arrangement

The measured airborne sound insulation of the vertical arrangement is given on the left side of Figure 6 in terms of standardized level difference D_{nT}. The results are given for both upward (sound source in the bottom module) and downward (sound source in the top module) directions. For the upward direction, measurements have been performed also without the mineral wool in the cavity, except around the edges.

The measured impact sound insulation of the vertical arrangement is given on the right side of Figure 6 in terms of standardized impact sound pressure level L_{nT}. The results are given for the standard configuration as well as without the mineral wool in the cavity, except around the edges. In addition, measurements have been performed with a different type of floating floor, comprising of two 18 mm plates (>1200 kg/m^3) separated by a 20 mm dense mineral wool layer (the floating floor was replaced only at the measuring locations). The tapping machine was placed in the top module.

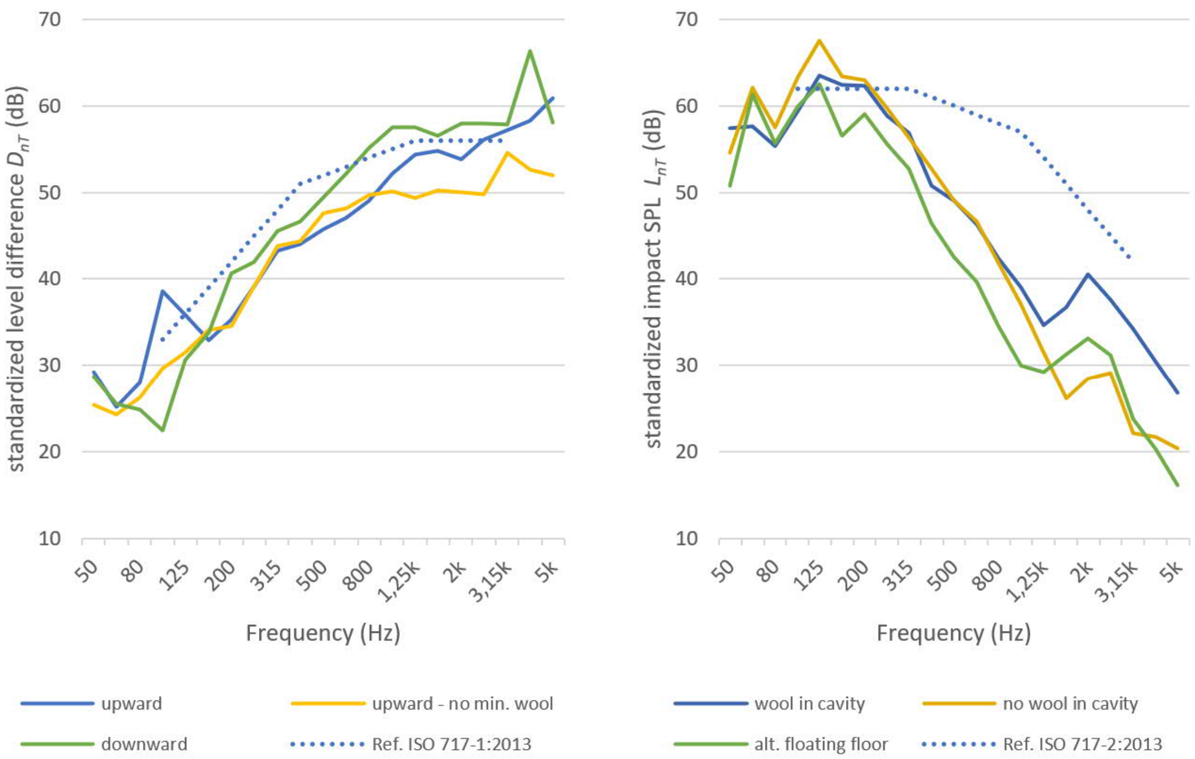

Figure 6. Measured airborne (left) and impact (right) sound insulation for the vertical arrangement

Table 2 below shows the single-number ratings for airborne and impact sound insulation in the vertical arrangement. The $D_{nT;A;k}$ is 1 dB higher than the A-weighted airborne sound level difference $D_{nT;A}$.

Table 2. Single-number ratings for airborne and impact sound insulation in the vertical arrangement

	description	**$D_{nT;A}$ [dB] 100-3150 Hz**	**$D_{nT;A}$ [dB] 50-5000 Hz**	**$L_{nT;w}$ [dB] 100-3150 Hz**	**$L_{nT;A}$ [dB] 100-3150 Hz**
1	Upwards, with mineral wool in cavity	48	48	-	-
2	As 1, without mineral wool in cavity	47	46	-	-
3	Downwards, with mineral wool in cavity	48	47	-	-
4	Downwards, with mineral wool in cavity	-	-	54	54
5	As 4, without mineral wool in cavity	-	-	55	56
6	As 5, with alternative floating floor	-	-	51	52

3.2 Measurement results for the horizontal arrangement

The measured airborne sound insulation of the horizontal arrangement is given on the left side of Figure 7 in terms of standardized level difference D_{nT}. The results are given for the standard configuration as well as without the mineral wool in the cavity, except around the edges. Measurements have been performed also for an increased cavity of approximately 60 mm, without the mineral wool in the cavity except around the edges.

The measured impact sound insulation of the horizontal arrangement is given on the right side of Figure 7 in terms of standardized impact sound pressure level L_{nT}. The results are given for the standard configuration as well as without the mineral wool in the cavity, except around the edges. In addition, measurements have been performed for an increased cavity of approximately 60 mm, without the mineral wool in the cavity except around the edges.

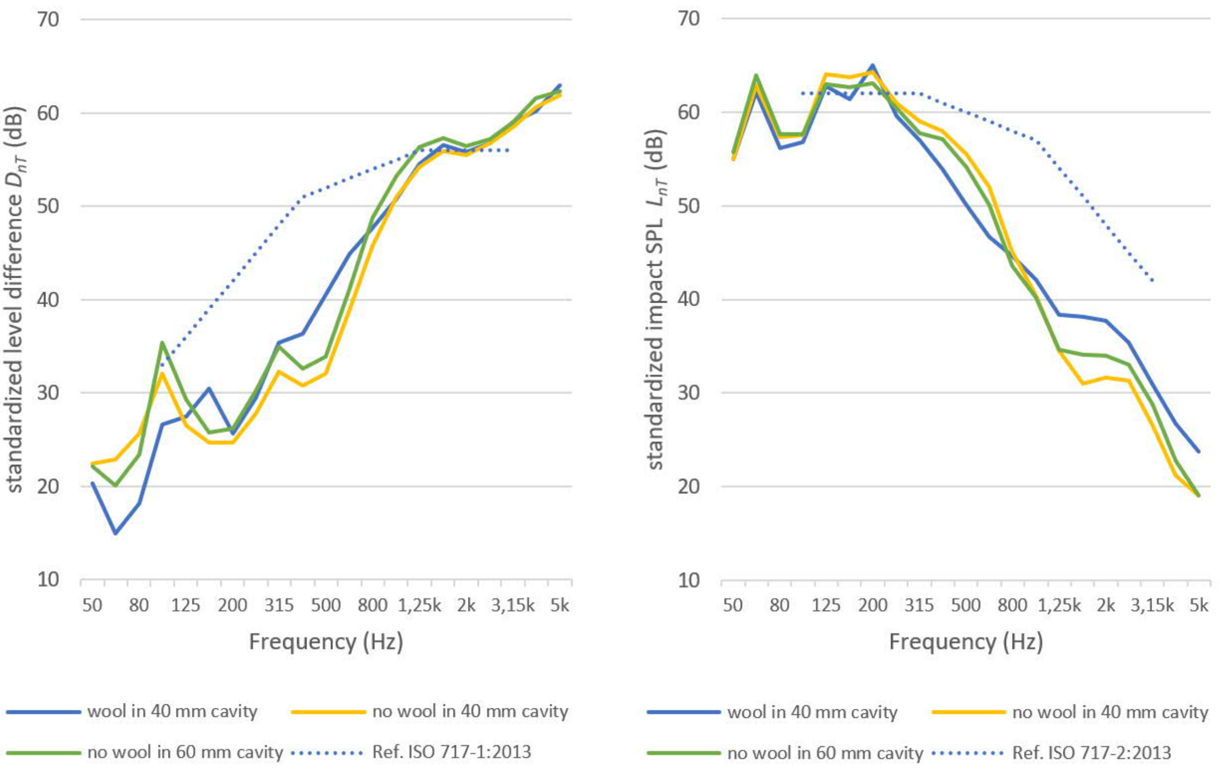

Figure 7. Measured airborne (left) and impact (right) sound insulation for the horizontal arrangement

Table 3. Single-number ratings for airborne and impact sound insulation in the horizontal arrangement

	description	$D_{nT;A}$ [dB] 100-3150 Hz	$D_{nT;A}$ [dB] 50-5000 Hz	$L_{nT;w}$ [dB] 100-3150 Hz	$L_{nT;A}$ [dB] 100-3150 Hz
1	Standard, with mineral wool in 40 mm cavity	42	42	54	54
2	As 1, without mineral wool in 40 mm cavity	38	39	55	56
3	As 2, without mineral wool in 60 mm cavity	40	41	54	55

4 Discussion

The modules are originally intended to be used as a hotel function. Even though no requirement is generally set by law for sound insulation in a hotel, the acoustic comfort of the guests is very important. This means that the speech and noise produced by other guests in the next room or the noise of footsteps in the room above should be sufficiently attenuated not to create a disturbance.

4.1 Vertical arrangement

Measurement results in the vertical arrangement given in Figure 6 show the positive effect of adding mineral wool in the cavity created by the floor and the ceiling CLT panels. This effect is more visible in the low frequency region of the cavity resonances and in the higher frequencies. To be noticed is the difference in sound insulation performance between the *upwards* and *downwards* setup. Even though the $D_{nT;A}$ values are the same, the sound insulation curves present quite some differences. These are likely due to the large difference in weight and stiffness of the floor and ceiling panels (and partially to the large reverberation time variations at low frequencies). Also noticeable is the relatively large effect of replacing 9 mm felt with 20 mm mineral wool as the resilient layer of the dry floating floor, with an improvement of 4 dB in the standardized impact sound pressure level.

From the measurement results in the vertical arrangement it can be concluded that the ceiling-floor system of the prototype modules reaches a good level of airborne and impact sound insulation thanks to a total mass of around 200 kg/m^2 and the combination of mineral wool in the cavity and as the resilient layer of the dry floating floor. From the graph no evident negative influence of flanking noise through the steel elements is noticed.

4.2 Horizontal arrangement

Measurement results in the vertical arrangement given in Figure 7 show a more complex behavior of the airborne sound insulation at low and mid frequencies. The reason is likely due to the low weight of the 80 mm wall CLT panels, which results in a relatively low sound insulation below 250 Hz. The degraded performance below 100 Hz for the configuration with mineral wool in the cavity is probably a result of the high degree of compression of the wool mats. The left graph also shows a 2 dB increase in airborne sound insulation over the whole frequency spectrum as a result of the slight increase of the distance between the modules. Regarding the impact sound insulation in the horizontal arrangement, a small positive effect of an increase of the distance between walls and the use of mineral wool within can be seen in the right graph of Figure 7.

From the measurement results in the vertical arrangement it can be concluded that the wall-wall system of the prototype modules is capable of reaching a good level of airborne and impact sound insulation with a rather small total thickness and without lining. It is, however, acknowledged that the total weight of the partition wall is not sufficient to provide the right level of acoustic comfort against speech and other noises that may occur in a hotel room, for which additional measures are suggested (see the following paragraph). From the graph is difficult to distinguish any influence of flanking noise through the steel elements. Measurements obtained with an accelerometer suggest that the transmission through the columns and the steel connections provide good dampening except at low frequencies (between 50 Hz to 80 Hz). This aspect is left for future investigation.

4.3 Possible use in buildings with residential function

Given the increasing housing demand in The Netherlands, it is here discussed whether the CLT modules under study could be used in residential buildings. The Dutch Building Decree [12] states well-defined acoustic requirements for new buildings, given in Table 4. Requirements are given for residential spaces, such as partitions between two apartments, and non-residential spaces within a residential building, such as corridors. In addition, less stringent requirements (with a difference of 10 dB) are given for residential buildings intended for a time-limited use (up to 15 years).

Table 4. Requirements for airborne and impact sound insulation in the Dutch Building Decree (2012)

Bouwbesluit (2012)	$D_{nT;A;k}$ [dB]		$L_{nT;A}$ [dB]	
	residential spaces	non-residential spaces	residential spaces	non-residential spaces
New construction	≥ 52	≥ 47	≤ 54	≤ 59
Temporary construction	≥ 42	≥ 37	≤ 64	≤ 69

From the comparison of Table 4 with Table 2 and Table 3, it is concluded that, in order to be able to use these modules in new constructions with residential function, some additional measures are required, especially in the wall-wall system. The current setup of these modules could be used for temporary buildings with a maximum lifespan of 15 year.

From the measured situation in the vertical arrangement, a characteristic weighted standardized level difference ($D_{nT;A;k}$) of 49 dB and an A-weighted impact sound level ($L_{nT;A}$) of 54 dB are calculated. The airborne sound insulation requirements for a residential function are not met. Possible solutions are the use of a thicker ceiling panel and a slightly larger cavity. A suspended sound absorbing ceiling is also an option.

From the measured situation in the horizontal arrangement, a characteristic weighted standardized level difference ($D_{nT;A;k}$) of 42 dB and an A-weighted impact sound level ($L_{nT;A}$) of 54 dB are calculated. The airborne sound insulation requirements for a residential function are not met. In this case, more drastic measures are necessary. Given the insufficient performance of the wall at low frequencies, both weight and thickness must be increased. It is expected, however, that a double-leaf wall with reasonable dimensions without any lining will not achieve the required sound insulation. Therefore, the use of a timber or metal frame construction with heavy plating is most likely required. It is also possible that, to achieve high sound insulation, a resilient layer should be added at the point of connection of the steel elements. This is left for future research.

In order to use the modules in residential buildings and to achieve a satisfying level of acoustic comfort, it is also important to consider sound insulation at frequencies below 100 Hz, which is known to be prone to large variations [10,19]. In the fully assembled situation, other aspects should be taken into consideration, such as the flanking transmission path through the connections of the modules with the central steel core, which was not present in the measured situation, and the higher load in the vertical direction, which may present small variations in the sound insulation curves compared to the measured situation with only two modules.

5 Conclusions

In this paper, the results of sound insulation measurements performed on a pair of CLT prototype modules have been shown. These modules use a novel connection system which create a load-bearing columns when modules are stacked on top of each other by means of steel connectors embedded in the CLT floor panel. Such a system creates a double-leaf partition between two adjacent modules, both in the horizontal direction (wall-wall) and in the vertical direction (floor-ceiling), with the steel connection representing the only acoustic coupling. Airborne and impact sound insulation measurements in both directions have shown that the current prototype is providing good levels of sound insulation in the vertical direction and an average performance in the horizontal direction. It was also discussed whether the current system can achieve the level of airborne and impact sound insulation required by the Dutch Building Decree (2012) for residential buildings. Measurement results have shown that limited additional measures are necessary for the floor-ceiling system, whereas more drastic measures are needed for the wall-wall partitions.

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