Validation of prediction tools and constructions – grouping, verification measurements and trend analysis

Anders Homb
Catherine Guigou-Carter
Klas Hagberg
Moritz Späh
Heinz Ferk

Report no STB02 WG2
RISE report 2017:57

RISE Research Institutes of Sweden AB

RISE rapport 2017:57
ISBN: 978-91-88695-24-6
Göteborg

Table of Contents

1. Introduction

This report comprises results from Work Package 2 (WP 2) within the European Wood Wisdom Net+ research project "Silent Timber Build" (www.silent-timber-build.com). The title of WP 2 was – "Validation of prediction tools and constructions" and the aim was to validate the theoretical models developed in WP 1 by using already available and also new measurements from laboratory and field. Analysis have been made and optimized constructions was used in validation procedure. Hence the input from WP 2 is of major importance to make sure that the models (the software SEA Wood and assumptions in the FEM modelling) are correct in their predictions for various structural elements and assemblies.

The report includes an overview of different floor assemblies used all over Europe. They have been selected and evaluated carefully and from that the floor assemblies are divided into different groups in order to fit to limit the number of possible setups. Hence the grouping is made in a manner that will facilitate modelling of floor assemblies using the different methods as developed within this project, Silent Timber Build. It can also be used in order to recommend different floor assemblies for different buildings and usage. The software that has been used and further developed within this project is a French software adapted to wooden building floor and wall components, "SEA Wood". In addition FEM software is used in order to improve and verify the results particularly in the low frequencies, which is of particular interest for structural solutions in wood.

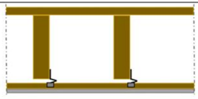
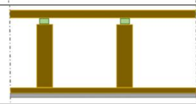
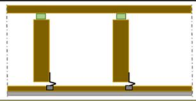
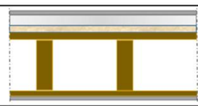
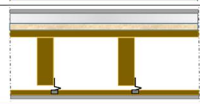
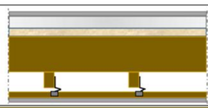
The grouping is made out of existing typical floor assemblies measured in various laboratories. The results are compared and from that a grouping is made out of different aspects as shown in table 1 below. The floor structures are normally built up from joists or homogeneous CLT elements. These two main groups can also be completed with screed and then they are denoted as hybrid floor assemblies (joists or CLT). All in all there are four main groups. There are other odd types existing however they might fit in to one of the groups below. Then there are a number of subgroups as displayed in table 1 below, within each of the main group; that is denoted with different combination of letters.

1. FS = Floor with stiff connection to the main structure (or no floor above the structure)
2. FR = Floor with resilient connection to the main structure
3. CS = Ceiling with stiff connection to the main structure (or no ceiling below the structure)
4. CR = Ceiling with resilient connection to the main structure
5. CN = Ceiling with no connection to the main structure

Using this grouping it is possible to see some important patterns between the single number ratings and the floor assembly mass per unit area (*mpua*). These grouping results is of big importance for any probability estimation of calculated results not least using the methods developed within this project. They cannot be used for exact verification but at least to secure that calculated results are in the correct single number range, e.g. reducing the risk for mistakes in calculation complex structures.

The grouping and a trend analysis connected to that is also presented and published in a scientific paper [10].

Table 1: Main groups and subgroups as they are used for the summary in this report. In the cases where pictures are missing, it implies that there is no results within this report but they might exist in reality.

Floor Assembly group	Name	Assembly	
Group A	Wood Joist	FS-CS	
		FS-CR	
		FS-CN	
		FR-CS	
		FR-CR	
Group B	Hybrid Wood Joist	FS-CS	
		FS-CR	
		FR-CS	
		FR-CR	
Group C	Massive wood	FS-CS	
		FS-CR	
		FS-CN	
		FR-CS	
		FR-CR	
Group D	Hybrid Massive element	FR-CS	
		FR-CR	

This report also comprises results from a setup of measurements in the laboratory in IBP in Fraunhofer in Stuttgart. The series of measurements were selected during a project meeting held in Trondheim in April 2016. They were mounted in the laboratory by one of the project partners (Bauer Holzbau in Germany) and measured during summer 2016. The results were used to calibrate the theoretical model and the comparisons between the measured value and the calculated results are presented in report from WP 1.

In the final chapter a trend analysis is described The trend analysis is carried out in order to create basis for engineers to compare predicted values with expected values for various assemblies to make a qualified probability evaluation for the predicted values.

2. Data collection - Wooden joist floor assemblies

In the following chapter, typical timber floor assemblies for residential buildings will be presented. The data collection presented in this section concentrates mainly on typical national solutions from various European countries, divided into different groups depending on structural differences. The grouping of constructions has been based on work in the Silent Timber Build project, see Homb [10]. Floor assemblies presented in chapter 2 are the following main types according to the grouping:

- Construction group A: Wooden joist floor assemblies
- Construction group B: Hybrid wooden joist floor assemblies with gravel or concrete

From the participating countries, quite different solutions are found but also in some cases there are identical constructions when considering the principal solutions given by the grouping of the constructions. Due to traditions, it is not surprising that many of the same solutions are found in Sweden and Norway, however also in France similar floor assemblies are detected. Also due to traditions, Switzerland and Germany are often using a combination of concrete and wood. Therefore, such solutions dominate the findings when we collect laboratory measurement data from these countries. Even if France has some floor assemblies similar to Scandinavia, they are also using a combination of concrete on various wooden joist solutions.

2.1 Construction group A: Rigidly connected top floor and stiff suspended ceiling

A principal drawing of a typical French solution with stiff top floor and a suspended ceiling with stiff connections is presented in Figure 2.1. Wooden joist constructions have not been very common in residential buildings in France, and therefore more simple solutions, based on a stiff top floor solution of chipboards rigidly connected to the beams have been used, i.e. falling within the group A constructions. These solutions typically has a ceiling solution based on steel suspension products, often non-spring types (however resilient systems occur, see subsequent sections). The solution as described above is in the following coded as FS-CS solutions (stiff top floor and stiff suspended ceiling). In Norway and Germany, results from FS-CS solutions are also available, but then typically with the plasterboard in the ceiling mounted on laths rigidly connected to the wooden joists.

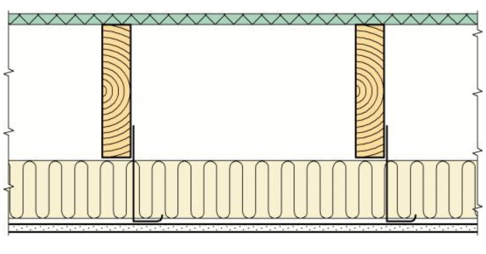


Figure 2.1 Common types of French wooden joist constructions type A, FS-CS

Laboratory measurement results of wooden floor constructions with stiff top floor and stiff suspended ceiling are presented in figure 2.2. Even if the material specification may vary, it is an impressive correlation between measurements from Germany and Norway. The French measurement deviates with more than 10 dB from German and Norwegian (to the better), but this solution cannot be considered as equal with the others. The reason for this is the use of a ceiling (stiff suspended but) based on steel furring channels (rather than wood battens for the German and Norwegian systems). Such solutions will of course reduce the sound radiated from the ceiling due to some resiliency. The measurement curve therefore verifies the effect of this suspension, with result similar to solutions with resilient steel profiles as presented in figure 2.4.

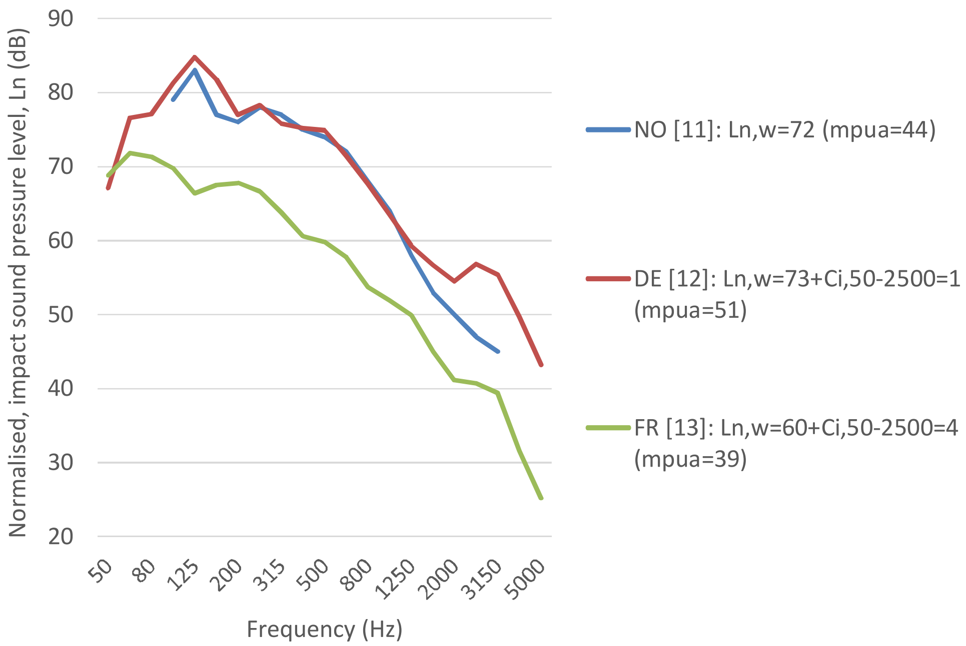


Figure 2.2 Measurement results from construction type A, FS-CS

Results in figure 2.2 shows that construction type FS-CS present high similarities in the frequency domain, but also a clear effect of mounting details and sound radiation from the ceiling.

2.2 Construction group A: Rigidly connected top floor and resilient suspended ceiling

A principal drawing of a typical solution from the Nordic countries with stiff top floor and resilient suspended ceiling is presented in Figure 2.3. Due to previous requirements in building regulations, in Norway for instance, it was common to use rigidly connected top floor solutions with resilient ceiling comprising two layers of gypsum, coded as FS-CR solutions. Due to sound insulation requirements the major choice has always been to use solutions based on resilient profiles for the mounting of the ceiling.

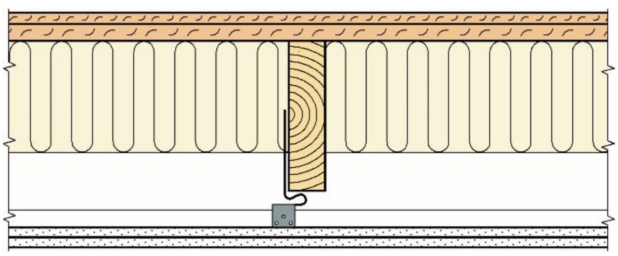


Figure 2.3 Common types of former Norwegian wooden joist constructions type A, FS-CR

Laboratory measurement results of floor constructions with stiff top floor and resilient suspended ceiling are presented in figure 2.4. In figure 2.4a, results are given for solutions with mass per unit area (mpua) below approximately 50 kg/m^2. The results deviate considerably in the frequency range below approximately 160 Hz and above 1600 Hz. The deviation in the high frequency range is not of importance since it depends very much on the softness of the floor covering and the fact that the impact sound insulation anyway is “good enough” in this frequency range. The deviation in the low frequency range needs to be investigated, due to a significant increase (more than 2 to 3 dB) of the $L_{n,w}$+$C_{I,50\text{-}2500}$ value. A hypothesis is an effect of the joist and floor stiffness and modal behaviour. In the middle part of the frequency range, the result seems to correlate well with the mpua. This effect is also clearly shown in figure 2.4b.

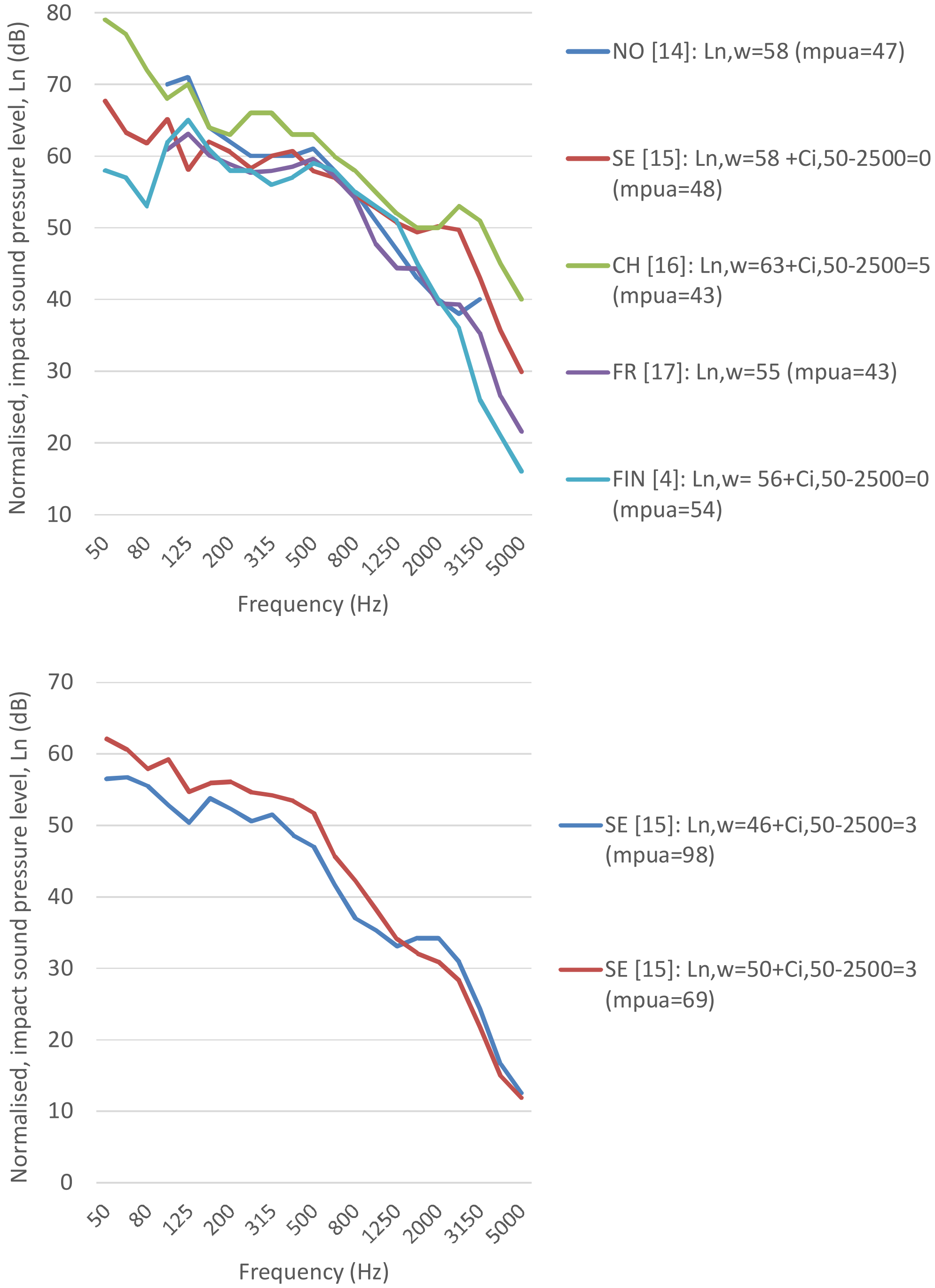


Figure 2.4 Measurement results from construction type A, FS-CR

Results presented in 2.4 show that construction type FS-CR generally present low similarities in the frequency domain, especially at low frequencies. This deviation is probably caused by floor stiffness and modal behavior.

2.3 Construction group A: Rigidly connected top floor and independent ceiling

A solution with rapidly increased market share has been module based solutions, principally based on a ceiling structurally independent from the joist floor in the upper section. For such solutions, floating floor on mineral wool products is rarely used. But, due to flanking transmission from the lightweight load bearing walls, it has been common to use vibration insulation products between the modules vertically, either point elastic solutions or line elastic solutions. But, due to the concept of complete 3D solutions, it is not possible to find laboratory measurements with the separate constructions itself. In the following, we code this as FS-CN solutions (no coupling between beams and ceiling construction). Example drawings of this construction type are presented in Figure 2.5.

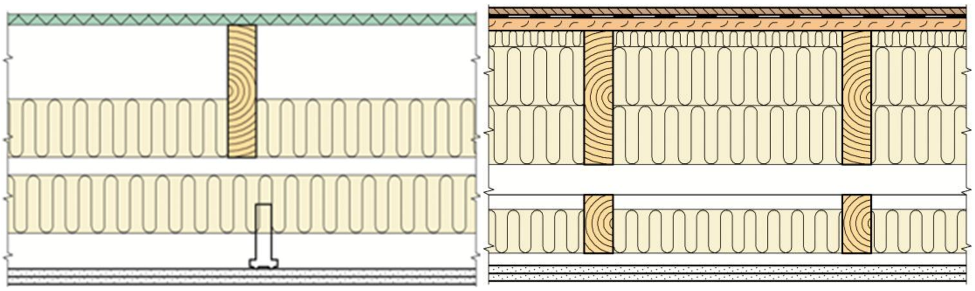


Figure 2.5 Common types of solutions with fully independent ceiling, type A, FS-CN. Left figure: example from France. Right figure: example from Norway

Laboratory measurement results of floor constructions with rigidly connected top floor and a ceiling, structurally independent from the loadbearing joist construction, are presented in figure 2.6. The results show a relative good correlation between the different measurements in the whole frequency range below approximately 1250 Hz. The deviation in the low frequency range seems to correlate with the mass per unit area. Different softness of the floor covering probably explains the deviations in the high frequency range.

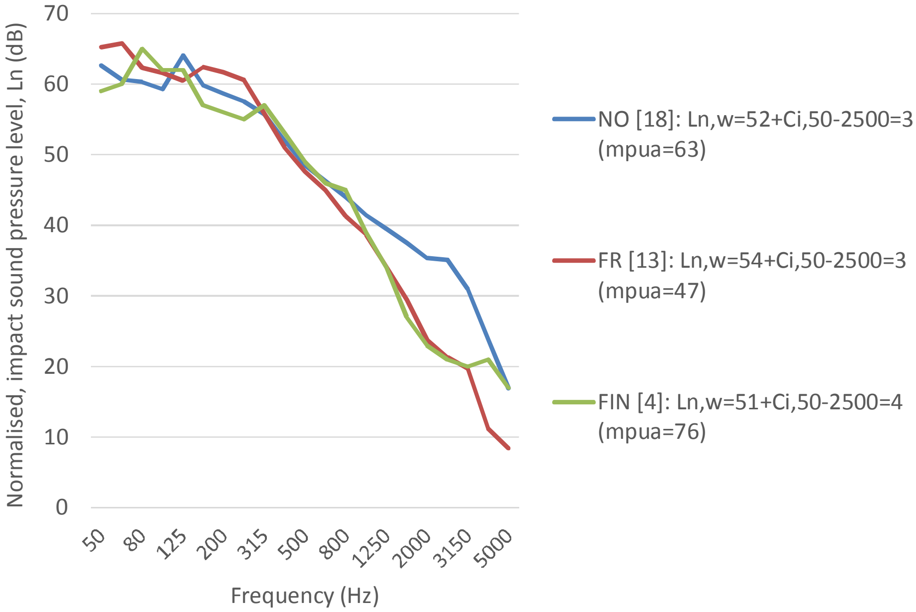


Figure 2.6 Measurement results from construction type A, FS-CN

2.4 Construction group A: Resilient top floor and stiff suspended ceiling

Examples and measurement results also exist regarding lightweight floors with a resilient top floor and rigidly connected plasterboards at ceiling. These solutions are in the following coded as FR-CS solutions (resilient top floor and stiff suspended ceiling), see example in figure 2.7.

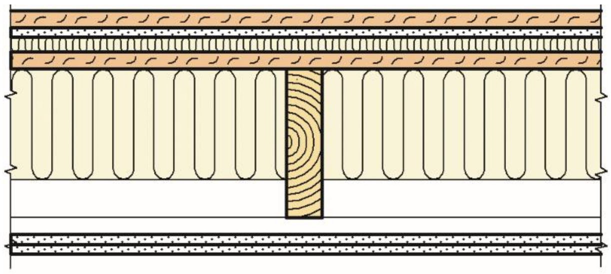


Figure 2.7 Lightweight solution with resilient top floor and rigidly connected plasterboards at ceiling type A, FR-CS.

Laboratory measurement results of floor constructions with this FR-CS solution are presented in figure 2.8.

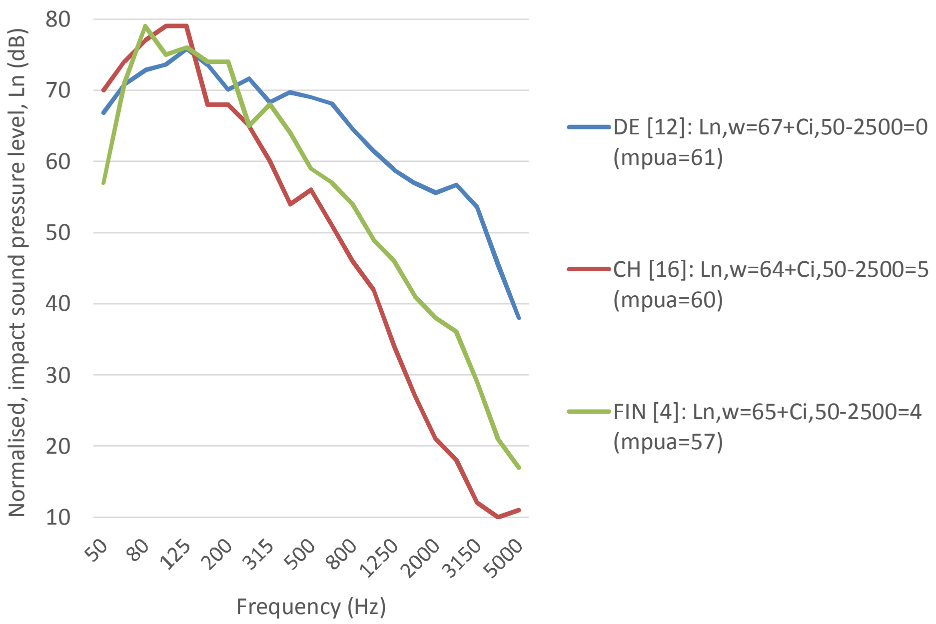


Figure 2.8 Measurement results from construction type A, FR-CS

The results show deviation of 5 to 10 dB between the curves in the most important frequency range below 400 Hz even if the mass per unit area is comparable. This might be caused by different frequencies of the resilient top floor layer, causing resonance peaks at different frequencies between 50 and 125 Hz due to different dynamic stiffness of the resilient layer. Another reason is the ceiling solution details and sound radiation from the ceiling. This probably explains huge deviations in the high frequency range, but this is of minor importance with respect to the single number quantity of $L_{n,w}+C_{I,50\text{-}2500}$ and the subjective annoyance of such floors.

2.5 Construction group A: Resilient top floor and resilient suspended ceiling

In the Nordic countries, the major choice of floor constructions within the last 10 to 15 years has been the use of solutions based on resilient profiles in the ceiling and in addition a resilient top floor solution. Different types of steel springs or resilient steel channels have been mounted underneath the timber beams. At the top of the floor, a floating floor on top of mineral wool products with a certain limit of dynamic stiffness have been most common. These solutions are coded as FR-CR solutions (resilient floor and resilient ceiling). A principal drawing of this construction type is presented in figure 2.9.

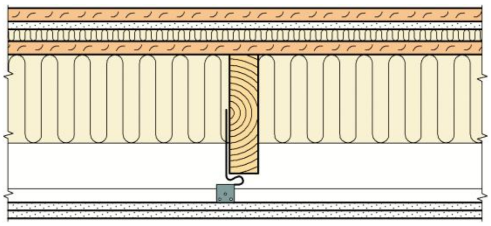


Figure 2.9 Common types of Norwegian wooden joist constructions type A, FR-CR

Laboratory measurement results of floor constructions with resilient top floor and resilient suspended ceiling are presented in figure 2.10. The results show some deviation of up to approximately 10 dB between the curves in the whole frequency range below 400 Hz, but with respect to the single number quantities, the maximum difference is $L_{n,w}+C_{I,50\text{-}2500}$ = 6 dB. The results correlate to some degree with the mass per unit area, as shown by curve SE-03 with the highest mass per unit area and lowest single number quantity. With increasing number of layers, resilient products and a numerous possible combinations of sheet layers, it is not surprising that such spreading will occur. But it is important to investigate the deviations between the different solutions in the low frequency range, due to the necessity to limit the sound pressure level in the low frequency range and optimize solutions. Such investigations should at least include the joist and floor stiffness in combination with the effect of the resilient top floor behaviour.

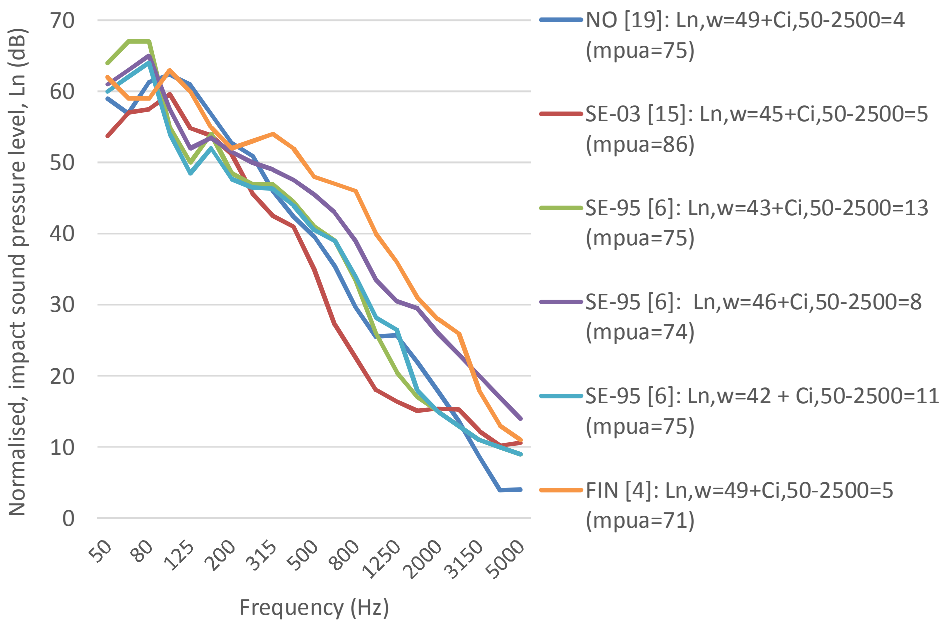


Figure 2.10 Measurement results from construction type A, FR-CR

Generally, the results presented in figure 2.10 show relatively low similarities in the frequency domain. This means that the involved resilient products, combined with other construction details, have a major influence of the impact sound insulation properties in a broad frequency range.

2.6 Construction group B: Rigidly connected top floor and stiff suspended ceiling

Due to traditions, Switzerland and Austria are often using a combination of concrete and wood. Therefore, such solutions dominate the findings when we collect laboratory measurement data from these countries. One typical solution is in the following coded as FS-CS solutions (Rigidly connected top floor, added mass, and stiff suspended ceiling), is shown in figure 2.11.

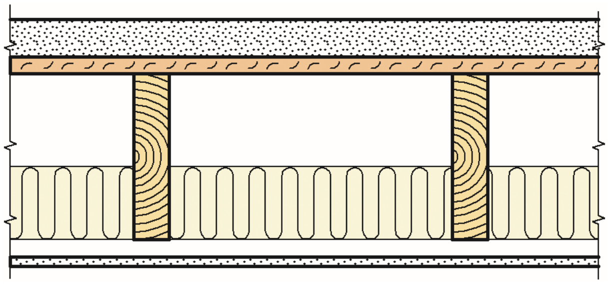


Figure 2.11 Hybrid solution with rigidly connected (added mass) top floor and stiff suspended ceiling, type B, FS-CS.

Laboratory measurement results of wooden floor constructions with rigidly connected top floor, added mass, and suspended ceiling with stiff connections from Germany and France are presented in figure 2.12.

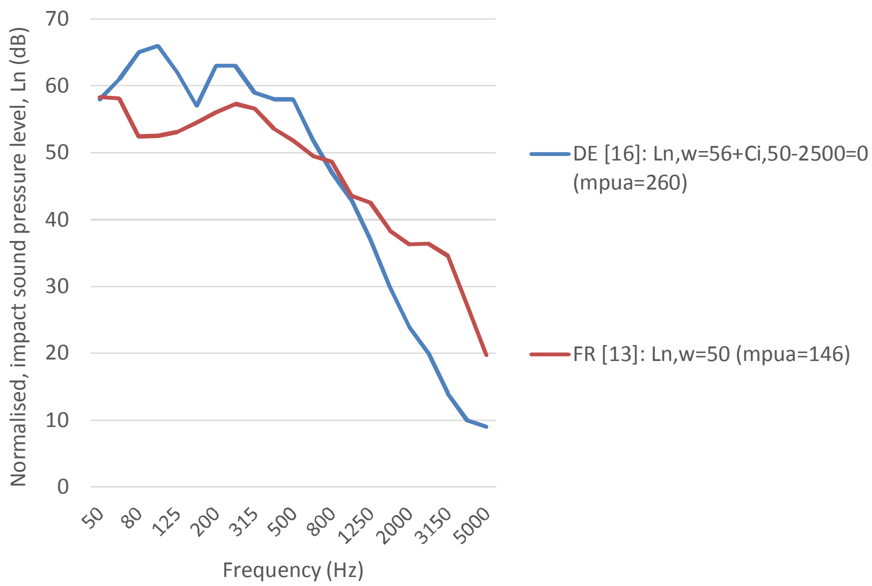


Figure 2.12 Measurement results from construction type B, FS-CS

In the frequency range between 160 and800 Hz, the deviation between the curves appears to be relatively small. But in fact, it is a huge difference regarding the mass per unit area (mpua). The results therefore show a small effect of the relatively high mpua of the DE case [16], but a huge effect of the suspended ceiling system of the FR case [13]. As mentioned before, the sound pressure level in the receiving room is sensitive to the connections used (semi-resilient or stiff) and radiated sound can vary even if the suspended ceiling is classified as stiff here.

2.7 Construction group B: Rigidly connected top floor and independent ceiling

Laboratory measurement results of floor constructions with stiff top floor, added mass and a ceiling free from the loadbearing joist construction are presented in figure 2.11. This solution is in the following coded as FS-CN solutions (stiff top floor and fully independent ceiling).

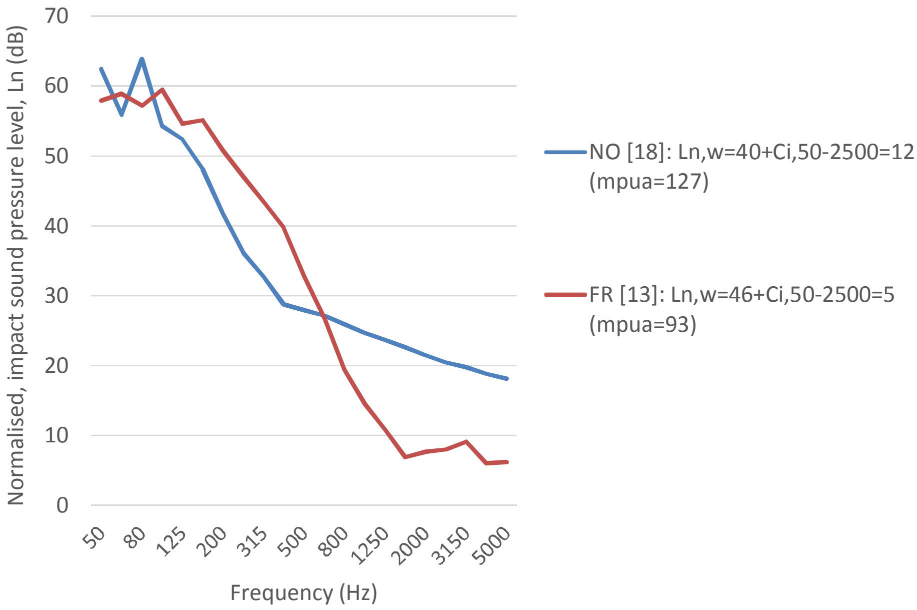


Figure 2.13 Measurement results from construction type B, FS-CN

The results presented in figure 2.11 exhibit low impact sound pressure level due to the independent ceiling construction, except in the frequency range below 100 Hz. Further studies should be focused on prediction of the impact sound insulation when adding masses to these wooden floors.

2.8 Construction group B: Resilient top floor and stiff suspended ceiling

Among the contributing countries in the STB project, it is an increasing interest of adapting solutions developed in Austria and Switzerland, to other European countries. Therefore examples and documentation exist, based on different hybrid timber-concrete composite floor solution (tccf). Examples of construction type B, FR-CS are with gravel or a concrete layer on the sub-floor (plywood/osb panel) or prefabricated concrete elements directly installed on the load bearing joists. In the FR-CS case, the ceiling consist of plasterboard on rigidly fixed laths. Principal drawing of this floor assembly are presented in figure 2.14.

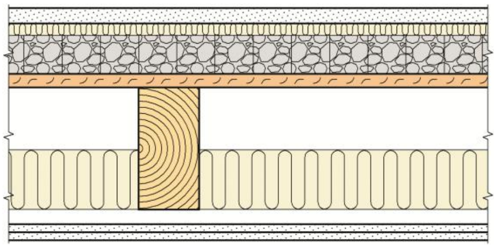
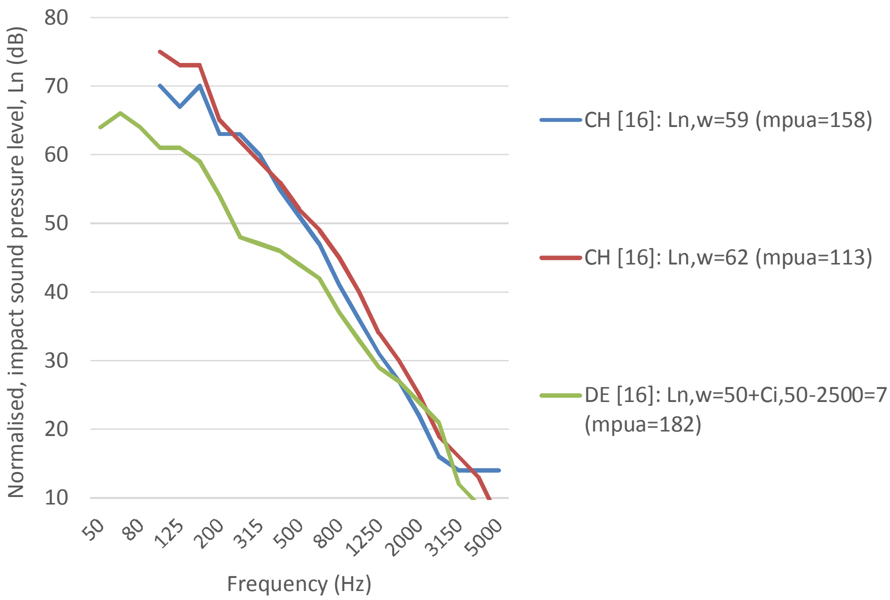


Figure 2.14 Common type of a hybrid floor construction type B, FR-CS with gravel

Laboratory measurement results of floor constructions with a resilient top floor and a stiff suspended ceiling are presented in figure 2.15. The results presented in figure 2.15a (mass per unit area < 200 kg/m^2) show deviation of approximately 5 to 15 dB in the frequency range below 800 Hz. Some part of this deviation is explained by differences of the mpua. Similar to other objects with stiff suspended ceiling, connections and sound radiation from the ceiling may be an important reason for differences between these measurement curves. The results presented in figure 2.15b (mpua > 200 kg/m^2) show deviation of approximately 5 to 20 dB in the frequency range below 630 Hz. But looking into the single number quantity $L_{n,w}$+$C_{I,50\text{-}2500}$, a strong correlation between the mpua and single number quantity is achieved. For these heavy solutions with use of gravel to increase the mass, variations due to the ceiling solution seems to be of minor importance.



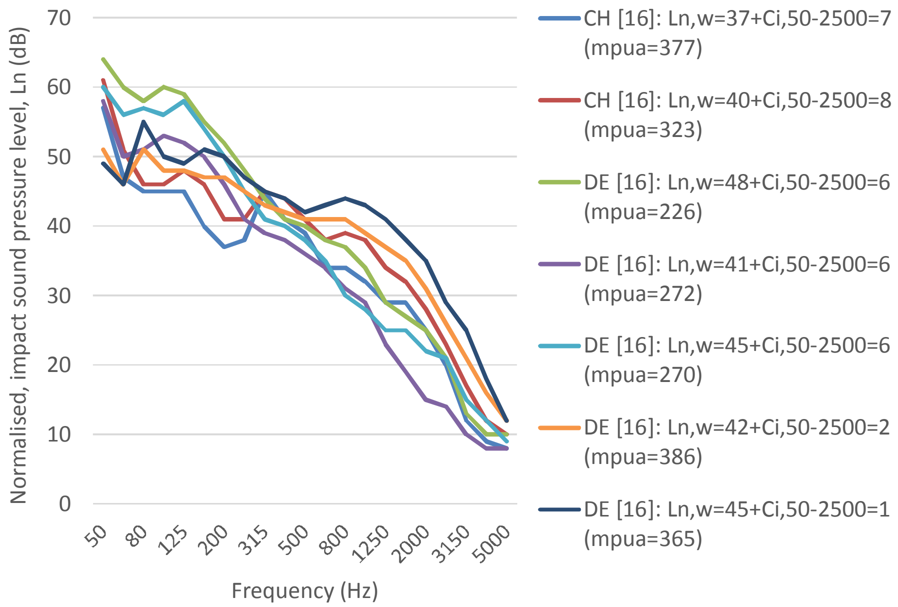


Figure 2.15. Measurement results from construction type B, FR-CS:
a) mass per unit area < 200 kg/m^2
b) mass per unit area > 200 kg/m^2

2.9 Construction group B: Resilient top floor and resilient suspended ceiling

Example of construction type B, FR-CR with resilient top floor and resilient suspended ceiling are presented in figure 2.16. In this case, with the concrete installed above the continuously elastic interlayer and a suspended ceiling on resilient hangers.

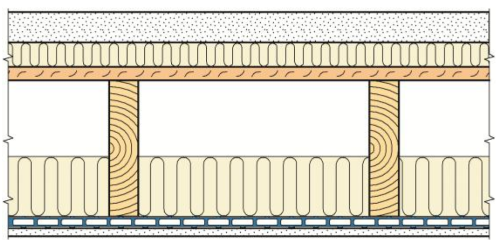


Figure 2.16 Common type of German wooden joist construction type B, FR-CR

Laboratory measurement results of floor constructions with a resilient top floor and a suspended ceiling on resilient hangers are presented in figure 2.17. In the middle frequency range there are significant differences between the NO result from [20] and CH results from [16], see figure 2.15a. A possible explanation is the position of the gravel. The gravel is at a sub-board for the NO case and above chipboard on the wooden beams for the CH cases. The deviation between the two CH cases correlates well with the differences of the mass per unit area in the low frequency range. The results presented in figure 2.15b show a total spreading of 9 dB with respect to the $L_{n,w}+C_{I,50-2500}$, but these variations do not correlate with the mass per unit area levels. The deviation occurs at frequencies below approximately 200 Hz, but it is difficult to point out a reliable explanation of these results. In the NO case from [21], concrete tiles have been installed on a relatively stiff resilient layer, while the concrete screed in the DE case from [16] have been installed on a soft resilient layer. The low impact sound pressure levels for the NO case might be due to small concrete tiles in the floor. In the DE case a sharper peak level at the resonance frequency of the system can be expected compared to the NO case. In the FIN case from Sipari [4], a relatively thin resilient layer may explain poor results in the low frequency range compared to the DE floor with the higher mass per unit area.

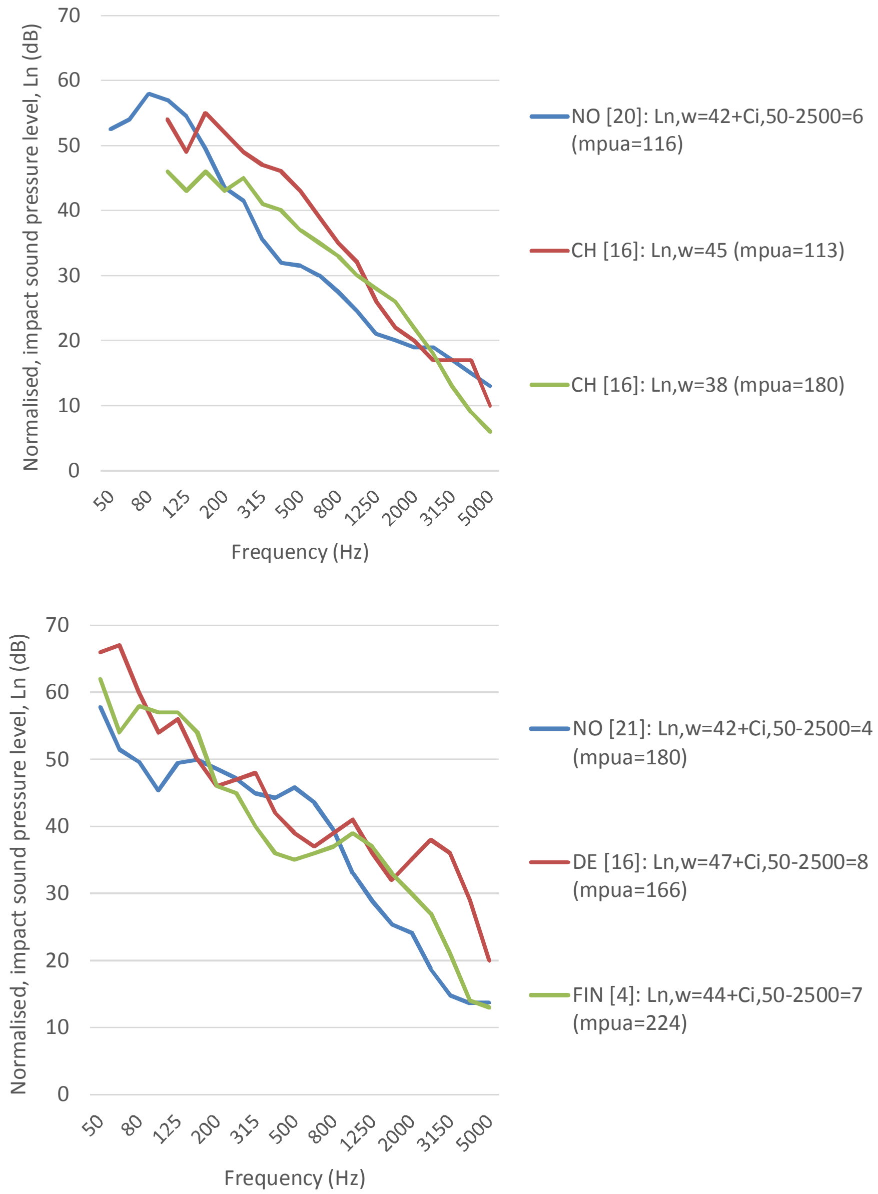


Figure 2.17. Measurement results from construction type B, FR-CR

a) with gravel

b) with concrete/cement casted on top

3. Data collection - CLT/massive wood floor assemblies

In the following section, typical CLT/massive wood floor constructions will be presented. The data collection presented in this section concentrates mainly on typical national solutions, but divided into different types, depending on structural differences. The grouping of constructions have been based on work in the Silent Timber Build project, see [B9]. Floor assemblies presented in this section are the following main types:

Construction group C: Massive wood
Construction group D: Hybrid massive wood elements

I: Single CLT/massive wood floor element
II: Floor assembly with resilient light weight top floor assemblies
III: Floor assembly with suspended or independent ceiling
IV: Hybrid CLT/massive wood constructions with resilient heavyweight top floor
V: Hybrid CLT/massive wood constructions with resilient floor and resilient suspended ceiling

Among the European countries investigated, quite different solutions are found. However, in some cases, solutions correspond to identical or very similar constructions especially when considering the basic solutions given by the grouping of floor construction. It is not surprising that lightweight floor constructions have been a common tradition in the Nordic countries. The use of hybrid solutions using gravel or concrete is more traditional in the German speaking countries. Therefore, such solutions dominate the findings when collecting laboratory measurement data from these countries.

3.1 Construction group C: Basic floor structures

Bare CLT or massive wood structural elements are relatively light and do not exhibit sound insulation properties enough high in order to fulfil some relevant requirement levels. However, they might be useful for single family houses and the knowledge regarding sound insulation properties of the bare elements are important when developing floor assemblies with high performance. Laboratory measurement results of single CLT/ massive structural wood element of type I are presented in figure 3.1. Even if the assemblies vary between CLT, glulam and stacked beams, the similarities in the frequency domain is conspicuous between approximately 100 and 2500 Hz. With respect to the impact sound pressure level, the measurement results seem to vary between different objects and not directly with respect to mpua. In the high frequency range, the impact sound pressure level depends to a high degree on the softness of the contact area between the impact hammer and the material, which is not relevant for the most annoying low frequency walking noise. Further evaluation of the results are given in section 4.

Laboratory measurement results of a CLT structural element with an additional layer of concrete casted directly on top are presented in figure 3.2 together with one glulam type of structural element from figure 3.1. In this case, the concrete has been casted directly (glued) on the CLT element. Similar to standard concrete floors, the impact sound pressure level increases towards higher frequencies, typically according to basic equations in EN 12354-2 [B20] . Regarding the two objects with a concrete layer, the shape in the frequency domain correlates well, but the deviation with respect to the impact sound pressure level at medium and high frequencies is rather high. The reason for this is not investigated. Deviation from a typical curve in the high frequency range is not important because it depends very much on the softness of some floor covering normally applied on the top floor surface. All results presented in figure 3.1 and 3.2 are floor assemblies without a floor covering.

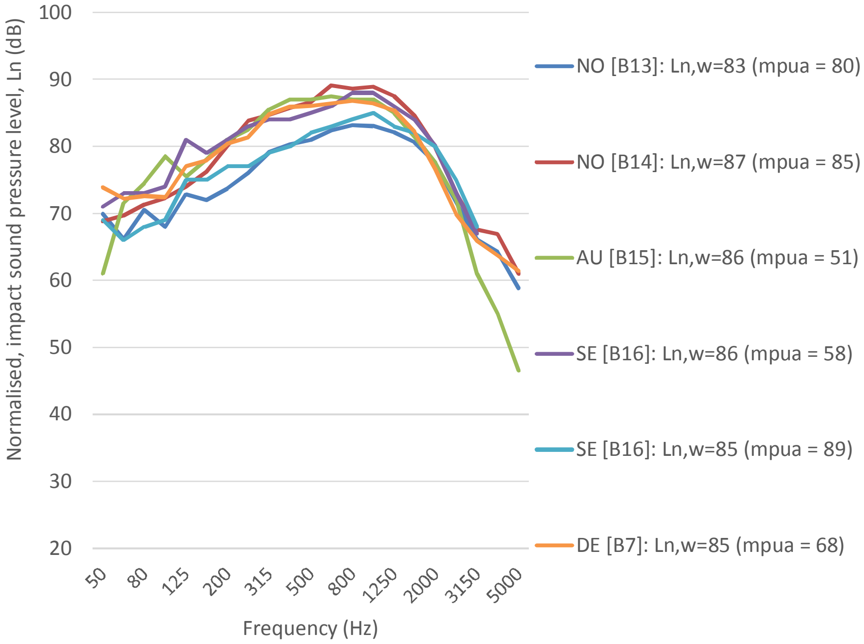


Figure 3.1. Measurement results of construction group C, single CLT/massive wood floor elements (FS-CS)

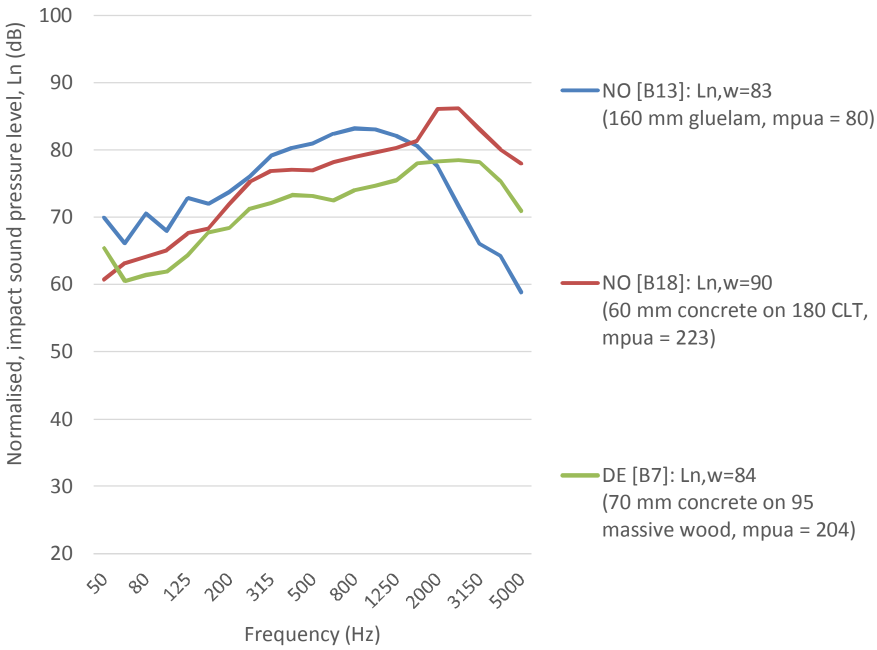


Figure 3.2. Measurement results of construction group C, CLT element with a concrete layer on top (FS-CS)

3.2 Construction group C: Floor assembly with resilient light weight top floor

Examples of lightweight floor assemblies with resilient top floor are presented in figure 3.3 and 3.4. They correspond to type II floor assemblies with different kinds of resilient solutions above the CLT element. The solutions vary between continuous elastic layer (the dynamic stiffness varies), line elastic or point elastic support between the CLT element and the top floor. These are encoded as type II, FR-CS solutions (resilient floor on the wooden element), typically used in Norway. A basic drawing of this construction type using a continuous elastic layer is presented in figure 3.3, and a solution based on line elastic support in figure 3.4.

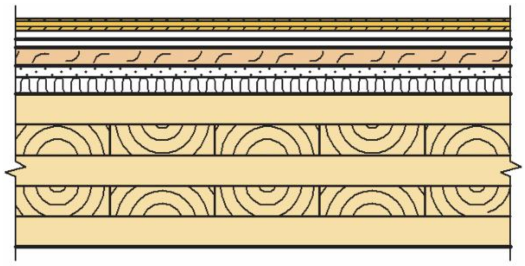


Figure 3.3. CLT wood floor constructions group C, FR-CS with continuous elastic interlayer

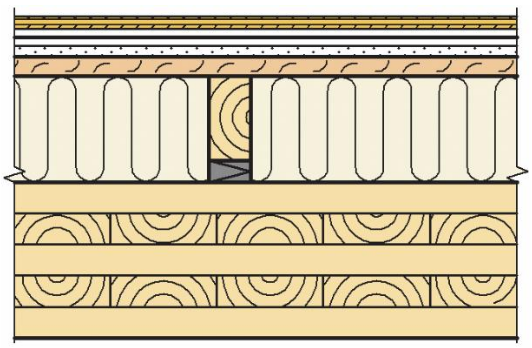


Figure 3.4. CLT wood floor constructions group C, FR-CS with line elastic support

Laboratory measurement results of CLT/massive wood floor element with resilient top floor solutions are presented in the following. Figure 3.5 focuses on type II solutions with some kind of lightweight top floor assemblies, i.e. point elastic, line elastic or continuous elastic interlayer, see figure 3.3 and 3.4. The DE floor assembly corresponds to measurement without a floor covering applied (plastic floor covering or parquet for instance).

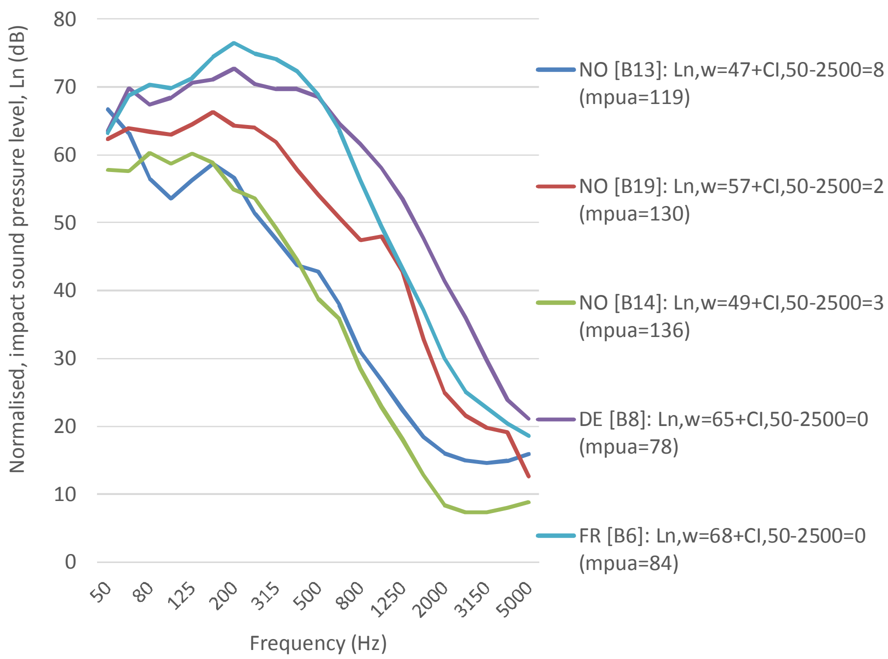


Figure 3.5. Measurement results from constructions with resilient top floor group C, FR-CS

The results show huge differences between the different solutions. Looking into the properties and principles of the assemblies, the results seem logical from an acoustical point of view. In the DE and FR case, the mpua (respectively 78 and 84 kg/m^2) is rather low and the dynamic stiffness of the continuous elastic interlayer rather high. The measurement object from NO (mpua = 130 kg/m^2) is based on a point elastic top floor (also called technical subfloor), product name "Granab". This kind of product has been developed to be installed on a basic floor of concrete. This solution does not give the same improvement when installed on a lightweight and softer element of CLT. Measurement cases NO (mpua =119 and 136 kg/m^2) are based on an optimization of line elastic support with a resilient layer of rock wool. The correlation between these two independent experiments is rather high.

3.3 Construction group C: Floor assembly with suspended or independent ceiling

Generally, the interest of wooden building technique using CLT/massive wood elements are increasing all over Europe. A number of laboratory measurements have therefore been carried out to prepare the construction sector with new possible floor and wall assemblies. There are a huge number of different solutions, amongst those one is to add lightweight building parts, either above the CLT element, below the CLT element or a combination of both. A basic drawing of a typical floor construction with a suspended ceiling from a French study is presented in figure 3.6. This type of floor assembly is in the following coded as group C, FS-CS solutions (corresponding to Floor Stiff – Ceiling Stiff). Common for these solutions is a ceiling solution based on steel suspension products, in this case with very small resiliency (therefore “stiff”). However they also exist with resilient hangers. The ceiling comprises almost always a layer of mineral wool. In the Nordic countries, a solution with the use of a set of separate independent beams for the ceiling, have been used. In the following, this floor assembly is coded as a group C, FS-CN solution (no coupling between CLT element and ceiling construction). A basic drawing of this construction type is presented in figure 3.7.

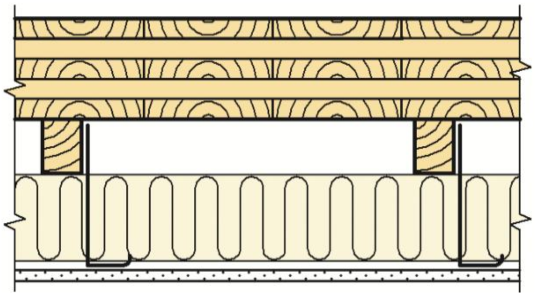


Figure 3.6. Construction group C, floor construction using CLT elements with suspended ceiling with stiff hangers (FS-CS)

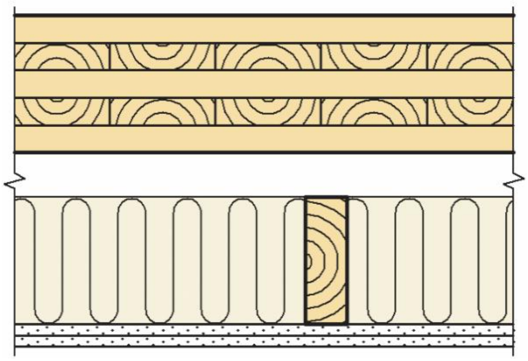


Figure 3.7. Construction group C, CLT floor construction with independent ceiling (FS-CN)

Laboratory measurement results of CLT floor elements with a semi-stiff suspended ceiling or independent ceiling are presented in figure 3.8. The suspended ceiling system (French [FR] objects) is a solution based on steel hangers with low resiliency, with (red curve) and without (blue curve) a soft floor covering (of PVC type) respectively, on top of the CLT element. One laboratory measurement result of a floor assembly with the ceiling decoupled from the loadbearing CLT element is also presented in figure 3.8, in this case there is no additional floor covering on the CLT element (green curve). Hence the measurement corresponds to the floor assembly displayed in figure 3.7.

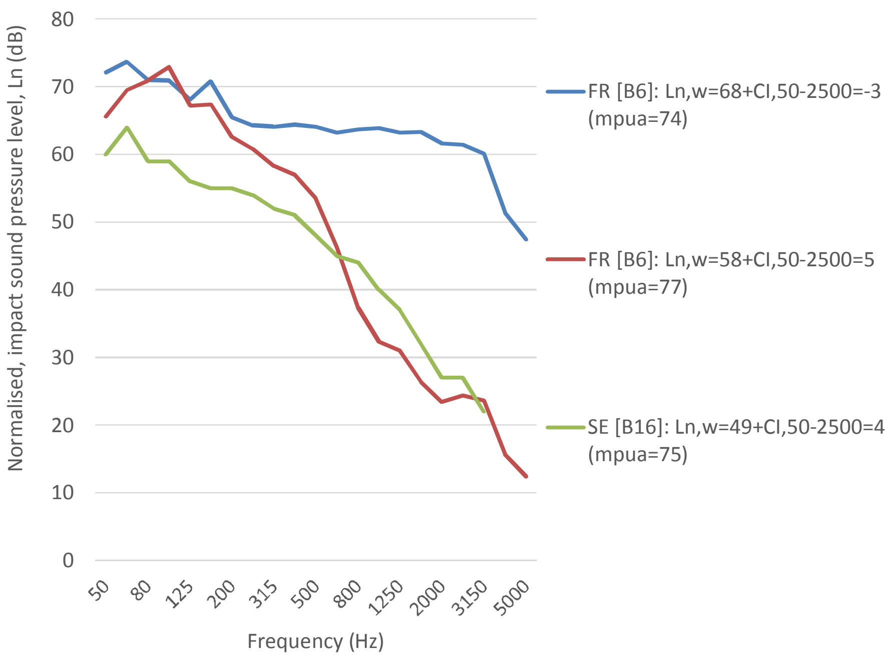


Figure 3.8. Measurement results from construction group C, respectively FS-CS (FR) and FS-CN (SE)

Results presented in figure 3.8 illustrate the challenge to achieve low impact sound pressure levels in the low frequency range with lightweight constructions, which was well achieved by the Swedish construction SE. Even when the ceiling is mechanically decoupled, the limitations in the low frequency range due to low mass of the floor are clearly seen from the measurement curve. The figure also shows limitations due to stiff suspension of the ceiling system, and the huge effect of the soft floor covering at middle and high frequencies.

3.4 Construction group D: Hybrid floor assembly with resilient heavyweight top floor

In Austria, Germany and Switzerland similar floor assemblies with load bearing CLT elements are used. Due to several reasons, a floating floor screed (cement screed on impact insulation material) is often used as resilient top floor solution. Due to the sound insulation requirements, additional mass might be added by applying gravel on the structural CLT element. Basic drawings of these floor assemblies are presented in figure 3.9 and 3.10, respectively with and without a layer of gravel.

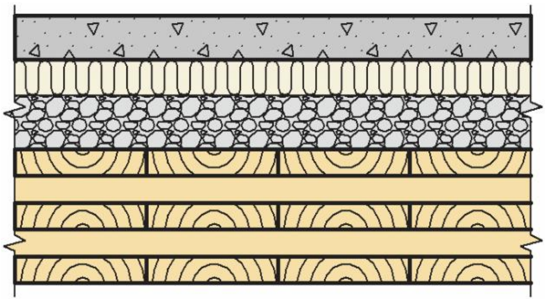


Figure 3.9. Typical construction group D, with resilient top floor with gravel (FR-CS)

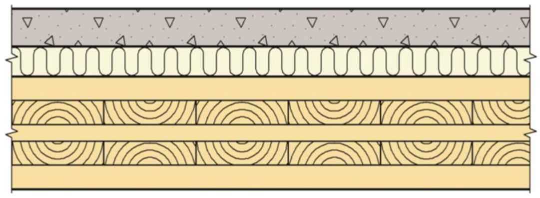


Figure 3.10. Typical construction group D with resilient top floor without gravel (FR-CS)

Figure 3.11 shows results from construction group D solutions with gravel below (i.e. directly on the CLT element) and lightweight materials on top of a continuously elastic interlayer (FR-CS, schematic description similar to figure 3.3). The results show a total difference of 7 dB with respect to the $L_{n,w}+C_{I,50-2500}$ values and apparently high correlation between the DE (mpua= 282 kg/m^2) and NO (mpua=245 kg/m^2) case. However, the dynamic stiffness of the elastic interlayer is low in the NO (mpua=245 kg/m^2) case but rather high in the DE case, which is important for the floor resonance frequency and thereby the impact sound insulation at low frequencies. Instead, the dynamic stiffness of the NO (mpua=235 kg/m^2) and the DE case (mpua= 282 kg/m^2) is in the same range. It means that the impact sound insulation properties seem to depend very much on the gravel composition or density in combination with the softness or resilience of the continuously elastic interlayer.

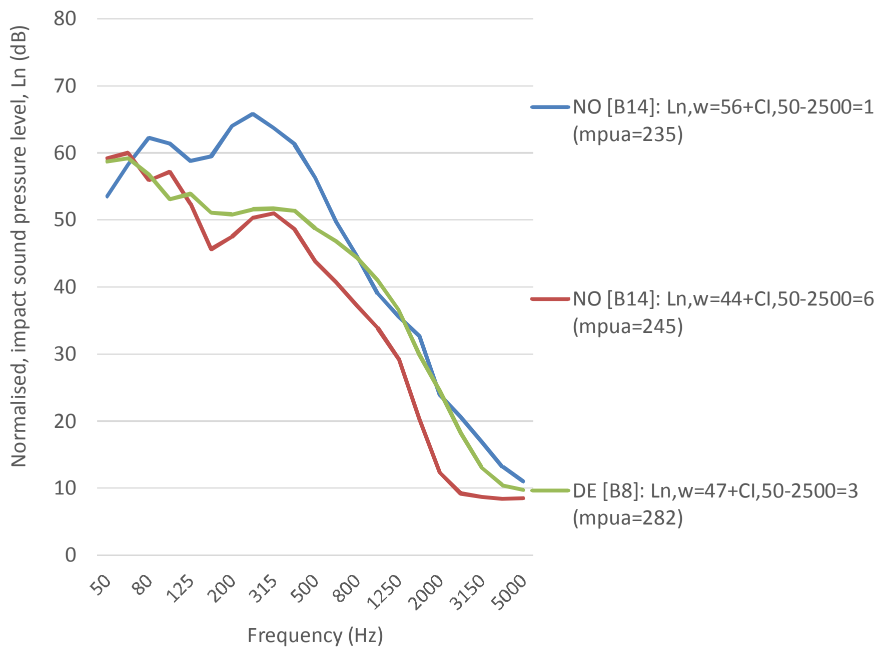


Figure 3.11. Measurement results from constructions group D, FR-CS with lightweight resilient floor on gravel

Figure 3.12 shows also results from a construction group D floor assembly with concrete layer either below or above a resilient layer (FR-CS). See figure 3.10 regarding the latter solution. In the case with the concrete layer below the resilient layer, it is casted directly on the CLT element; on top of this concrete/CLT combination there is a floating floor system (including a resilient layer) installed (the schematic description is similar to figure 3.9, however the layer of gravel is replaced by a layer of concrete).

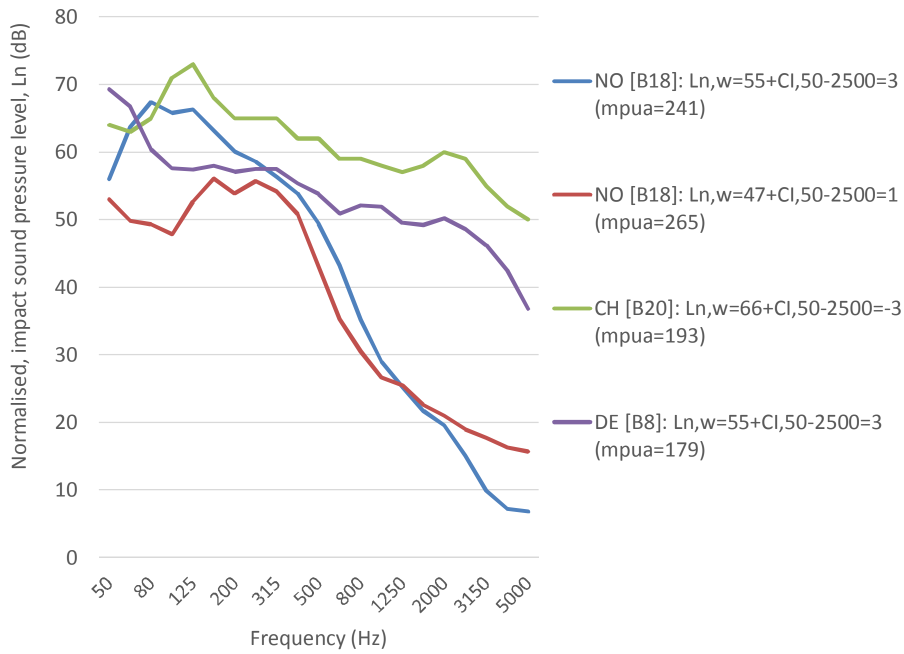


Figure 3.12. Measurement results from construction group D, FR-CS with concrete layer

In the CH [B19] and DE [B8] case with concrete above the resilient layer, the objects have been measured without a top floor covering, i.e. the tapping machine operating directly on the concrete surface. With a floor covering installed as is normally the case, the high levels in the high frequency range will automatically decrease and is then of minor importance. The huge differences between these two results relate probably to the different dynamic stiffness of the continuous elastic interlayer, leading to an approximate resonance frequency of 125 Hz for the CH case and to approximately 50 Hz for the DE case. In the two NO [B16] cases, the 60 mm thick concrete layer has been casted directly on the CLT element, and then a floating system (including a resilient layer) has been applied on top. The results is according to what is expected since they reveal typical impact sound insulation differences between continuously elastic interlayer with relatively low dynamic stiffness (mpua = 241 kg/m^2) and a line elastic interlayer (mpua=265 kg/m^2). Similar to other results, a relatively thin continuous elastic interlayer provides limited improvement compared to an optimization of line elastic interlayer.

Figure 3.13 shows results from a construction group IV solution with heavy materials both below (i.e. directly on the CLT element) and above a continuous elastic interlayer (see figure 3.9 regarding the typical solution). All these floor assemblies have been measured without a floor covering.

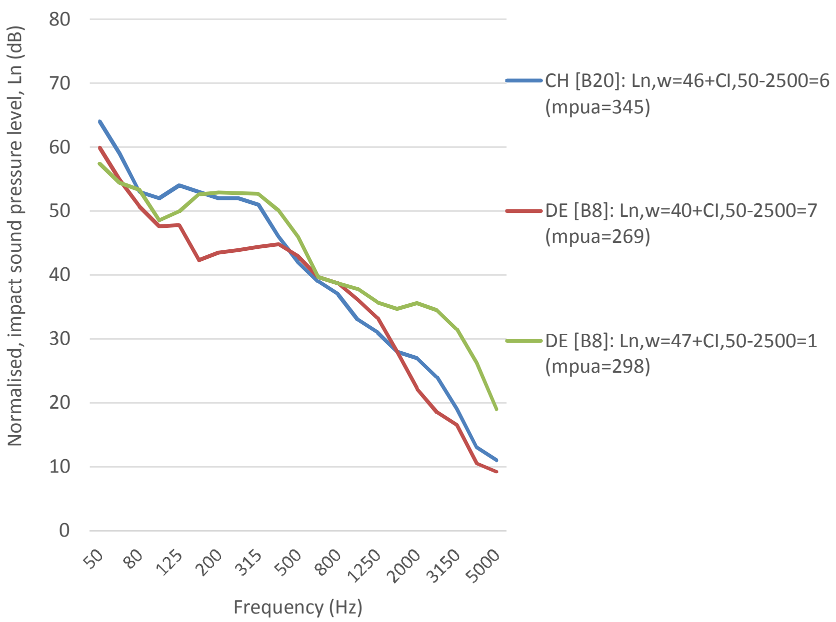


Figure 3.13. Measurement results from construction group D, FR-CS

The results show a total difference of 5 dB with respect to the $L_{n,w}$+$C_{I,50-2500}$ values. In major parts of the frequency domain, results from CH [B19] and DE [B8] with concrete below the resilient layer, show quiet good correlation. Higher mpua from the CH [B19] case seems to compensate for a higher dynamic stiffness of the resilient interlayer compared to the DE [B8] case with concrete also below the elastic interlayer. Solution from DE [B8] with gravel below a soft elastic interlayer is slightly better in the medium frequency range, but not necessarily in the low frequency range, which is often the most important frequencies.

3.5 Construction group D: Floor construction with resilient floor and resilient suspended ceiling

Within construction group D, floor constructions with both resilient floor and resilient suspended ceiling have been used. An example construction are presented in figure 3.14.

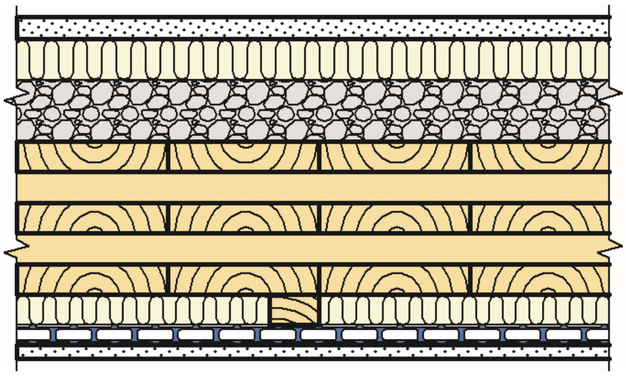


Figure 3.14. Construction group D with resilient floor and resilient suspended ceiling (FR-CR)

Laboratory measurement results of floor constructions with resilient floor and resilient suspended ceiling are presented in figure 3.15. The AU [B17] measurement object is a group D solution with one layer of gravel below a continuously elastic layer (i.e. gravel directly on the CLT element) and a lightweight top floor solution without floor covering (schematic description similar to figure 3.9) and an additional a resilient ceiling. The other two measurement objects presented in figure 3.15 are from construction group C with a lightweight floor solution. The construction of the ceiling also varies. In the AU [B17] case the plasterboard ceiling is connected with a resilient hanger (FR-CR). In the FR [B6] cases, the suspended ceiling system is based on non-spring steel suspension products (FR-CS).

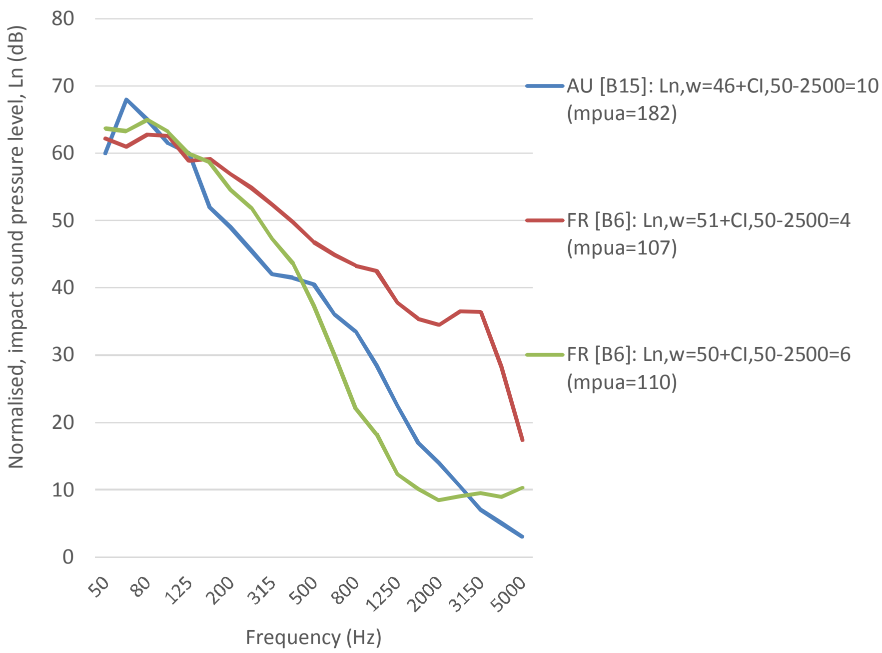


Figure 3.15. Measurement results from construction group D: FR-CS [B6]) and FR-CR [B17]

Results presented in figure 3.15 illustrate that increased mass not necessarily improves the impact sound properties in the low frequency range, i.e. $L_{n,w}+C_{I,50\text{-}2500}$ values. Resonance frequencies due to the elastic interlayer and small cavities between airtight layers prevent this. In the high frequency range, the AU [B17] case with gravel is certainly preferable, especially when a floor surface covering (such as plastic floor covering) will be included. Such solutions will therefore achieve high performance with respect to $L_{n,w}$-values. However keep in mind that the annoying frequencies normally appear in the low frequency range.

4. Advanced measurements for verification

4.1 Aim of the measurements

To provide real floor data for the verification of the calculation models by the project partners, measurements in the laboratory on different floor assemblies were provided and measured within this project. In real situations, the sound transmission of a floor is rather complicated, since flanking transmission influence the total sound transmission between rooms in buildings. However, in order to have full control of the sound transmitted directly through the floor assembly, it was decided to perform measurements in the laboratory. It might be better to carry out measurements in a completed building, however, even if a completed building contains all necessary “flanking information” it is difficult to draw conclusions from field measurements since details are not known regarding junctions etc. In a laboratory the floor assemblies can be controlled much better and it is possible to perform more detailed measurements at a higher precision then in the field.

The first floor of which data was provided from the AcuWood-Project was a standard floor in the laboratory and for which the data was already available. Therefore the data was provided at the beginning of the project. With this data it was possible to start out with the modelling in an early stage of the project. All information on this floor is taken from the AcuWood-Project report No.1 [C1].

Further measurements were planned during the project, providing data for normal constructed floors and for optimized floor constructions. The choice of the floors to be measured were discussed within the project and included the input of the project members dealing with the modelling of floor constructions, as well as the members gathering data for the acoustic database. The floor constructions were provided and installed in the laboratory by the German industry project partner Bauer Holzbau, and the aim was to use “standard” and “optimized” constructions, which are commonly used in Germany. The discussion of the floors to be measured and the planning of the measurements lead to a time window from May 2016 to December 2016 to conduct the measurements. During this time, new data was directly provided to the project members so it was useable for verification purposes of the models within this project.

4.2 Description of the laboratory

The described measurements were conducted in the laboratory p8 of the IBP in Stuttgart. The laboratory is made to test wooden floor constructions. It consists of concrete walls and floors and offers a frame, where a lightweight floor can be installed. All walls are equipped with lightweight linings with resonance frequency of approximately 60 to 80 Hz, reducing the flanking transmission in the frequency bands for standard testing from 100 to 5000 Hz. A sectional drawing of the laboratory is shown in figure 4.1. The room sizes are 4.78 m x 3.78 m x 3.82 m for the sending room and 4.78 m x 3.78 m x 2.67 m.

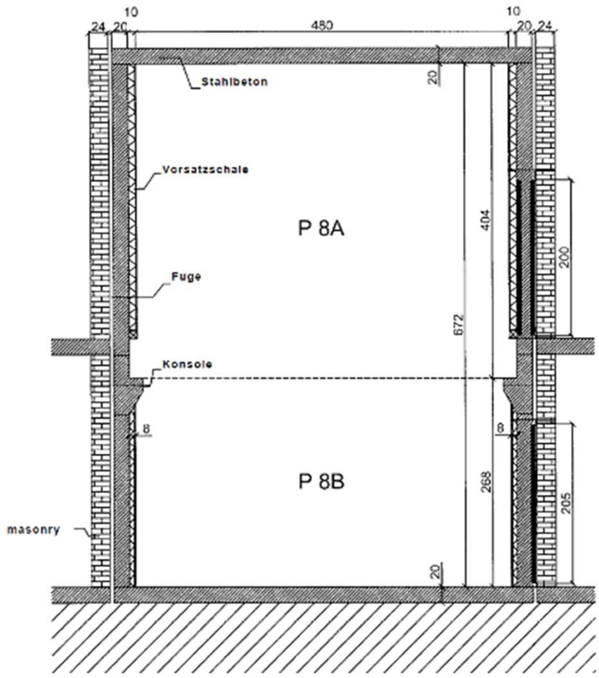


Figure 4.1: Sectional view of the laboratory p8 of IBP. The wooden floor construction was installed on the console, separating the laboratory into two rooms.

4.3 Conducted measurements

All measurements were conducted on the basis ofISO 10140-4 [C2]. The weighted sound reduction index R_w and the spectrum adaptation terms were calculated according to DIN EN ISO 717-1 [C3], the weighted normalized impact sound pressure level and the spectrum adaption terms were calculated according to DIN EN ISO 717-2 [C4]. The reverberation time in the receiving room in the frequency range from 100 Hz to 3150 Hz was between 1 and 2 s, at low frequencies between 50 and 80 Hz it was lower than 1 s, due to the linings of the laboratory. The measurements were performed with stationary microphones. The number of microphone positions in the receiving room was 6, in the sending room the number was 2. The number of loudspeaker positions in the sending room was 2. This leads to 12 independent measurements in the receiving room and 4 independent measurements in the sending room. The reverberation time was measured by the method of stationary signal suddenly turned off. In the receiving room, the measurement of the reverberation time was executed at 4 independent microphone positions and two different loudspeaker positions, giving a total of 8 independent measurements that were averaged. The signal was pink noise. The sound reduction index was calculated according to [C2].

In some cases of the measurements, where a high sound reduction index and a low receiving sound pressure level was measured, a background noise correction was applied. This correction was limited to 1.3 dB. Additionally, the limit of the sound reduction index of the laboratory by flanking sound transmission was reached in some cases, then a correction of up to 1.3 dB was additionally applied. The results of the sound reduction index were indicated when corrected by giving the value with "≥" sign, indicating that the value might be higher than given.

The normalized impact sound pressure level of the tapping machine was measured by using the same 6 stationary microphone positions in the receiving room and the normalized impact sound pressure levels was calculated according to [C6].

In some cases of the measurements, where the floor was equipped with floating floor and suspended ceiling, giving a low impact sound pressure level, a correction of the airborne sound transmission for the impact sound pressure level was performed. This correction was limited to 1.3 dB. Additionally, for very low measured impact sound pressure levels a background noise correction was applied for the impact sound pressure level. This correction was also limited to 1.3 dB. The results of the normalized impact sound pressure level were indicated when corrected by giving the value with ≤ sign, indicating that the value might be smaller than given.

Additionally to the sound reduction index R' and the normalized impact sound pressure level L_n , velocity measurements of L_v (re. 5E-8 m/s) of the wooden floor constructions were performed to give detailed data of the vibration of the floor to the project partners for check validation of the floor models. For the first provided floor construction, velocity data of the floor was provided for one excitation position of the tapping machine and for 6 receiver positions on the top of the floor (in the sending room) and for 4 positions on the lower side of the floor (at the ceiling of the receiving room). Additionally, the velocity level was provided at one accelerometer position on the top of the floor (in the sending room), when different excitation positions of the tapping machine where used.

For the measurements within the project, the measurement template of the project [C5] was applied. It contains Information which data should be measured for the floors. According to it, the impact sound pressure level, the airborne sound pressure levels (for the sound reduction index) and the reverberation time in the receiving room was measured in the extended frequency range of 20 – 5000 Hz.

For the standard tapping machine, additional velocity data of the floor was provided. On top of the floor (in the sending room), four accelerometers were placed on the diagonals of the floor at fixed positions. On the lower side of the floor, four additional accelerometers were placed (in the receiving room at the ceiling) at the beams and between the beams in the bays of the floor, or when measuring floors with suspended ceiling, on the same positons on the suspended ceiling. All accelerometer positions where kept throughout the measurements on all four floors measured within this project.

Additionally to the measurements with the tapping machine, measurements in the extended frequency range were performed with the Japanese rubber ball, according to ISO 10140-3 Annex A [C6]. For this source, four excitation positions, the same as for the tapping machine, where used and 5 impulses of the ball drop from a height of 1.0 m were energetically averaged. The measured values of $L_{F,max}$, at the 6 microphone positions in the receiving room, the 2 microphone positions in the sending room and the velocity data of the 8 accelerometers (integrated accelerations) $L_{v,F,max}$ were provided for all four measured floors.

A further measurement was the measurement of the mobility of the floor by impulse hammer excitation. For these measurements, one impulse hammer and the described 8 accelerometers (four on the top of the floor, four on the lower side of the floor) where used. The measurements were performed at three excitation positions. At each position, five impulse hammer strokes were measured and the mobilities were averaged. The averaged values were given as amplitude and phase data. To indicate the quality of the measurements, the coherence of the measurements was also provided for the project partners.

For the basic floor construction, the beams with the plate layer of OSB on top, from the project partners modelling the structure it was requested to have some mobility data to set-up the model and to control it as an interim step for the total model of the different floors. Therefore the same mobility measurements and velocity measurements when the floor was excited with the tapping machine were additionally performed, similar to the above described measurements.

4.4 Floor assemblies

The first floor for which data was provided from the AcuWood-Project was the standardised floor according to DIN EN ISO 10140-5 Appendix C, floor C1 [C7], which is a lightweight wooden beam floor. This kind of floor represents approximately standard floors of (prefabricated) wooden single family houses in Germany, where no regulations on sound insulation and impact noise are given. The floor is shown in figure 4.2.

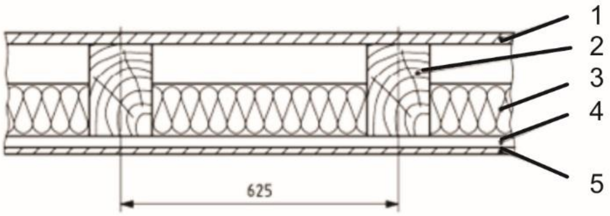


Figure 4.2: Sectional view of the first wooden beam floor according to DIN EN ISO 10140-5.

The floor consists of the following layers (from top to bottom):

1. Floor plate wooden chip board with 22±2 mm thickness, screwed into beams every 300 ±50 mm
2. Wooden beams with 120 mm width and 180 mm height
3. Mineral wool with 100 mm thickness and flow resistance between 5 and 10 kPa s/m² according to ISO 9053
4. Wooden battens with 24 mm width and 48 mm height and with 625 mm distance screwed into the beams
5. Gypsum cardboard with 12,5 mm thickness and density of 800 ±50 kg/m³, screwed directly into the bat-tens every 300 ±50 mm)

The beam positions of the first floor are shown in figure 4.3.

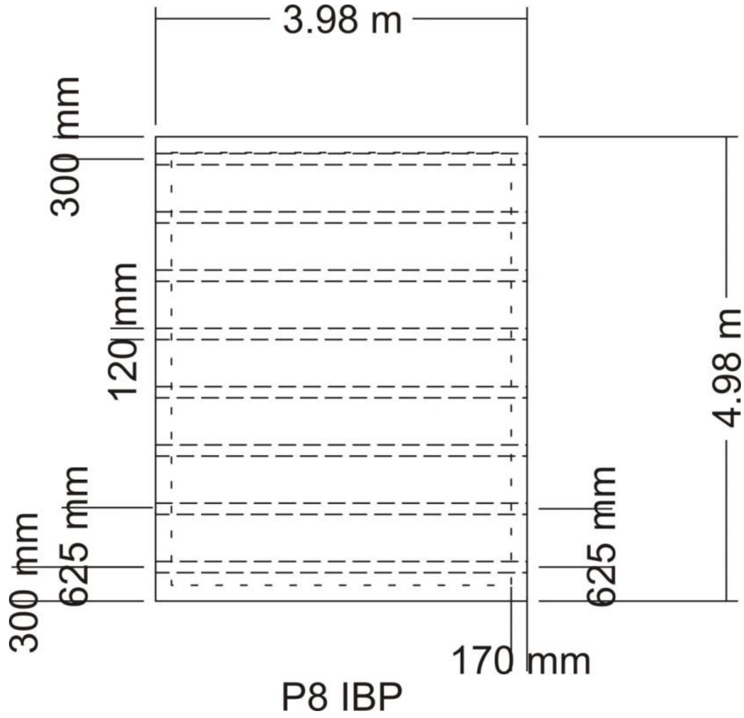


Figure 4.3: Top view onto the floor with wooden beams. The beams are drawn with dotted lines. The dotted line with short dots depict the concrete console, where the beams are supported (left and right side of figure)

The weighted sound reduction index of the bare floor shown in figure 2 is R_w = 45 dB, the weighted normalized impact sound pressure level of the floor is $L_{n,w}$ = 73 dB. The graph of the sound reduction index and the standard impact noise level is shown in section 4.7 in Figure 4.21 and in figure 4.22, respectively.

For further measurements, the intention was to use a floor construction which is common in Germany. The above described bare floor is nowadays rarely found in Germany, as the acoustic performance is too low. Very common is the use of a floating floor to improve the acoustic properties of floors in new single family houses as well as for refurbishment of old buildings. Therefore, a dry floating floor system was applied to the bare floor. It consists of a 18 mm thick gypsum fibre board, laminated on 10 mm thick wood fibre (KNAUF BRIO18WF). The wood fibre acts as a resilient layer between the bare floor and the gypsum fibre board. The floor construction is shown in figure 4.4.

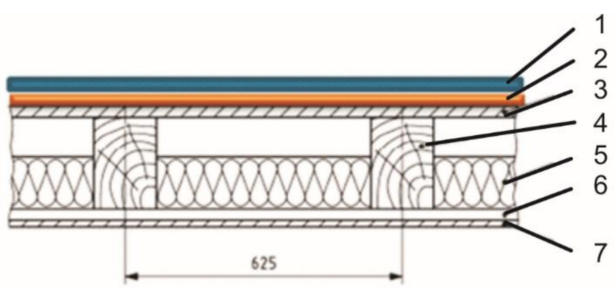


Figure 4.4: Sectional view of the first wooden beam floor with floating floor.

The first floor with floating floor consists of the following layers (from top to bottom):

1. Gypsum fibre board with 18 mm thickness
2. Wood fibre layer of 10 mm thickness (KNAUF BRIO 18 WF)
3. Floor plate wooden chip board with 22±2 mm thickness, screwed into beams every 300 ±50 mm
4. Wooden beams with 120 mm width and 180 mm height
5. Mineral wool with 100 mm thickness and flow resistance between 5 and 10 kPa s/m² according to ISO 9053
6. Wooden battens with 24 mm width and 48 mm height and with 625 mm distance screwed into the beams
7. Gypsum cardboard with 12,5 mm thickness and density of 800 ±50 kg/m³, screwed directly into the bat-tens every 300 ±50 mm)

The second floor and the succeeding floors that were measured in this project were constructed by the German project partner Bauer Holzbau. The basic floor construction is a common wooden floor construction which is used in single family and multi-family and multi-storey houses build by Bauer Holzbau and by other German building companies. Similar to the first floor, it is a wooden beam construction with a similar distance of the centre of the beams (625 mm, see figure 4.2), but consists of different beams and different construction details. The construction of the second floor is shown in figure 4.5:

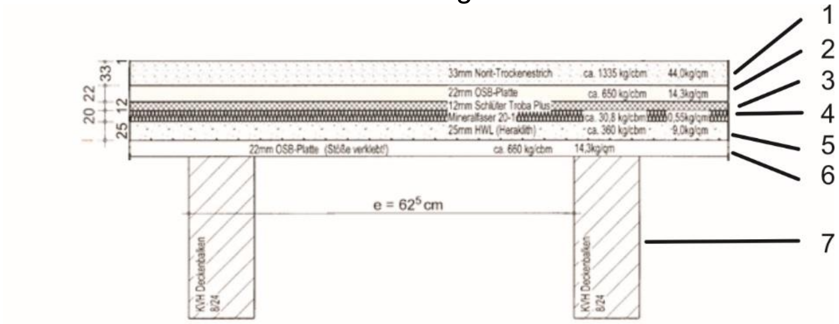


Figure 4.5: Sectional view of the second wooden beam floor with dry floating floor.

The floor layers of the second wooden beam floor construction are:

1. Dry floating floor of 33 mm thickness, ρ = 1335 kg/m³, m' = 44.1 kg/m² (Norit)
2. OSB plate of 22 mm thickness, ρ = 650 kg/m³, m' = 14.3 kg/m² (OSB4, Kronspan)
3. Plastic interlayer, m' = 0.76 kg/m² (Troba-Plus, Schlüter)
4. Mineral wool impact sound insulation plate of 20 mm thickness, ρ = 30.8 kg/m³, m' = 0.6 kg/m², s< 50 MN/m³ (TP 20-1, Knauf)
5. Heraklith plate of 25 mm thickness, ρ = 360 kg/m³, m' = 9.0 kg/m² (Heraklith BM, Heraklith)
6. OSB plate of 22 mm thickness, ρ = 650 kg/m³, m' = 14.3 kg/m² (OSB4, Kronspan)
7. Wooden beams with 80 mm width and 240 mm height, distance between Beams 625 mm

A model of the floor construction above the wooden beams was made from the original materials to show the build-up to the project partners. This model was presented to the project partners at the project meeting in Stuttgart. The model of the build-up of the second and third floor is shown in figure 4.6.

Figure 4.6: Model of the second wooden beam floor with dry floating floor (layers above the wooden beams).

The third floor was an optimized version of the second floor, consisting of the same top layers, but additionally was equipped with an elastically suspended ceiling. This ceiling was suspended by a simple installation, commonly used in German buildings, but slightly modified to gain a softer connection to the beams. The construction of the third floor is shown in figure 4.7:

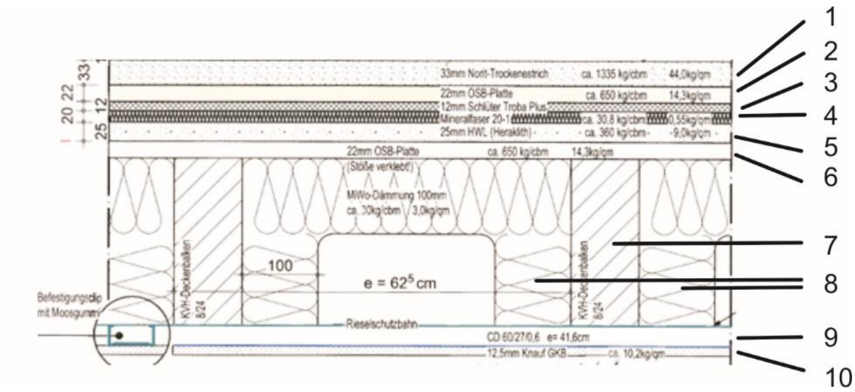


Figure 4.7: Sectional view of the third wooden beam floor with dry floating floor.

The floor layers of the third wooden beam floor construction are:

1. Dry floating floor of 33 mm thickness, ρ = 1335 kg/m³, m' = 44.1 kg/m² (Norit)
2. OSB plate of 22 mm thickness, ρ = 650 kg/m³, m' = 14.3 kg/m² (OSB4, Kronspan)
3. Plastic interlayer, m' = 0.76 kg/m² (Troba-Plus, Schlüter)
4. Mineral wool impact sound insulation plate of 20 mm thickness, ρ = 30.8 kg/m³, m' = 0.6 kg/m², s< 50 MN/m³ (TP 20-1, Knauf)
5. Heraklith plate of 25 mm thickness, ρ = 360 kg/m³, m' = 9.0 kg/m² (Heraklith BM, Heraklith)
6. OSB plate of 22 mm thickness, ρ = 650 kg/m³, m' = 14.3 kg/m² (OSB4, Kronspan)
7. Wooden beams with 80 mm width and 240 mm height, distance between Beams 625 mm
8. Filling of the space between the beams with mineral wool, ρ = 30 kg/m³,
9. Metal profile CD Profile with 22 mm thickness, attached to clip connectors with elastic interlayer, screwed into the beams
10. Gypsum board with 12.5 mm thickness, ρ = 816 kg/m³, m' = 10.2 kg/m² (GKB, Knauf), screwed into the CD Profile

The CD Profile with the clip connectors are shown in figure 4.8.

Figure 4.8: CD Profile with clip connectors. In the front the clip connector, which is screwed into the beams, the second clip connector is shown in the rear, equipped with the elastic interlayer for less stiff connection of the suspended ceiling. The CD-profile is held by the clip-connectors, the gypsum boards were screwed from below into the CD-profile.

The fourth floor measured within this project was again a floor construction with optimised acoustical performance. For this floor, the floor top layers of the third floor were removed and replaced by ballast and a concrete floating floor. The sectional view of the fourth floor is shown in figure 4.9.

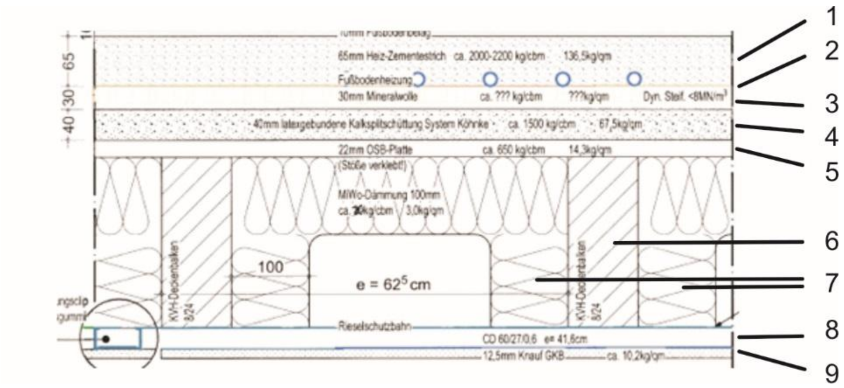


Figure 4.9: Sectional view of the fourth wooden beam floor with dry floating floor.

The floor layers of the fourth wooden beam floor construction are:

1. Concrete floating floor of 65 mm thickness, ρ = 1928 kg/m³, m' = 125.0 kg/m² (weighted) (Cemflow, Heidelberger Zement)
2. Plastic interlayer with clip system for floor heating system of 1 mm thickness, heating pipes not installed, ρ = 700 kg/m³, m' = 0.7 kg/m²
3. Mineral wool impact sound insulation plate of 30 mm thickness, ρ = 30 kg/m³, m' = 0.9 kg/m², s< 8 MN/m³ (TS 032, Superglass)
4. Ballast of gravel of 40 mm thickness, ρ = 1600 kg/m³, m' = 64 kg/m² (System Köhnke)
5. OSB plate of 22 mm thickness, ρ = 650 kg/m³, m' = 14.3 kg/m² (OSB4, Kronspan)
6. Wooden beams with 80 mm width and 240 mm height, distance between beams 625 mm
7. Filling of the space between the beams with mineral wool, ρ = 30 kg/m³,

8. Metal profile CD Profile with 22 mm thickness, attached to clip connectors with elastic interlayer, screwed into the beams
9. Gypsum board with 12.5 mm thickness, ρ = 816 kg/m³, m’ = 10.2 kg/m² (GKB, Knauf), screwed into the CD Profile

To show the build-up of the upper floor layers a model was made from the material used on the real floor. This model was presented to the project partners at the project meeting in Stuttgart. Parts of the models where given to the project partners for further testing of material data necessary for the modelling of the floor. The model of the upper floor layers of the fourth and fifth floor is shown in figure 4.10.

Figure 4.10: Model of the upper layers of the fourth and fifth wooden beam floor with dry floating floor (layers above the wooden beams).

The fifth floor measured within this project was a wooden beam floor with the same top layers of the fourth floor, and the suspended ceiling was removed, leaving the beam construction in the receiving room visible. The sectional view of the fifth floor is shown in figure 4.11.

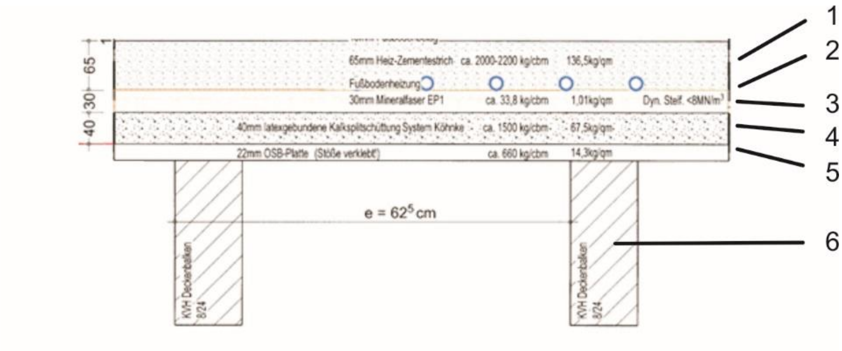


Figure 4.11: Sectional view of the fifth wooden beam floor with dry floating floor.

The floor layers of the fifth wooden beam floor construction are:

1. Concrete floating floor of 65 mm thickness, ρ = 1928 kg/m³, m’ = 125.0 kg/m² (weighted) (Cemflow, Heidelberger Zement)

2. Plastic interlayer with clip system for floor heating system of 1 mm thickness heating pipes not installed, ρ = 700 kg/m³, m' = 0.7 kg/m²
3. Mineral wool impact sound insulation plate of 30 mm thickness, ρ = 30 kg/m³, m' = 0.9 kg/m², s< 8 MN/m³ (TS 032, Superglass)
4. Ballast of gravel of 40 mm thickness, ρ = 1600 kg/m³, m' = 64 kg/m² (System Kohnke)
5. OSB plate of 22 mm thickness, ρ = 650 kg/m³, m' = 14.3 kg/m² (OSB4, Kronspan)
6. Wooden beams with 80 mm width and 240 mm height, distance between beams 625 mm

During the construction of the different floors, some interim measurements were performed to check the basic values of R and L_n and to give interim results to the project partners. As these interim measurements were performed during the changing of the constructions, there was no time to perform time consuming vibration measurements at the structure.

From the project partners that were modelling the structure, it was requested to have some data of vibration measurements of the basic floor structure, the beams with the upper plate layer. These measurements were performed after measuring the second to fifth floor constructions and after removing the upper layers of the fifth floor. This basic construction is shown in figure 4.12.

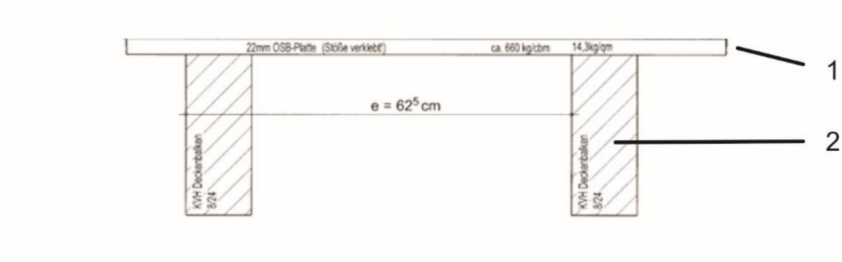


Figure 4.12: Sectional view of the basic wooden beam floor construction without upper layers and without suspended ceiling.

The floor layers of the basic wooden beam floor construction are:

1. OSB plate of 22 mm thickness, ρ = 650 kg/m³, m' = 14.3 kg/m² (OSB4, Kronspan)
2. Wooden beams with 80 mm width and 240 mm height, distance between beams 625 mm

For this basic floor, again all measurements performed on the second to the fifth floor were measured and provided to the project partners.

4.5 Equipment used

For the measurements of the sound reduction index and the reverberation time following equipment was used:

- Real Time Analyser Norsonic type 840 S.-No.: 18727
- Power Amplifier Klein und Hummel, type AK 180
- Dodecahedron loudspeaker Norsonic type 229, S.-No. 22568
- Microphones B&K type 4165, S.-No.: 1368102 and S.-Mo.: 688083
- Calibrator B& K 4230 S.-No. 1472576

For the recording of the calibrated signals, the following equipment was used:

- Head Acoustics Frontend SQLab III, S.-No.: 35020102
- Microphones G.R.A.S. type 46 AE, S.-No.: 88719, 88720, 88723, 88724, 88726, 88727, 88730, 88731
- Accelerometers on floor in receiving room B&K type 4371 S.-No.: 16232490, 16232491, 16232494, 16232495
- Accelerometers on floor in sending room Kistler type 8702B25 S.-No.: C139830, C139815, C139814, BBN type 505 S.-No.: 124
- Calibrator B& K 4230 S.-No. 1472576
- Impuls Hammer B&K type 8200 S.-No.: 1288471
- Tapping machine Norsonic type 211, Sr.-No. 706
- Tapping machine Norsonic type 211, Sr.-No. 12958

4.6 Measurement positions

As the measurements for the first floor were performed within the AcuWood-Project the measurement positions on the first floor were different than for all other floors. For the first floor without and with dry floating floor, shown in figure 4.2 and 4.4, the measurement positions are shown in figure 4.13 and 4.14 are given in table 4.1 to table 4.4. Here, the position of the standard tapping machine is depicted by 5 red dots, representing the 5 hammers of the tapping machine. Measurement positions on top of the floor (on the wooden chip board above the beams) are shown by blue rectangles (position 1 to 6), positions on the lower part of the floor (the ceiling form receiving room, measurement on the gypsum cardboard) are given by yellow rectangles (Position 7 to 10).

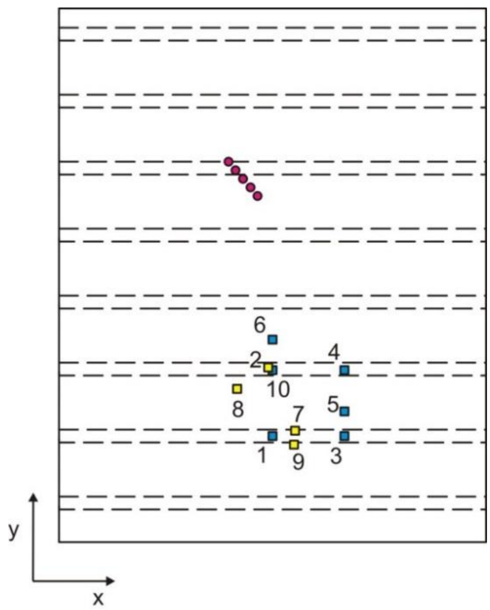


Figure 4.13: Top view onto the first floor with wooden beams. The beams are drawn with dotted lines. The position of the tapping machine is shown by red dots, the positions of the accelerometers on top of the floor are shown by blue rectangles. The positions of the accelerometers on the bottom side of the floor (from receiving room below the ceiling) are shown with yellow rectangles.

The distances of the tapping machine hammers on the floor in figure 4.13 are given in Table 4.1.

Table 4.1: Distances of the tapping machine (from the lower left corner of the floor in figure 4.13 in meters)

Number of Hammer	Distance in x-direction [m]	Distance in y-direction [m]
1	1.6	3.53
3	1.735	3.37
5	1.87	3.21

The distances of the accelerometers on the floor in figure 4.13 are given in Table 4.2.

Table 4.2: Accelerometer position on top of the floor (distance from the lower left corner of the floor in figure 13) and their position in relation to the floor structure.

Number of accelerometer	Distance in x-direction [m]	Distance in y-direction [m]	Position in relation to the floor construction
1	2.01	0.9	above beam
2	2.01	1.55	above beam
3	2.68	0.9	above beam
4	2.68	1.55	above beam
5	2.68	1.2	above bay
6	2.01	1.85	above bay

The distances of the accelerometers on the bottom of the floor of figure 4.13 (measured from the receiving room on the ceiling) are given in Table 4.3.

Table 4.3: Accelerometers on the bottom of the floor (measured from the receiving room on the ceiling; distances from the lower left corner of the floor in figure 4.13 in meters) and position in relation to the floor structure.

Number of accelerometer	Distance in x-direction [m]	Distance in y-direction [m]	Position in relation to the floor construction
7	2.19	1.04	below batten below beam
8	1.66	1.43	below batten below bay
9	2.19	0.91	below screw into batten below beam
10	1.95	1.63	below bay

An additional Measurement of the vibration velocity of the floor (measured on the top layer) was performed within the AcuWood-Project. In this case the accelerometer measuring the vibration velocity was fixed to one location, and the measurement was performed at four different locations of the standard tapping machine on the floor. The tapping machine locations and the measurement position are shown in figure 4.14.

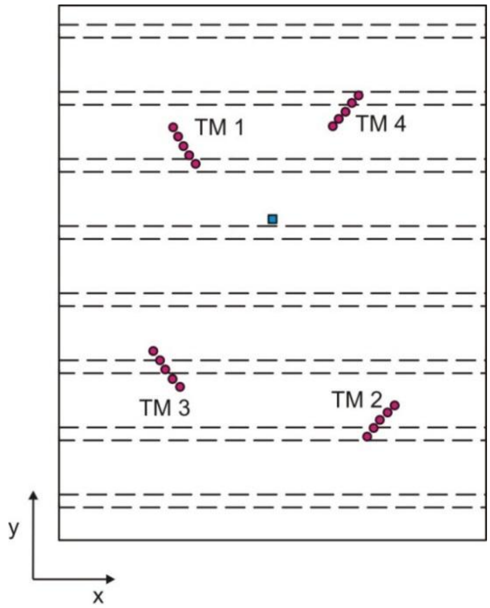


Figure 4.14: Top view onto the first floor with wooden beams. The beams are drawn with dotted lines. The positions of the tapping machine are shown by red dots, the position of the accelerometer on top of the floor is shown by a blue rectangle.

The measurement positions in figure 4.14 are given in Table 4.4.

Table 4.4: Location of the middle hammer (number 3) of the tapping machine and location of the accelerometer on top of the floor

Equipment	Position	Distance in x-direction [m]	Distance in y-direction [m]
Tapping machine	TM 1	1.17	3.68
	TM 2	3.02	1.13
	TM 3	1.00	1.60
	TM 4	2.68	4.00
Accelerometer	1	1.99	2.99

The measured data on the first floor is given in the Excel file “20141013_IBP-Data_Wooden-Beam-Floor_P8.xlsx”, a detailed description was given to the project partners in the file “20141021_IBP_Description_Measurements_Wooden-beam-floor.pdf”. This description is incorporated in this report.

For the second to fifth floor and the basic floor, different measurement positions were used, according to a proposal given by the project partners [C5], suggesting at which positions the measurements should be conducted. In figure 4.15 and figure 4.16 the microphone positions of the sending room are shown.

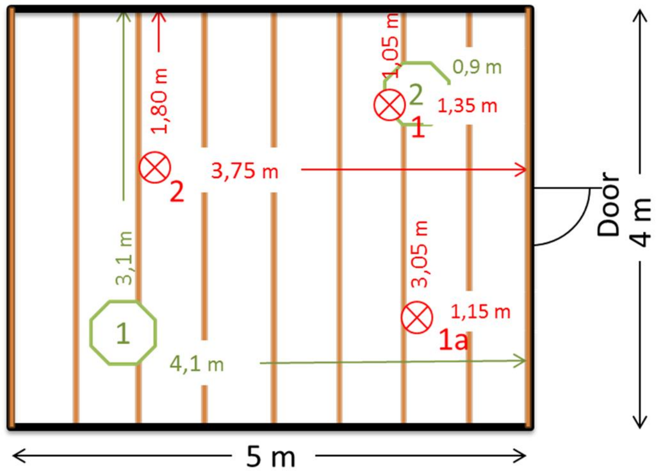


Figure 4.15: Top view of the sending room of the second to fifth floor and the basic floor. The beams are indicated by lines. The positions of the loudspeakers (green octagon) and the microphones (red circle with cross) are given. Microphone position 1a was used when the loudspeaker was placed at position 2 and microphone position 1 was used when the loudspeaker was placed at position 1.

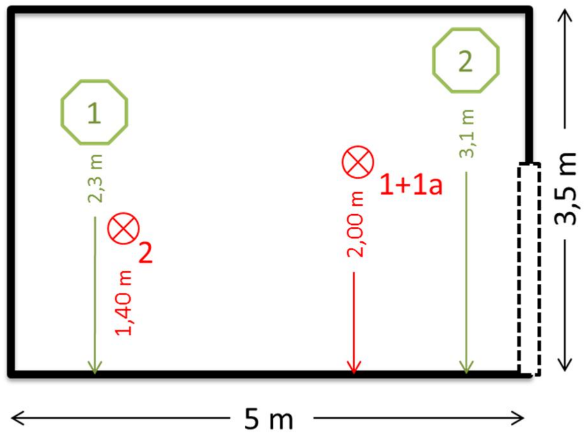


Figure 4.16: side view of the sending room for the second to fifth floor and the basic floor. The positions of the loudspeaker (green octagon) and the microphones (red circle with cross) in the sending room are shown.

For the receiving room, the microphone positions are shown in figure 4.17 and figure 4.18:

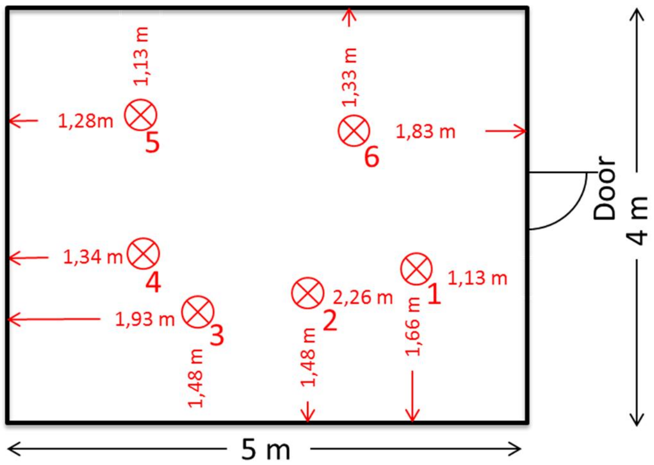


Figure 4.17: Top view of the receiving room of the second to fifth floor and the basic floor. The positions of the microphones in are given.

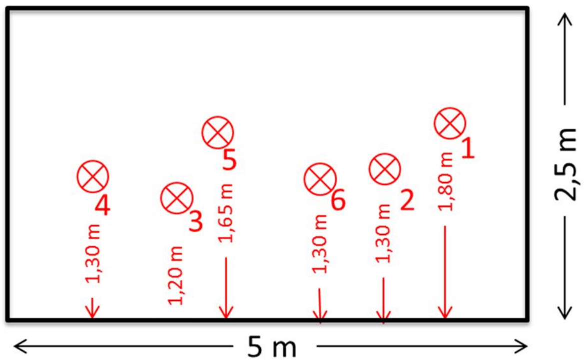


Figure 4.18: Side view of the receiving room for the second to fifth floor and the basic floor. The positions of the loudspeaker and the microphones in the sending room are shown.

For the vibration measurements at the second to fifth floor and the basic floor, the excitation positions of the tapping machine and the rubber ball, the positions of the accelerometers and the excitation positions of the impulse hammer are shown in figure 4.19 for the sending room and in figure 4.20 for the receiving room.

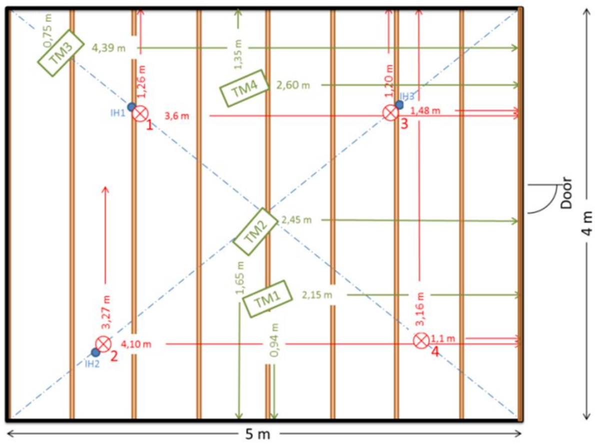


Figure 4.19: Top view of the sending room of the second to fifth floor and the basic floor. The beams are indicated by lines. The positions of the tapping machine and the Japanese ball are indicated by TM1 to TM4, the positions of the accelerometers are shown by the red circle with cross (no. 1 to 4) and the excitation positions of the impact hammer are indicated by blue small dots (IH1 to IH3).

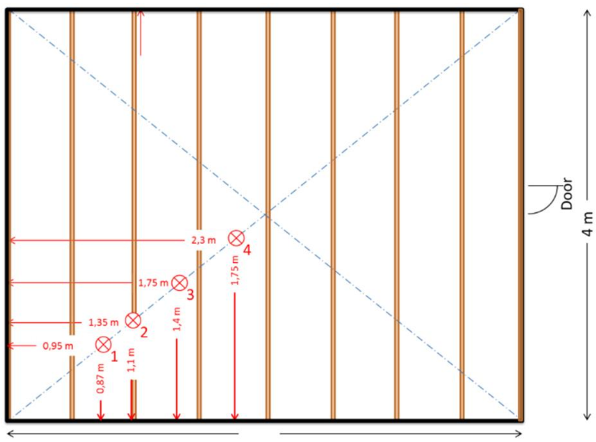


Figure 4.20: Top view of the receiving room of the second to fifth floor and the basic floor. The beams are indicated by lines. The positions of the accelerometers are shown by the red dots with cross (no. 1 to 4). The accelerometers are attached at the ceiling of the receiving room, no 2 on the beam lower side or on the suspended ceiling directly below the beam, no 1, 3 and 4 in the bay between the beams or at the same positions on the suspended ceiling.

4.7 Results of the measurements

The weighted sound reduction index of the first floor of the AcuWood-Project, a floor without floating floor in figure 4.2 is R_w = 45 dB with $C_{50-5000}$ = -3 dB, the one of the same floor with dry floating floor, see figure 4.4, is R_w = 54 dB with $C_{50-5000}$ = -5 dB. The graph of the sound reduction index is shown in figure 4.21.

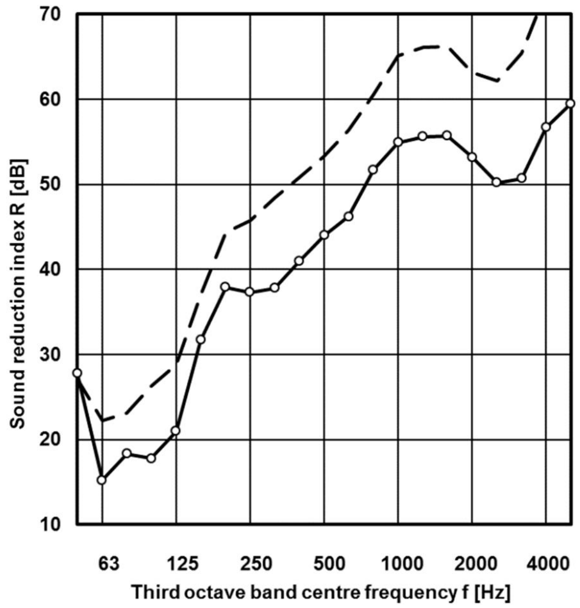


Figure 4.21: Measured sound reduction index of the first wooden floor (bare floor: line with dots; floor with dry floating floor: dashed line).

The weighted normalized impact sound pressure level of the floor without floating floor in figure 4.2 is floor is $L_{n,w}$ = 74 dB with $C_{I,50-2500}$ = 1 dB, for the case the dry floating floor was installed, figure 4.4, the weighted normalized impact sound pressure level is $L_{n,w}$ =68 dB with $C_{I,50-2500}$ = 0 dB. The graphs of the normalized impact sound pressure level of both constructions are shown in figure 4.22.

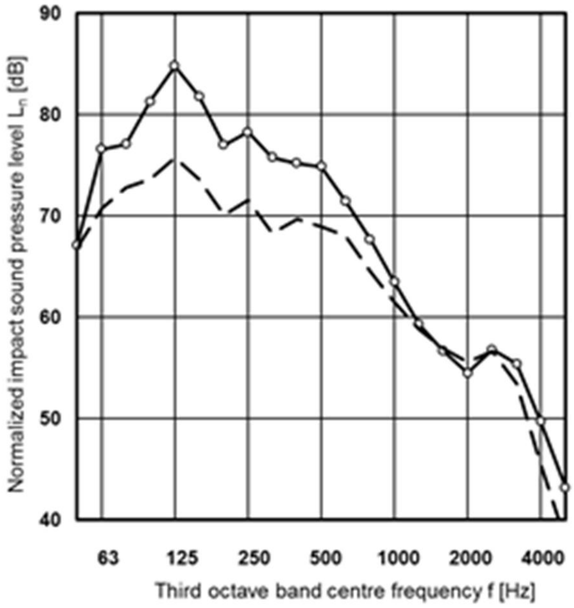


Figure 4.22: Measured normalized impact sound pressure level of the first wooden floor (bare floor: line with dots; floor with dry floating floor: dashed line).

The graph in Figure 4.21 shows an improvement in the airborne sound insulation of the floor by the dry floating floor above 50 Hz of more than 10 dB at higher frequencies, but also some improvement at lower frequencies. For the impact sound insulation, an improvement above 50 Hz is also apparent; at higher frequencies the impact level of the floor with dry floating floor approaches the levels of the bare floor. It is assumed that this is due to the much harder surface of the gypsum dry floating floor, which increases the power input into the structure at higher frequencies by the tapping machine.

Also on the floor with this dry floating floor, measurements of the vibration velocity of the top layer (the dry floating floor) were performed within the AcuWood-Project at the same accelerometer positions shown in figure 4.14 and described in table 4.4. Again, all 4 tapping machine positions where measured, the results are given to the project partners for use in the floor simulation in the excel file “20141013_IBP-Data_Wooden-Beam-Floor_P8.xlsx”.

The sound reduction index for the second to fifth floor is shown in figure 4.23:

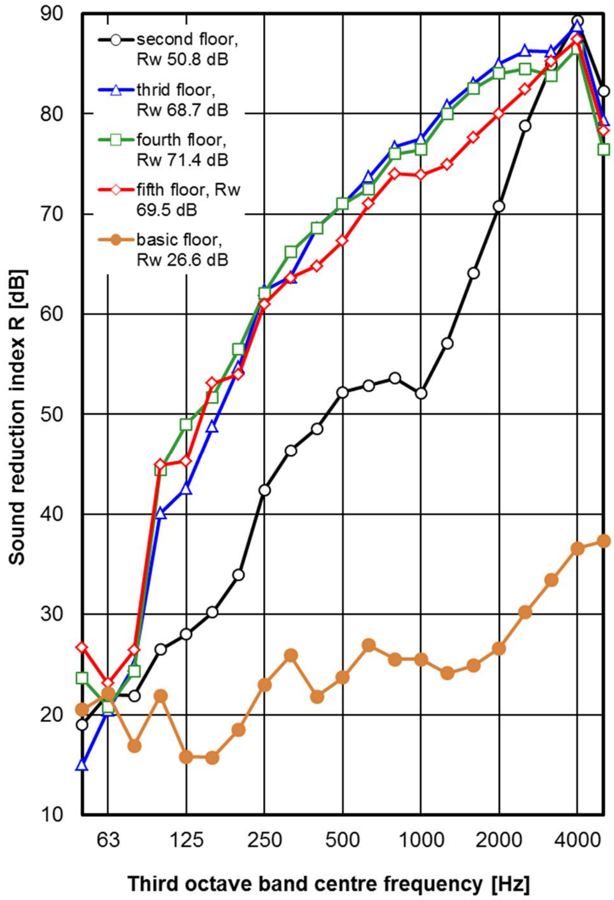


Figure 4.23: Measured sound reduction index R of the second to fifth wooden floor and the basic floor.

The third, fourth and fifth floor have a quite high airborne sound reduction index, with relatively similar spectrum and weighted sound reduction index. The analysis of the measurements shows that for the airborne sound reduction, the flanking transmission of the test suite of IBP is highly influential and the maximum possible sound reduction index of the test suite is nearly reached. For the third, fourth and fifth floor the limited correction for flanking transmission of 1.3 dB is reached and the values of the weighted sound reduction index are R_w = 50 dB with $C_{50-5000}$ = -6 dB for the second floor, $R_w \geq$ 68 dB with $C_{50-5000}$ = -16 dB for the third floor, $R_w \geq$ 71 dB with $C_{50-5000}$ = -17 dB for the fourth floor, $R_w \geq$ 69 dB with $C_{50-5000}$ = -13 dB for the fifth floor and R_w = 267 dB with $C_{50-5000}$ = 0 dB for the basic floor.

The measured impact sound pressure levels of the second to fifth floor are shown in figure 4.24.

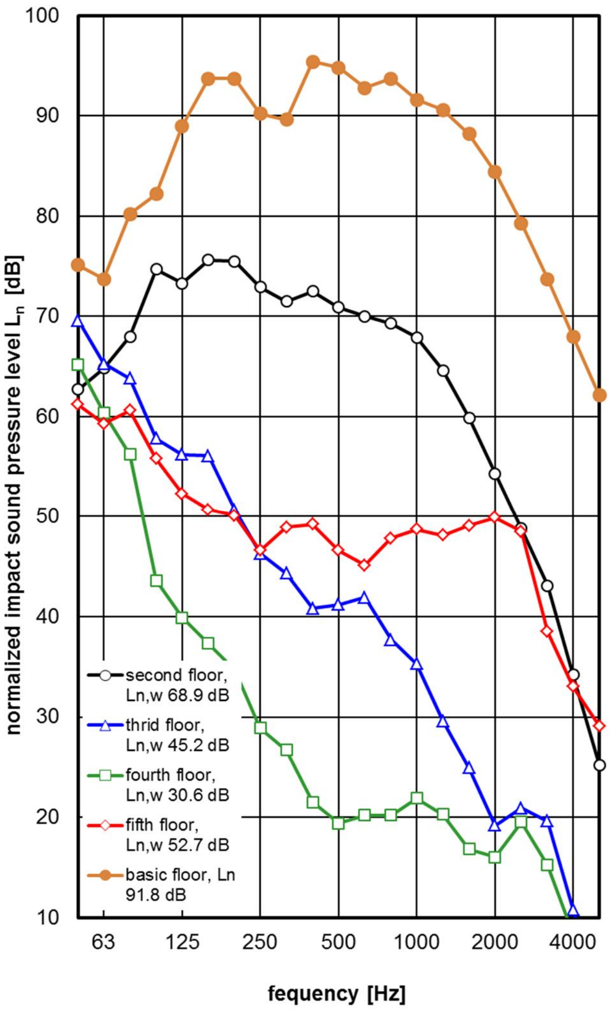


Figure 4.24: Measured normalized impact sound pressure level L_n of the second to fifth wooden floor and the basic floor.

For the second, the fifth floor and the basic floor, no background or airborne correction had to be applied for the normalized impact sound pressure level. For the third floor, a small airborne sound correction of 0.5 dB was applied at 2000 Hz and a background correction of 0.5 dB was applied for 4 kHz. For the fourth floor an airborne correction was applied for the frequencies between 250 and 2000 Hz as well as for 4 and 5 kHz. Additionally at the high frequencies some background correction was applied. The weighted normalized impact sound pressure levels of the second floor was $L_{n,w}$ = 69 dB with $C_{I,50\text{-}2500}$ = -1 dB, for the third floor it was $L_{n,w}$ = 46 dB with $C_{I,50\text{-}2500}$ = 11 dB, for the fourth floor it was $L_{n,w} \leq$ 31 dB with $C_{I,50\text{-}2500}$ = 21 dB, for the fifth floor it was $L_{n,w}$ = 53 dB with $C_{I,50\text{-}2500}$ = -1 dB and for the basic floor it was $L_{n,w}$ = 92 dB with $C_{I,50\text{-}2500}$ = -4 dB.

For the airborne sound insulation, the third to fifth floor gave quite high values which reached the flanking transmission limit of the laboratory and are therefore quite similar. For wooden constructions, in many cases the impact noise is normally the main issue. In figure 4.24 we can see that both optimised floors with suspended ceiling give values lower than the requirements of DIN 4109:2016 [C8] with $L'_{n,w} \leq$ 50 dB and of the proposal for enhanced requirements of DIN 4109:1989 BBI 2 [C9] of $L'_{n,w} \leq$ 46 dB for floors between dwellings. As the low frequencies are often the main problem, caused by walking noise, we can see from figure 4.24

that the fourth floor with the concrete floating floor and the suspended ceiling gives the best results in $L'_{n,w}$ and at low frequencies. This was expected by the high mass of this floor and of the floating floor. The plateau for this floating floor construction at frequencies between 500 Hz and 3150 Hz for the fourth floor and between 250 Hz and 3150 Hz for the fifth floor was not expected. It was explicitly investigated, if the reason for this plateau were sound bridges. First, at the edges a strip of the floating floor of approximately 18 cm width was removed and the impact measurement was repeated. No physical edge sound bridges were found and the measurement results showed similar normalised impact sound pressure levels for the floor with floating floor with reduced size, compared to the full size floor. When removing the entire floating floor, it was again checked if sound bridged were present. No indication for any sound bridges was found when removing the floating floor. Therefore we can conclude that no sound bridges were present in the construction of the floating floor and that the floating floor was properly installed.

For the second to fifth floor and the basic floor, mobility and velocity measurements were performed according to the measurement template given by the project partners. The data of all measurements were distributed to the project partners by the Silent Timber Build Website (http://team.splogin.se/sites/silenttimberbuild/SitePages/Home.aspx) and the denotation is given in table 4.5.

Table 4.5: Denotation of all measurement data provided for the project partners

Descriptive name of floor construction in this report	Naming of the data set provided for the project partners
First floor	20141013_IBP-Data_Wooden-Beam-Floor_P8.xlsx
Second floor	20160727_Data Floor 1 STB.zip
Third floor	20160728_Data Floor 2 STB.zip
Fourth floor	20161005_Data Floor 3 STB.zip
Fifth floor	20161115_Data Floor 4 STB.zip
Basic floor	20161221_Data raw Floor STB.zip

This data is used to validate and refine the modelling of the wooden floors in the project by using the software further developed within the project (SEAWood) and FEM analysis. This is reported by the project partners in the report of work package WP1.

During the changes of the floors, some interim-measurements were performed to check different stages of the floor. Impedance and velocity measurements were not performed at the interim-measurements. The measurements of the sound reduction index and the normalized impact sound level were partly made with reduced number of excitation positions, as full measurements were not possible within the building process. Results of these interim measurements are shown in figure 4.25.

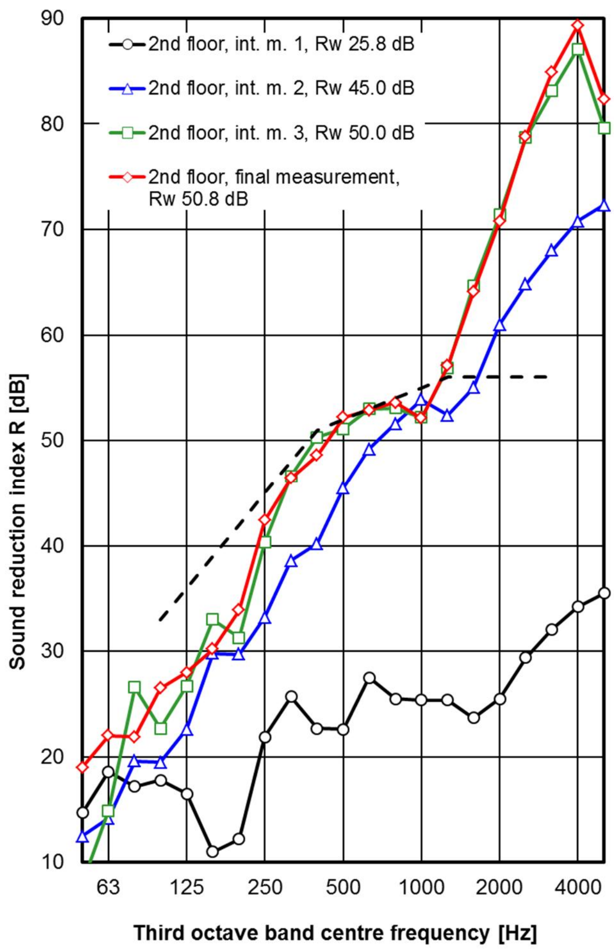


Figure 4.25: Measured sound reduction index R of the interim measurements during build-up of the second wooden beam floor. (Interim measurement 1: with the first OSB layer installed on top of the beams. Interim measurement 2: floor with the second OSB-plate on top of plastic interlayer Troba-Plus, mineral wool impact sound insulation, Heraklith plate and first OSB-plate. Third interim measurement: complete second wooden beam floor with reduced number of microphone positions; the final measurement was performed with the full number of excitation positons and microphone positions.)

The measurements during build-up of the second floor show between interim measurement 1 and 2 the benefit of the dry floating floor by a much steeper increase of the sound reduction index with rising frequency. The additionally added dry floating floor for the interim measurement 3 and the final measurement increases the mass of the upper layers above the impact sound insulation by approximately a factor of 4, compared to interim measurement 2. This leads to a shift of the sound reduction index curve to lower frequencies and to a 5 dB higher weighted sound reduction index. The comparison of interim measurement 1 to the measurement of the basic floor, both performed at the similar construction, interim measurement 1 before the installation of the dry floating floor and the basic floor measurement after removal of both floating floors at the end of the measurement series, show quite similar spectra and a difference in R_w of 0.8 dB (compare figure 4.23 and 4.25).

The measurement of the normalized impact sound pressure levels at the interim floors is shown in figure 4.26.

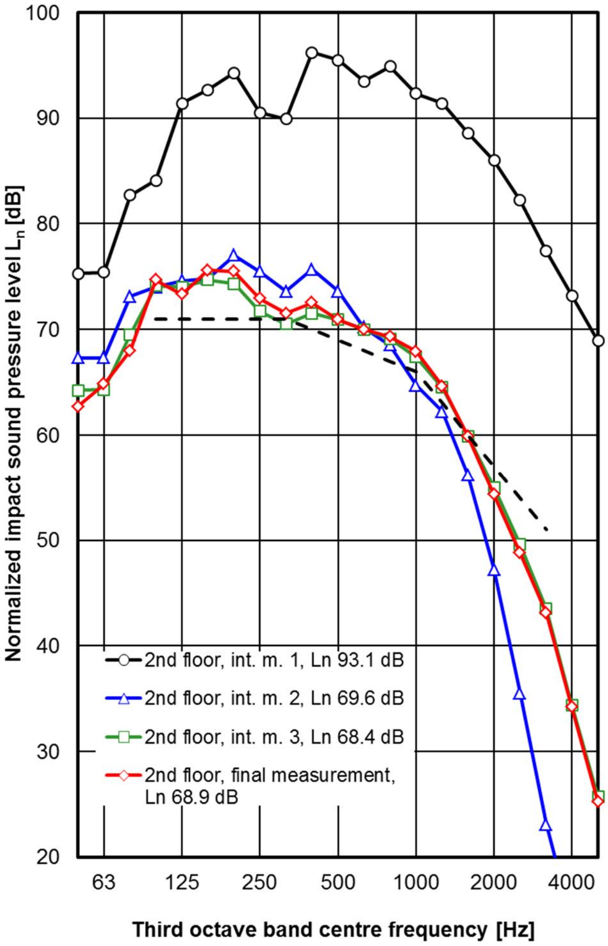


Figure 4.26: Measured normalized impact sound pressure level L_n of the interim measurement during build-up of the second wooden beam floor. Interim measurement 1: with first OSB layer installed on top of the beams. Interim measurement 2: with second OSB-plate on top of the plastic interlayer (Troba-Plus, Schlüter), mineral wool impact sound insulation, Heraklith plate and first OSB-plate. The third interim measurement: complete second wooden beam floor with reduced number of microphone positions; the final measurement was performed with the full number of excitation and microphone positions.

The comparison of the normalized impact sound pressure level in figure 4.26 shows slightly lower impact levels for the complete second wooden beam floor at the low frequencies below 100 Hz, compared to interim measurement 1 and 2. At higher frequencies between 200 and 500 Hz, the impact sound pressure levels of the 2nd floor are lower than for interim measurement 2. At the frequencies above 630 Hz, the impact sound pressure levels of the 2nd floor are higher than for interim measurement 2. It is assumed that this is caused by the harder surface of the dry floating floor material, compared to the OSB plate material of interim measurement 2, leading to more energy input into the top plate by the standard tapping machine.

The comparison of interim measurement 1 to the measurement of the basic floor, both performed at the similar construction, interim measurement 1 before the installation of the dry floating floor and the basic floor measurement after removal of both floating floors at the end of the measurement series, show quite similar spectra and a difference in $L_{n,w}$ of 1.3 dB, compare figure 4.24 and 4.26.

4.8 Conclusions of the measurements at IBP

For the verification of the modelling, laboratory measurements on six wooden floors were provided. The first wooden floor, with and without a dry floating floor, are measurements from the previous AcuWood-Project. The data was provided at the beginning of the project and enabled the verification of wooden beam floor models from the start of the project. During the project, five additional floor assemblies were designed and measured, based on a different wooden beam floor construction, typical for German market but still adapted to the verification procedure, after agreement between the project Work Packages during the meeting in Trondheim in April 2016. Hence the layups were choosen in order to make sure that the verification procedure is as efficient as possible. The floors were built up in the laboratory by the project partner Bauer Holzbau. For the project, a measurement template [C5] was worked out describing what measurements were needed for the verification of the models, and the measurements were made according to the template and, as mentioned above, the input of the work packages / project partners. Because of practical reasons, the measurements were performed as a series of different floor constructions from July 2016 to December 2016. The measurements included a basic floor construction as well as two floor constructions with different floating floors and two optimised constructions with additional suspended ceiling. The measurement results included airborne and vibration measurements with a large amount of data and were provided to the project partners by the Silent Timber Build Website (http://team.splogin.se/sites/silenttimberbuild/SitePages/Home.aspx). Main results from airborne sound insulation measurements at IBP are given in table 4.6.

Table 4.6. Main results, airborne sound insulation from IBP measurements

Wooden floor	$R_{,w}$ (dB)	$C_{50\text{-}5000}$ (dB)	SUM (dB)	Mass per unit area (kg/m^2)	Dynamic stiffness (MN/m^3)	Floor thickness (mm)
AcuWood-1	45	-3	42	52	-	238
AcuWood-2	54	-5	49	77	60	267
WP-2: Basic	26	0	26	36	-	262
WP-2: Second	50	-6	44	105	< 50	374
WP-2: Third	68*	-16	52	118	< 50	417
WP-2: Fourth	71*	-17	54	240	< 8	440
WP-2: Fifth	69*	-13	56	227	< 8	398

* Limitation of the R_w-value due to sound transmission in the test suite

Main results from impact sound insulation measurements at IBP are given in table 4.7.

Table 4.7. Main results, impact sound insulation from IBP measurements

Wooden floor	$L_{n,w}$ (dB)	$C_{I,50\text{-}2500}$ (dB)	SUM [1)] (dB)	Mass per unit area (kg/m^2)	Dynamic stiffness (MN/m^3)	Floor thickness (mm)
AcuWood-1	74	1	75	52	-	238
AcuWood-2	68	0	68	77	60	267
WP-2: Basic	92	-4	92	36	-	262
WP-2: Second	69	-1	69	105	< 50	374
WP-2: Third	46	11	57	118	< 50	417
WP-2: Fourth	31	21	52	240	< 8	440
WP-2: Fifth	53	-1	53	227	< 8	398

1) Negative values of $C_{I,50\text{-}2500}$ neglected in the sum

5. Trend analysis and optimization of floor assemblies

5.1 Joist based constructions, group A

In the following, the main results from chapter 2 are compiled and further analyzed in order to reduce the number of various floor assembly layouts and facilitate modelling. Table 5.1 shows single number values and corresponding mass per unit area (mpua) and floor thickness of constructions type A. Figure 5.1, shows $L_{n,w}+C_{I,50\text{-}2500}$ – values as a function of the mpua for solutions with stiff connected top floor. The figure also includes a curve based on a ratio between $L_{n,w}+C_{I,50\text{-}2500}$ – values and the mpua of -30 log (mpua). The -30 log term refers to the basic equation of impact sound insulation of homogeneous floors.

Table 5.1. Main results, impact sound insulation from construction group A

Type A	$L_{n,w}$ (dB)	$C_{I,50\text{-}2500}$ (dB)	SUM (dB)	Mass per unit area (kg/m^2)	Floor thickness (mm)	Source
FS-CS	60	4	64	39	364	FR
FS-CS	72	-	-	44	256	NO
FS-CS	73	1	74	51	238	DE
FR-CS	65	4	69	57	333	FIN
FR-CS	64	5	69	60	346	CH
FR-CS	67	0	67	61	277	DE
FS-CR	55	-	-	37	452	FR
FS-CR	63	5	68	43	281	CH
FS-CR	58	-	-	47	296	NO
FS-CR	58	0	58	48	373	SE
FS-CR	56	0	56	54	352	FIN
FS-CR	50	3	53	69	402	SE
FS-CR	46	3	49	98	430	SE
FR-CR	49	5	54	71	338	FIN
FR-CR	46	8	54	74	335	SE
FR-CR	43	13	56	75	362	SE
FR-CR	49	4	53	75	349	NO
FR-CR	42	11	53	75	362	SE
FR-CR	45	5	50	86	430	SE
FS-CN	54	3	57	47	419	FR
FS-CN	52	3	55	63	562	NO
FS-CN	51	4	55	76	460	FIN

Looking into single number quantities, results given in figure 5.1 show a high correlation between the $L_{n,w}+C_{I,50\text{-}2500}$ value and the mass per unit area (-30 log mpua) of FS-CR solutions except in the low mpua region. An explanation for these findings are similar (or equal) properties of the resilient profiles used in the Nordic countries. For other floor assemblies with stiff connected top floor, it is not possible to establish a reliable correlation between the $L_{n,w}+C_{I,50\text{-}2500}$ value and the mpua from the collected data. Figure 5.1 also shows that a mpua of at least 75 kg/m^2 is necessary to get $L_{n,w}+C_{I,50\text{-}2500}$ – values below 53 dB with stiff connected top floor and no flanking transmission contribution.

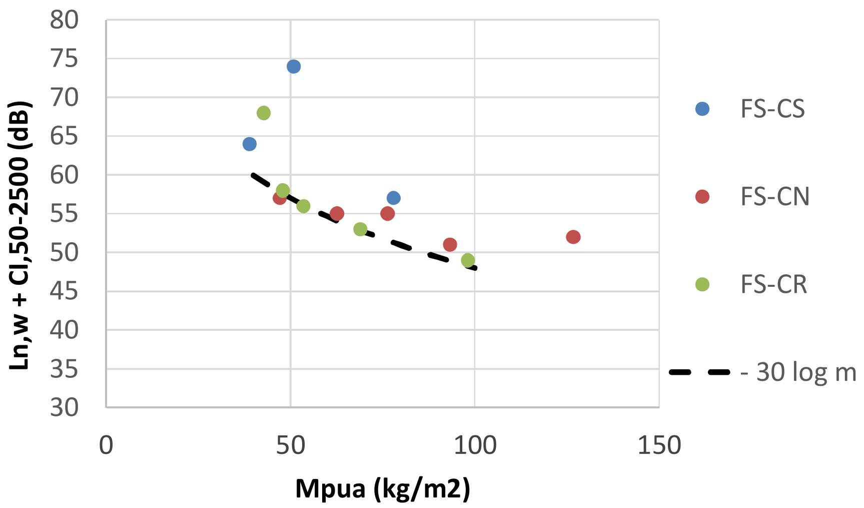


Figure 5.1. Single number values as a function of mass per unit area, construction group A: FS

Figure 5.2, show $L_{n,w}+C_{I,50-2500}$ – values as a function of the mpua for solutions with resilient connected top floor including a curve based on a ratio between $L_{n,w}+C_{I,50-2500}$ – values and the mpua of -50 log (mpua). The - 50 log(m) term refers to the basic equation of impact sound insulation of homogeneous floors including a resilient top floor solution.

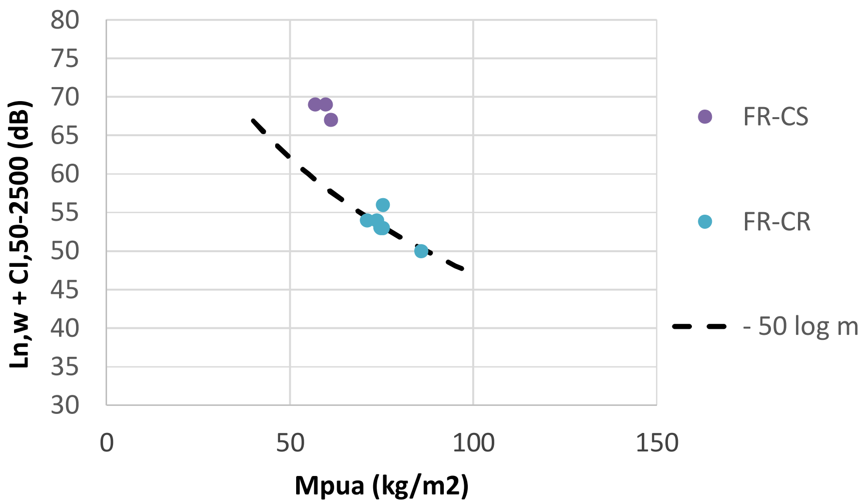


Figure 5.2. Single number values as a function of mass per unit area, construction group A: FR

Results given in figure 5.2 shows a high correlation between the $L_{n,w}+C_{I,50-2500}$ value and the mass per unit area of FR-CR solutions. However, since the dynamic stiffness of the resilient layer at the floor varies, it will be a scattering of these results depending on this parameter. Figure 5.2 also shows that a mpua of at least approximately 75 kg/m^2 is necessary to get $L_{n,w}+C_{I,50-2500}$ – values below 53 dB also with resilient connected top floor and no flanking transmission. Combining results from figure 5.1 and 5.2, the elastic properties of the resilient floors seems not to give any significant improvement of the $L_{n,w}+C_{I,50-2500}$ – values. The reason for this is a negative effect at the resonance frequency of the top floor solution normally within the frequency range 50 to 125 Hz for these relatively lightweight floors. When increasing the mass of the floor (on both sides of the resilient layer) lower single number values is expected for type A: FR compared to the type A: FS solution.

Figure 5.3, shows $L_{n,w}+C_{I,50\text{-}2500}$ – values as a function of the total thickness of the floor. For such lightweight floor constructions, the overall tendency of decreased single number value with increased floor thickness is clearly seen. As we also could expect, the scattering is huge due to the physical parameters determining the sound transmission and radiation. This information may be used to select a relevant solution when the limitation of one of these parameters has been set.

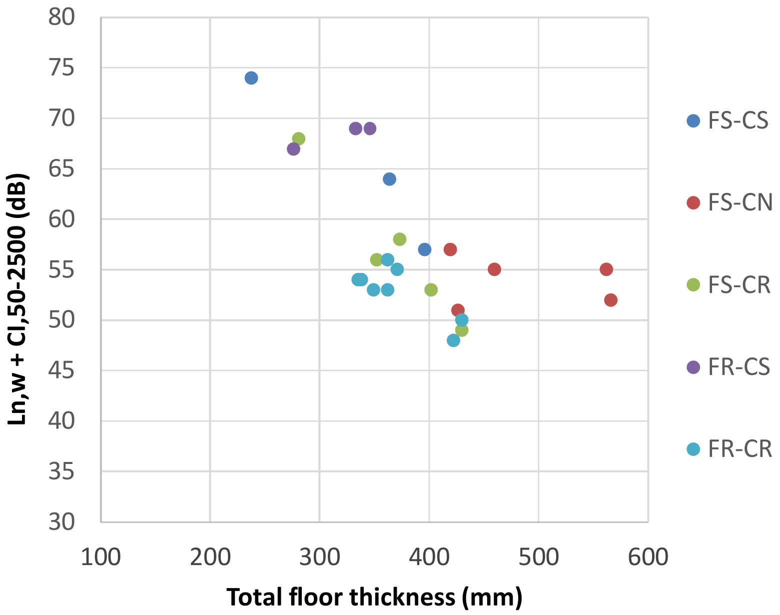


Figure 5.3. Single number values as a function of the total floor thickness, group A

Analysis have also been performed regarding the air cavity resonance, f_o of type A constructions with respect to the $L_{n,w}+C_{I,50\text{-}2500}$ – values. This parameter takes both the mass (divided into source and receiving part of the floor) and the enclosed cavity into account. Figure 5.4 and 5.5 shows $L_{n,w}+C_{I,50\text{-}2500}$ – values as a function of the air cavity resonance. The correlation between the air cavity resonance and the $L_{n,w}+C_{I,50\text{-}2500}$ – values is quite good for both FS-CS, FS-CN, FS-CR and FR-CR constructions. From calculations and results presented in figure 5.4 and 5.5 it looks reliable to achieve $L_{n,w}+C_{I,50\text{-}2500}$ – values below 53 dB when the f_o-value is below 28 Hz for FS-CR and FR-CR solutions.

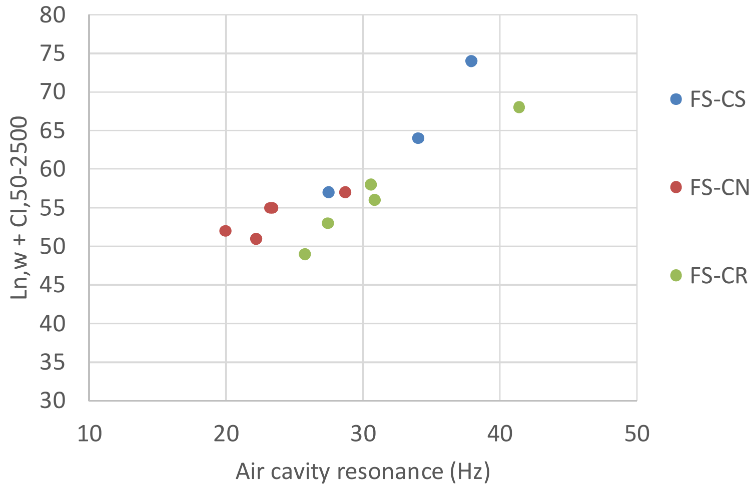


Figure 5.4. Single number values as a function of the air cavity resonance, group A: FS-CS, FS-CN and FS-CR

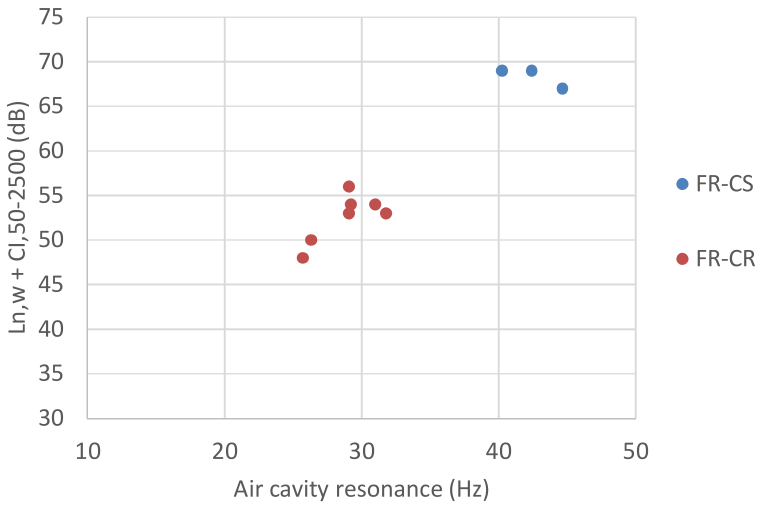


Figure 5.5. Single number values as a function of the air cavity resonance, group A: FR-CS and FR-CR

5.2 Hybrid joist based constructions, group B

Table 5.2 shows single number values and the corresponding mass per unit area of constructions type B. Figure 5.6 shows $L_{n,w}+C_{I,50\text{-}2500}$ – values as a function of the mass per unit area (mpua) for all available solutions. The figure also include a curve based on a ratio between $L_{n,w}+C_{I,50\text{-}2500}$ – values and the mpua of -40 log (mpua). The -40 log term refers to the basic equation of impact sound insulation of homogeneous floors including an effect of a resilient subfloor.

Table 5.2. Main results, impact sound insulation from construction group B

Type B	$L_{n,w}$ (dB)	$C_{I,50\text{-}2500}$ (dB)	SUM (dB)	Mass per unit area (kg/m^2)	Floor thickness (mm)	Source
FS-CS	50	1	51	150	414	FR
FS-CS	56	0	56	260	409	DE
FR-CS	62	-	-	113	322	CH
FR-CS	59	-	-	158	352	CH
FR-CS	50	7	57	182	399	DE
FR-CS	48	6	54	226	411	DE
FR-CS	45	6	51	270	424	DE
FR-CS	41	6	47	272	444	DE
FR-CS	40	8	48	323	320	CH
FR-CS	45	1	46	365	387	DE
FR-CS	37	7	44	377	367	CH
FR-CS	42	2	44	386	412	DE
FR-CR	45	-	-	113	317	CH
FR-CR	42	6	48	116	422	NO
FR-CR	47	8	55	166	371	DE
FR-CR	42	4	46	180	539	NO
FR-CR	38	-	-	180	394	CH
FR-CR	44	7	51	224	497	FIN
FS-CN	40	12	52	127	566	NO

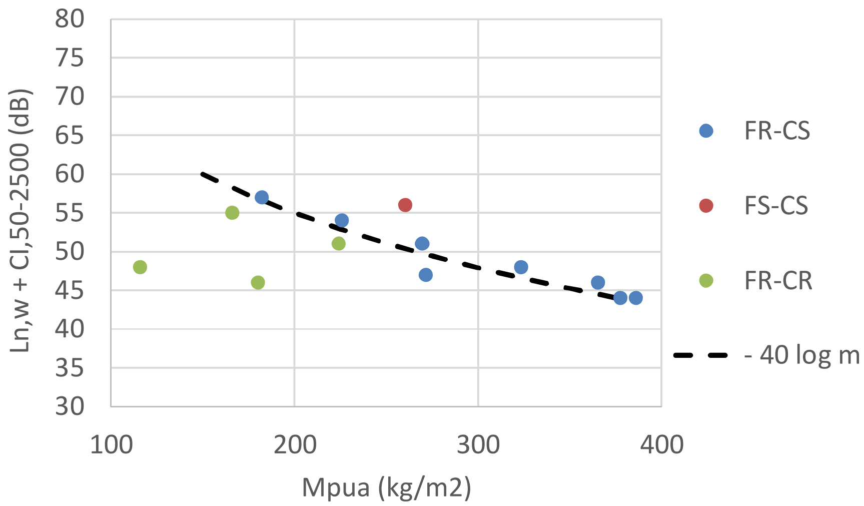


Figure 5.6. Single number values as a function of mass per unit area, construction groupB

Looking into single number quantities, results given in figure 5.4 show a high correlation between the $L_{n,w}+C_{I,50\text{-}2500}$ values and the mass per unit area (- 40 log mpua) of FR-CS solutions. This means that the resilient layer at the top floor used in these examples may have similar properties with respect to dynamic stiffness. However, some scattering occur (and partly seen from the figure) due to different dynamic stiffness of the resilient layer at the floor and thereby the resonance frequency of the top floor. The results will also depend on the connections at the ceiling of course, but this effect seems small from the collected measurement results. Results given in figure 5.6 shows a poor correlation between the $L_{n,w}+C_{I,50\text{-}2500}$ value and the mass per unit area of FR-CR solutions. The reason is probably variations of both the dynamic stiffness of the resilient layer at the floor and the resiliency of the ceiling hangers. But from the available information it is not possible to determine the limiting parameter. Figure 5.6 also shows that a mpua of at least 250 kg/m^2 is necessary to get $L_{n,w}+C_{I,50-2500}$ – values below 53 dB with resilient connected top floor, stiff connected ceiling and no flanking transmission contribution. Optimizing the elastic properties of both the floor and the ceiling, $L_{n,w}+C_{I,50-2500}$ – values well below 53 dB should be possible even for mpua below 200 kg/m^2, see FR-CR results in figure 5.6.

Figure 5.7, shows $L_{n,w}+C_{I,50-2500}$ – values as a function of the total thickness of the floor. For such hybrid floor constructions, the number of objects is limited and from the data available, there is no significant correlation between the single number value and the floor thickness.

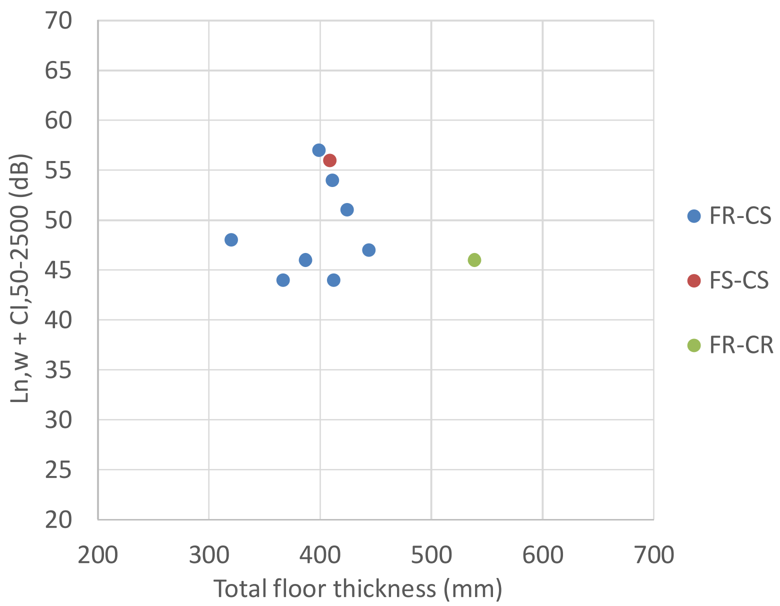


Figure 5.7. Single number values as a function of the total floor thickness, group B

Analysis have also been performed regarding the air cavity resonance, f_o of type B constructions with respect to the $L_{n,w}+C_{I,50-2500}$ – values. The correlation between the air cavity resonance and the $L_{n,w}+C_{I,50-2500}$ – values is available for FR-CS and FR-CR constructions. Regarding the FS-CS constructions, the number of examples is limited, and therefore an evaluation is not carried out. Figure 5.8 shows $L_{n,w}+C_{I,50-2500}$ – values as a function of the air cavity resonance. The figure shows a tendency of correlation between the f_o-value and the $L_{n,w}+C_{I,50-2500}$ – value, but the scattering is relatively high probably due to different properties of the resilient layer on top of the floor. However, it looks necessary to have a f_o-value of maximum 25 Hz to achieve $L_{n,w}+C_{I,50-2500}$ – values below 53 dB.

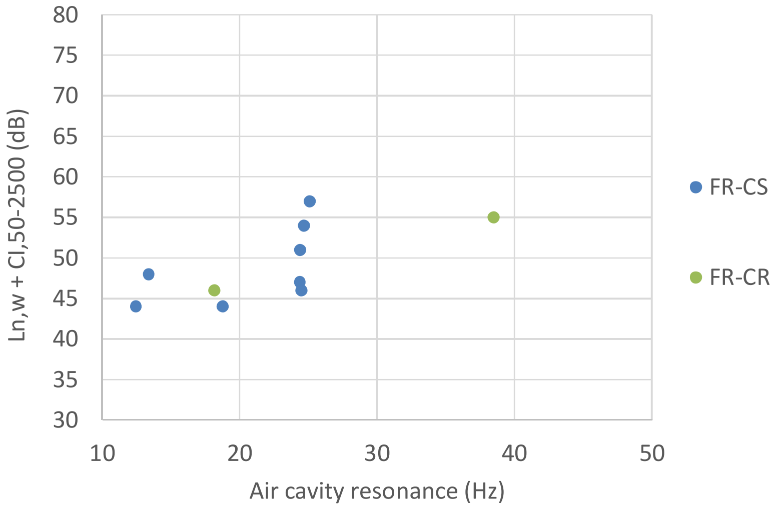


Figure 5.8. Single number values as a function of the air cavity resonance, group B:FR

5.3 CLT constructions, group C

In the following, the main results from chapter 3 are given. Table 5.3 shows single number values, the corresponding mass per unit area (mpua) and the total floor thickness of lightweight CLT floor assemblies. The dynamic stiffness is given for objects with continuous elastic floor interlayer. Figure 5.9 shows $L_{n,w}+C_{I,50-2500}$ – values as a function of the mpua for all objects of group C (FR-CS; FS-CS[2)] (some resiliency); FS-CN). The figure also includes a curve based on a ratio between $L_{n,w}+C_{I,50-2500}$ – values and the mpua of -50 log (mpua). The -50 log term refers to an empirical tendency of the available results with respect to the mpua value.

Table 5.3. Main results, impact sound insulation from lightweight floor assemblies

Type	$L_{n,w}$ (dB)	$C_{I,50-2500}$ (dB)	SUM [1)] (dB)	Mass per unit area (kg/m²)	Dynamic stiffness (MN/m³)	Floor thickness (mm)	Source
FS-CS [4)]	86	-5	86	51	-	102	AU
FS-CS [4)]	86	-5	86	58	-	115	SE
FS-CS [4)]	85	-4	85	68	-	150	DE
FS-CS [4)]	83	-7	83	80	-	160	NO
FS-CS [4)]	87	-5	87	85	-	180	NO
FS-CS [4)]	85	-5	85	89	-	190	SE
FR-CS	65	0	65	78	50	172	DE
FR-CS	68 [3)]	0	68	84	50	145	FR
FR-CS	47 [3)]	8	55	119	Line elast.	332	NO
FR-CS	57 [3)]	2	59	130	Point elast.	430	NO
FR-CS	49 [3)]	3	52	136	Line elast.	389	NO
FS-CS [2)]	68	-3	68	74	-	249	FR
FS-CS [2)]	58 [3)]	5	63	77	-	251	FR
FR-CS [2)]	51	4	55	107	40	290	FR
FR-CS [2)]	50 [3)]	6	56	110	40	292	FR
FS-CN	49	4	53	75	-	437	SE

1) Negative values of $C_{I,50-2500}$ neglected in the sum according to NS 8175 [B21]
2) Some elastic effect of the suspension system
3) Measurement object with some type of floor covering
4) Only the CLT element

Looking into the single number quantities, results given in figure 5.9 shows an overall tendency of correlation between the $L_{n,w}+C_{I,50-2500}$ value and the mass per unit area. The scattering with respect to the – 50 log m curve is approximately ± 2-3 dB for all examples except the FS-CN solution. The number of objects is rather limited, so it is necessary to pay attention on how to use these results. The FS-CN solution provides much better $L_{n,w}+C_{I,50-2500}$ value with respect to the mpua. The spreading of the single number quantities shows that the dynamic stiffness of the resilient layer at the floor (FR type of floors) determining the resonance frequency of the top floor and the structural connections between the CLT element and the ceiling are crucial.

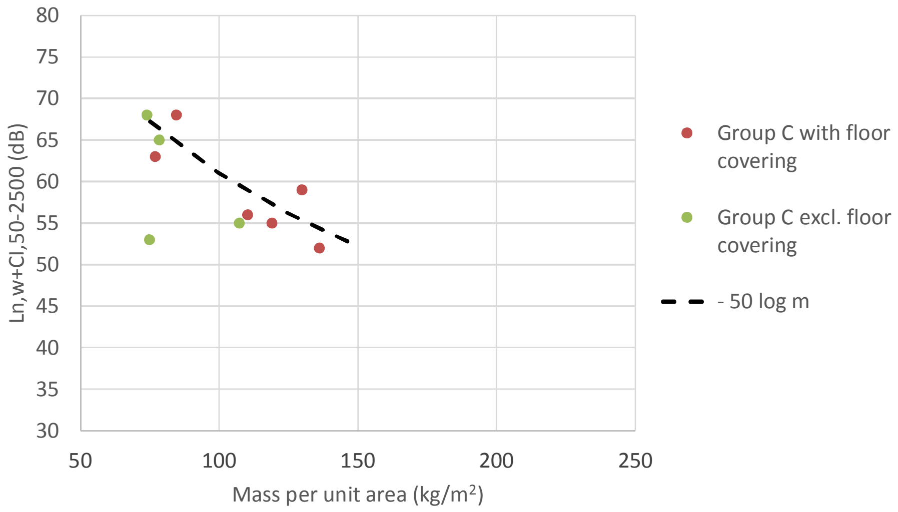


Figure 5.9. Single number values as a function of mass per unit area of group C (FR-CS; FS-CS[2)] (some resiliency); FS-CN), lightweight floor assemblies including a tendency curve of – 50 log mpua - single CLT element excluded

Figure 5.10 shows a similar comparison but limited to FR floor assemblies only and depending on high or low dynamics stiffness values. The effect of the dynamic stiffness is clearly visible as expected from basic theory, and it demonstrates that it is possible to optimize with respect to mpua or floor assembly thickness, for example. Results presented in table 5.3, figure 5.9 and 5.10 demonstrate that it is realistic to achieve $L_{n,w}+C_{I,50\text{-}2500}$ values in the range 52 – 56 dB for FR-CS floors. Based on the – 50 log m curve from figure 5.9, values below 53 dB should be possible when the mpua exceed 150 kg/m^2.

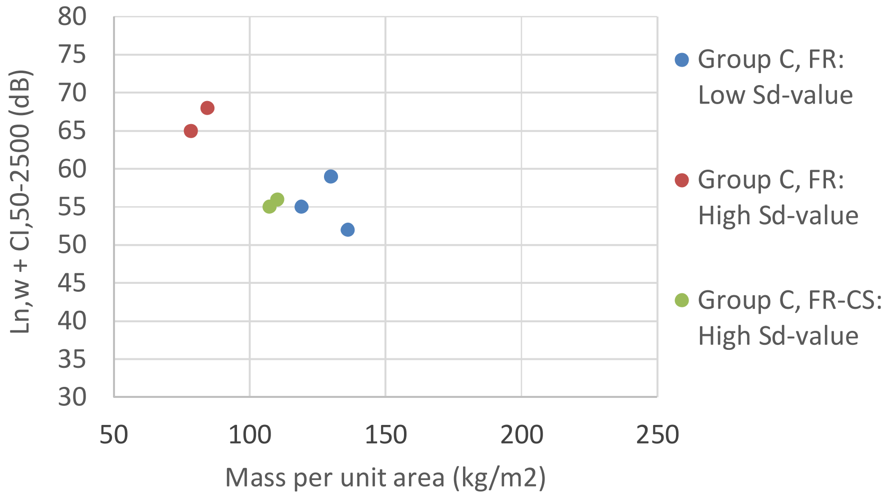


Figure 5.10. Single number values as a function of the mass per unit area of group C, FR and FR-CS solutions

Figure 5.11 shows $L_{n,w}+C_{I,50\text{-}2500}$ – values as a function of the total thickness of the floor. Hence, for lightweight floor assemblies described in this section, the overall tendency of decreased single number value with increased floor thickness is clearly seen. But as also expected, the scattering is large due to the various physical parameters determining the sound transmission and radiation. It is therefore possible to achieve the same $L_{n,w}$+$C_{I,50-2500}$ – value within a wide range of floor thicknesses. This information may be used to select a relevant solution when the limitation of one of these parameters has been set.

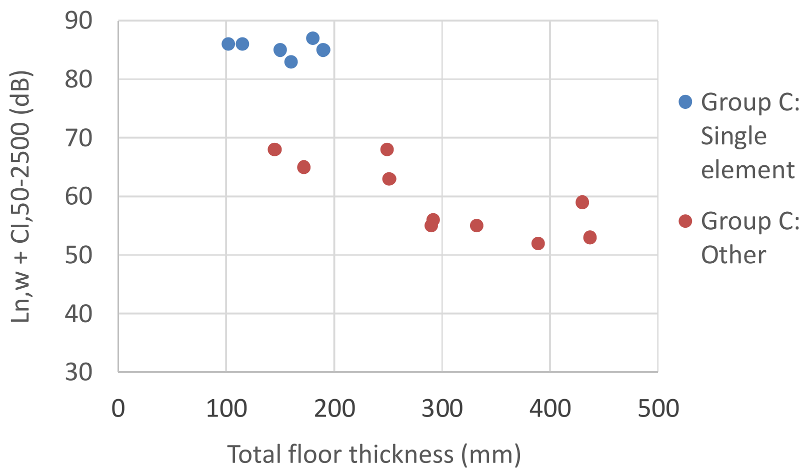


Figure 5.11. Single number values as a function of the total floor thickness, group C

5.4 CLT constructions, group D

Table 5.4 shows single number values, the corresponding mass per unit area and the total floor thickness of hybrid floor assemblies, type I, IV and V. The dynamic stiffness is given for objects with continuous elastic floor interlayer. Figure 5.12 shows $L_{n,w}$+$C_{I,50-2500}$ – values as a function of the mass per unit area (mpua) for solutions with resilient top floor, i.e. type IV assemblies. The figure also includes a curve based on a ratio between $L_{n,w}$+$C_{I,50-2500}$ – values and the mpua of - 60 log (mpua). The - 60 log(m) term refers to an empirical tendency of the available results with respect to the mpua value.

Table 5.4. Main results, impact sound insulation from hybrid floor assemblies

Type	$L_{n,w}$ (dB)	$C_{I,50\text{-}2500}$ (dB)	SUM [1)] (dB)	Mass per unit area (kg/m²)	Dynamic stiffness (MN/m³)	Floor thickness (mm)	Source
FS-CS [3)]	84	-12	84	204	-	165	DE
FS-CS [3)]	90	-13	90	223	-	240	NO
FR-CS	55	3	58	179	6	240	DE
FR-CS	66	-3	66	193	20	210	CH
FR-CS	56 [2)]	1	57	235	> 20	324	NO
FR-CS	55 [2)]	3	58	241	< 10	298	NO
FR-CS	44 [2)]	6	50	245	< 10	330	NO
FR-CS	47 [2)]	1	48	265	Line elastic	451	NO
FR-CS	40	7	47	269	6	300	DE
FR-CS	47	3	50	282	40	315	DE
FR-CS	47	1	48	298	6	255	DE
FR-CS	46	6	52	345	20	310	CH
FR-CR	46	10	56	182	< 15	297	AU

1) Negative values of $C_{I,50\text{-}2500}$ neglected in the sum according to NS 8175 [B21]

2) Measurement object with some type of floor covering

3) Concrete directly mounted on CLT

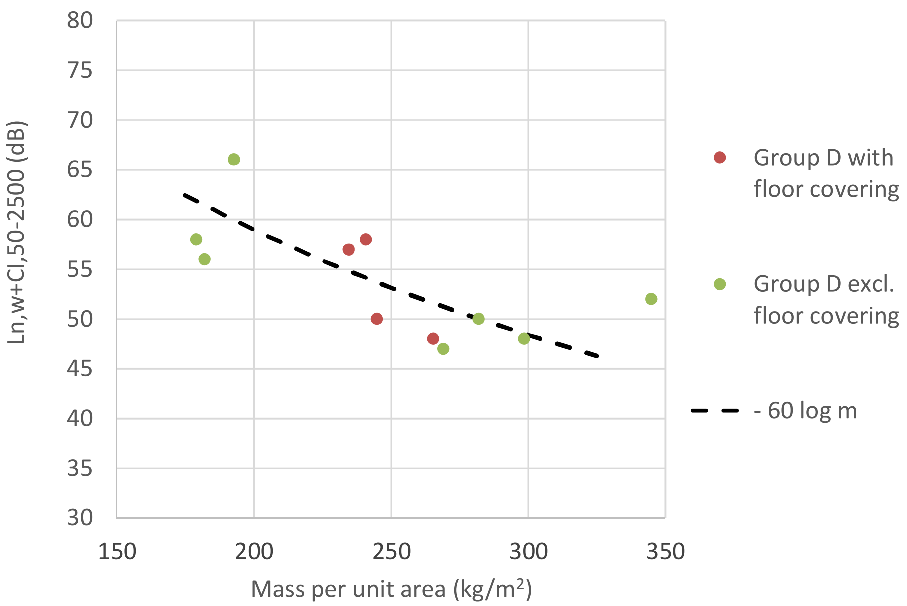


Figure 5.12. Single number values as a function of mass per unit area of group D (FR-CS; FR-CR), hybrid floor assemblies including a tendency curve of – 60 log mpua

The compilation of constructions presented in figure 5.12 also shows an overall tendency of correlation between the $L_{n,w}+C_{I,50\text{-}2500}$ value and the mass per unit area. The lack of floor covering limits the single number value of some objects, see table 5.4. But as seen from figure 5.12, the scattering is relatively high, approximately ± 5 dB for all examples and even higher for the heaviest FR example. The mpua value is therefore not a relevant parameter to estimate the single number value for these floor assemblies.

Figure 5.13 shows a similar comparison depending on high of low dynamics stiffness values. The effect of the dynamic stiffness is only at low mpua clearly seen, as we also could expect from basic theory, and it demonstrates that an optimization is possible with respect to for instance mpua or floor assembly thickness. Results presented in table 5.4, figure 5.12 and 5.13 demonstrate that it is realistic to achieve $L_{n,w}$+$C_{I,50\text{-}2500}$ values below 50 dB for type IV objects. Based on the – 60 log m curve from figure 5.12, values below 53 dB should be possible when the mpua exceed 250 kg/m^2.

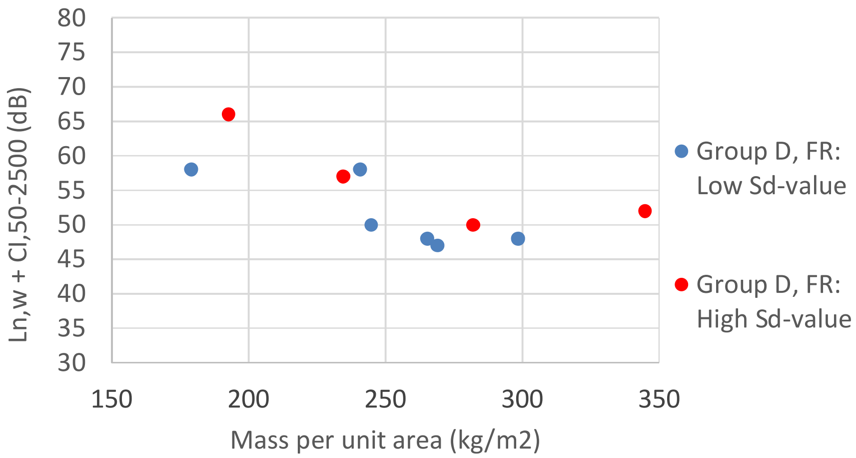


Figure 5.13. Single number values as a function of mass per unit area and dynamic stiffness values of group D (FR-CS; FR-CR) solutions

Comparing results from group C (FR-CS) and Group D (FR-CR), it would be possible to choose lightweight top floor solutions when the results is not expected to be lower / better than $L_{n,w}$+$C_{I,50\text{-}2500}$ 53 dB, and when flanking transmission is negligible. Figure 5.14 shows $L_{n,w}$+$C_{I,50\text{-}2500}$ – values as a function of the total thickness of the floor for group D floor assemblies. For such hybrid floor constructions, it is a tendency of correlation between the single number value and the floor thickness, but the scattering is huge. As seen from the figure, it is possible to achieve the same $L_{n,w}$+$C_{I,50\text{-}2500}$ – value within a very wide range of floor thicknesses. But the information may be used to select a relevant solution when the limitation of one of these parameters have been set.

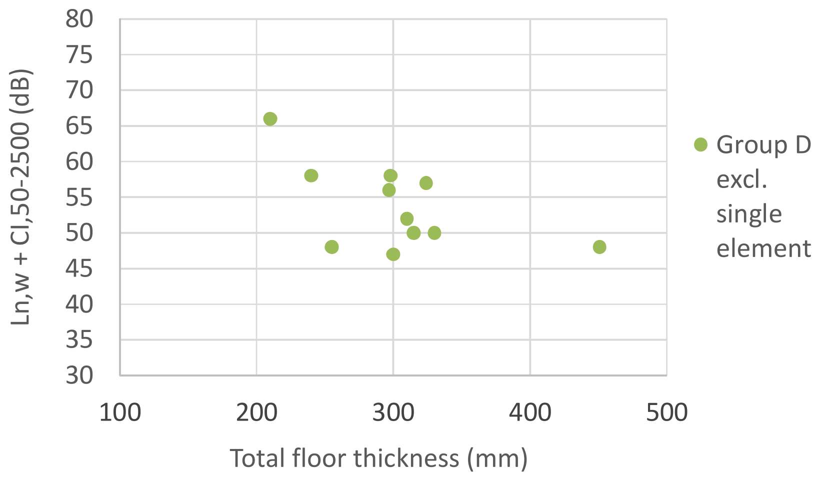


Figure 5.14. Single number values as a function of the total floor thickness, group D (FR-CS; FR-CR)

6. Conclusions

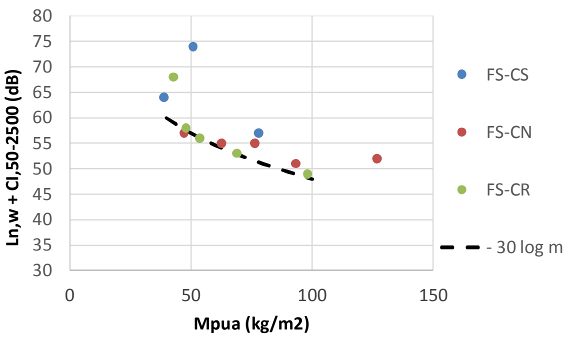
Current existing European wooden floor- and wall assemblies comprises a huge number of variables. The building materials involved in various solutions are numerous. All these variables make it difficult to predict and really identify what is most essential in order to optimize the structure in terms of acoustics and vibrations. When modelling, how can we really be sure that the correct assumptions are carried out and in the extension, that the results are trustable? That is the reason why this project started with collection of current data and then a following grouping of the building systems (floor assemblies primarily). The grouping were made in order to detect relations between important variables that might be used in order to make rough estimations of the floor assembly sound insulation characteristics. Hence, as a new wooden floor assembly is modelled, the grouping can be helpful by following the steps below:

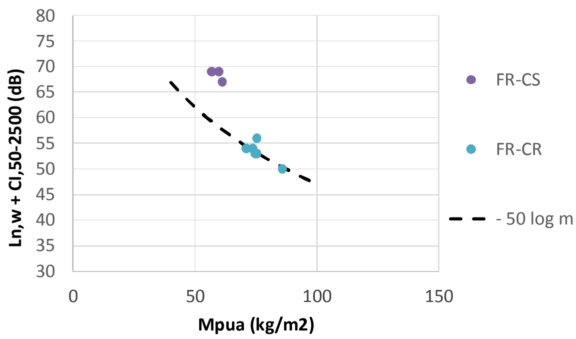
1. Identify which group the actual floor assembly belongs to
2. Make a rough estimation of the expected sound insulation by using the relations found in this project.
3. Does the model result fit to expected value, within reasonable range?
4. Refine your model
5. Optimize and propose improvements
6. And the more we use it the more we learn

The relations that was found by grouping is different for different groups, however generally they are all based on the mass per unit area (mpua). In previous section some other important parameters are raised as well, such as thickness and cavity resonance. Hence, the description in this concluding section is generalized – it is needed to read the entire chapter 4 in order to see all parameters that affects the results and consider them prior to make any conclusions. The groups are based on the bearing structural elements, the ceiling and its fixing and finally the flooring on top (and their resiliency) of the structural elements, see section 1 “Introduction”.

The relations are summarized in the graphs below. The results pre-assume that the basic design rules regarding floor thickness and cavity resonance and similar are followed. For group A the relations are different depending on the flooring on top of the structural element, whether it is connected with some resiliency or connected stiff to the structural components.

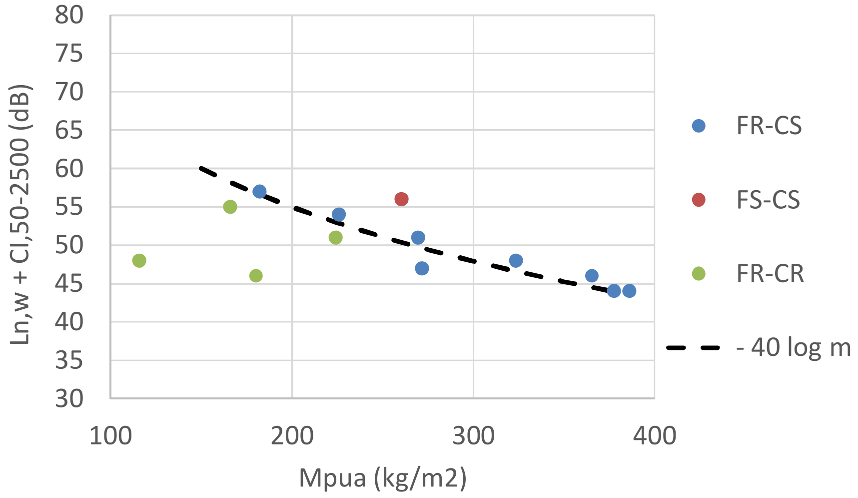
Group A (Wood Joists)





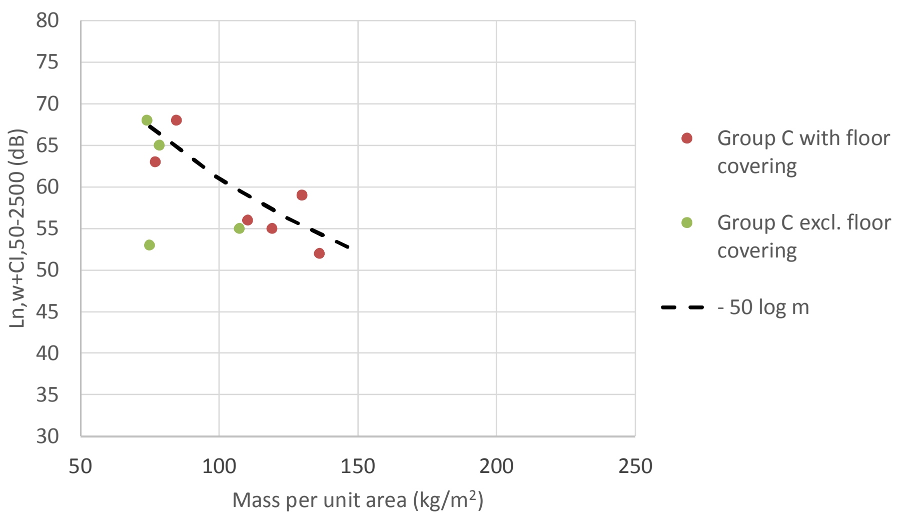
From these relationships it is obvious that it might be possible to create a floor assembly with a mpua = 75-100 kg, still performing acceptable sound insulation characteristics at least regarding the ISO single numbers from 50 Hz. For lower frequencies it might be unsatisfactory. As long as the ceiling is separated from the floor in a proper manner a specific resilient layer on the floor is not necessarily needed. Careful design has to be undertaken.

Group B (Hybrid wood Joists)



Adding mass contributes to a more safe solution. The “really bad” outliers reduces and the single numbers become rather low as the mpua increases. However, the levels below 50 Hz are not really known fully and yet another shortcoming is that the more you load the wood with gravel and / or concrete the more its advantages (for example in terms of environmentally friendly and span width) diminishes.

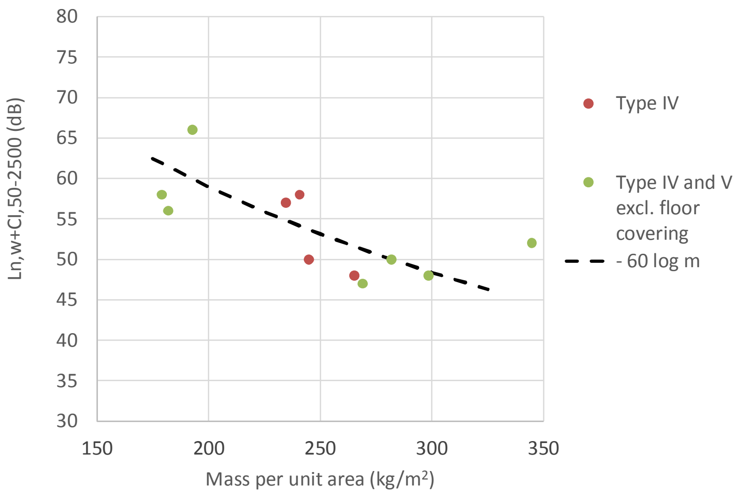
Group C (massive wood, CLT and similar)



Massive wood elements (Cross Laminated Timber, CLT, in particular) are currently growing quiet fast, gaining market shares. It can carry load and be used for high rise buildings in wood so the material has big advantages. For floor assemblies it is not the most efficient in case not increased in terms acoustics and vibrations and its mpua. Probably, the bearing element is not stiff enough making the design more insecure in terms of acoustics and vibration.

As long as massive wood elements are used additional measures should be undertaken, either adding mass or create a hybrid solution using CLT in combination with beams. See example developed in the project HCLTP (www.hcltp.com), figure….

Group D (Hybrid massive wood elements)



Again it is clear that adding mass contributes to a more "safe" solution and in this case it is almost necessary. The single numbers improve a lot as the mpua overrun 250 kg, however acoustically this solution is not an optimum. As seen from above Hybrid wood joist deign is more efficient than CLT design. However there are many aspects to consider and that have to be taken into account. And again, the levels below 50 Hz are not really known fully but the relationship above indicates that it might appear some low frequency issues at least if trying to reduce mpua. Similar to Group B yet another shortcoming is that the more you load the wood with gravel and / or concrete the more its advantages (for example in terms of environmentally friendly and span width) diminishes.

7. References

References from Chapter 2

[1] Johansson, C. Field measurements of 170 nominally identical timber floors – a statistical analysis. Proc InterNoise 2000;2000:4072-5.

[2] Ljunggren, F. & Ågren, A. Potential solutions to improved sound performance of volume based lightweight multi-storey timber buildings. Applied Acoustics 72 (2011), p. 231-240.

[3] Warnock, A.C.C., & Birta, J.A. Summary Report for Consortium on Fire Resistance and Sound Insulation of Floors: Sound Transmission Class and Impact Insulation Class results, Internal report IRC-IR-766. Canada 1998.

[4] Sipari, P., Heinonen, R. & Parmanen, J. Acoustic properties of wooden floor slabs. VTT Publications 345. VTT Technical Research Centre of Finland, 1998.

[5] Fothergil, L.C. & Royle, P. The Sound Insulation of Timber Platform Floating Floors in the Laboratory and Field. Applied Acoustics 33 (1991), p. 249-261.

[6] Johansson, C. Low-Frequency Impact Sound Insulation of a Light Weight Wooden Joist Floor. Applied Acoustics 44 (1995) p. 133-147.

[7] EN-ISO 717 Part 2. Acoustics – rating of sound insulation in buildings and of building elements – part 2: Impact sound insulation (1996)

[8] Simmons C., Hagberg K., Backman E. Acoustical Performance of Apartment Buildings – Resident's Survey and Field Measurements, SP report, 2011.

[9] Guigou-Carter C., Balanant N. Acoustic comfort evaluation in lightweight wood-based and heavy weight concrete-based building, Internoise 2015, USA 2015.

[10] Homb, A. Grouping of wood constructions. Silent Timber Build document, april 2015.

[11] SINTEF. Unpublished laboratory measurement results 1983.

[12] Späh, Moritz. Liebl, Andreas & Leistner, Philip. Acoustics in wooden buildings – Measurements in the Laboratory an in Single Family Houses. AcuWood Report 1. SP Report 2014:14.

[13] Acoubois Etapes 2 & 3. Rapport V2.0 Measures Acoustiques en laboratoire. Qualitel, FCBA & CSTB. France, june 2014 (in French).

[14] Homb, Anders. Hveem, Sigurd & Strøm, Svein. Sound insulating structures. Data collection and calculation method. Anvisning 28. Oslo: Norges byggforskningsinstitutt, 1983 (in Norwegian).

[15] Nilsson, Lars. SBUF-Projekt: Wood joist floors. Laboratory measurements at Engineering Acoustics, Lund University. Commisioned by Skanska Teknik AB. SBUF report nr. 1033, Sweden 2003 (in Swedish).

[16] Lignum. Database at: www.lignumdata.ch. Switzerland 2015.

[17] Bois-AcouTherm. Final report, FCBA and partners. Boredeaux, France November 2010 (in French).

[18] Homb, A. Low frequency sound and vibrations from impacts on timber floor constructions. Doctoral theses at NTNU, 2006:132. IME Faculty, Dep. of Electronics and Telecommunications. Trondheim, Norway 2006.

[19] Nemko report ABU0057/03. Sound insulation measurements of wooden joist floors. Commisioned by Arbor Hattfjelldal AS. Classified, contact publisher. Trondheim, Norway nov. 2003 (in Norwegian).

[20] IGP AS, report 215223. Wooden joist floor with gravel. Impact sound insulation measurements. Commisioned by Norske Skog. Classified, contact publisher. Trondheim, Norway 1995 (in Norwegian).

[21] Homb, A. (2003). Laboratory sound and vibration measurements of open web joist supported timber floors. Project report O 14168, Norwegian building research institute for “Norske Takstolprodusenters Forening” (not published). Trondheim June 2003 (in Norwegian).

References from Chapter 3 and 5

[B1] Homb, A., Austnes, J.A.: Experiences with sound insulation for cross-laminated timber floors. Proc. BNAM 2010. Baltic Nordic acoustical meeting, Bergen, Norway 10th to 12th of May 2010.

[B2] Homb, A., Brevik, B.G. Etasjeskillere i massivtre (Cross-laminated timber floors). SINTEF Building & Infrastructure, Building Detail Sheet no. 522.891 (in Norwegian). Oslo, Norway, November 2009. Available on http://www.sintefbok.no/

[B3] Homb, A. Flanking transmission measurements in a cross-laminated timber element building. Proc. Euronoise, Prague Czechoslovakia, 10-13. June 2012.

[B4] Homb, A. Vibrasjonsegenskaper til dekker av massivtre (Vibration properties of cross-laminated timber floors). Project report SINTEF Building & Infrastructure, no. 24 (in Norwegian). Oslo, Norway 2008. Available on http://www.sintefbok.no/

[B5] Homb, A., Hveem, S.: Lydoverføring i byggesystemer med massivtreelementer (Sound transmission in CLT element constructions). Project report SINTEF Building & Infrastructure, no. 80 (in Norwegian). Oslo, Norway 2011. Available on http://www.sintefbok.no/

[B6] Acoubois Etapes 2 & 3. Rapport V2.0, Mesures Acoustiques en laboratoire. Qualitel, FCBA & CSTB. France, june 2014. (in French). http://www.codifab.fr/sites/default/files/acoubois_mesures_laboratoire.pdf

[B7] Holtz, F., Rabold, A., Hessinger, J., Buschbacher, H.P., Oechsle, O., Lagally Th. Schalltechnische Kennwerte von Massivholzbauteilen, Bestandsaufnahme und Analyse (Acoustic parameters of solid wood elements, data collection and analysis). Labor für Schall- und Wärmemesstechnik, research report 2001.

[B8] Rabold, A. Anwendung der Finite Element Methode auf die Trittschallberechnung. Doctor Ingenieur Dissertation at Technischen Universität München. Fakultät für Bauingenieur- und Vermessungswesen, 27.05.2010. München, Germany 2010. https://mediatum.ub.tum.de/doc/965934/965934.pdf

[B9] Homb, A. Grouping of wood constructions. Silent Timber Build document, April 2015.

[B10] Homb, A. Guigou-Carter, C., Hagberg, K., Schmid, H. Impact sound insulation of wooden joist constructions: Collection of laboratory measurements and trend analysis. Building Acoustics 2016, Vol. 23(2) 73-91.

[B11] Simmons, C., Hagberg, K. & Backman, E. Acoustical Performance of Apartment Buildings – Resident's Survey and Field Measurements. AkuLite. report 2. SP Report 2011:58. Sweden, september 2011.

[B12] EN-ISO 717 Part 2. Acoustics – rating of sound insulation in buildings and of building elements – part 2: Impact sound insulation (1996)

[B13] NBI project report O 8788. Mockup-measurements at Norwegian Building Research Institute, NBI. Commissioned by TEFT/Stjern, Trondheim 2002.

[B14] NBI project report O 8788. Mockup-measurements at Norwegian Building Research Institute, NBI. Commissioned by Treteknisk institutt, NTI. Trondheim 2003.

[B15] SINTEF project report O 20723. Laboratory measurements of CLT floor constructions. Commissioned by NTI. Oslo 2007.

[B16] SINTEF project report. Laboratoriemåling av lydisolasjon for 140 mm massivtredekker med 60 mm påstøp (Laboratory measurement of 140 mm CLT floor with 60 mm concrete). Project report O 21362, Norwegian building research institute for “SundMo AS” (not published). Oslo 5.12.2006 (in Norwegian).

[B17] Ferk, H. Sound insulation in lightweight constructions – Austrian experiences with solid wood panel buildings. Proc. InterNoise 2006: 3-6 december 2006, Honolulu, Hawaii, USA.

[B18] Ljunggren, S. Ljudisolering i trähus – en handbok för konstruktörer. AkuLite Report 1, SP Report 2011:10.

[B19] Lignum. Database at: www.lignumdata.ch. Switzerland 2015.

[B20] EN 12354 Part 2. Building Acoustics – Estimation of acoustic performance of buildings from the performance of elements – Part 2: impact sound insulation between rooms (2000).

[B21] NS 8175:2012. Acoustical conditions in buildings. Sound classification of various types of buildings. Standard Norge 2012.

References from Chapter 4

[C1] Project report No. 1 “Measurements in the Laboratory and in Single Family Houses” WoodWisdom-Net: AcuWood – Acoustics in Wooden Buildings. SP Report 2014:14 available on www.sp.se/en/publications/Sidor/Publikationer.aspx?PubId=16327, ISBN 978-91-87461-64-4, ISSN 0284-5172

[C2] ISO 10140-4:2010: Acoustics – Laboratory measurement of sound insulation of building elements – Part 4: Measurement procedures and requirements.

[C3] ISO 717-1:2013: Acoustics – Rating of sound insulation in buildings and of building elements – Part 1: Airborne sound insulation

[C4] ISO 717-2:2013: Acoustics – Rating of sound insulation in buildings and of building elements – Part 2: Impact sound insulation

[C5] Measurements Template WP1 revCG_revGB.docx, Template for the Silent Timber Build Project, document from 2014/11/12.

[C6] DIN EN ISO 10140-3:2010: Acoustics – Laboratory measurement of sound insulation of building elements – Part 3: Measurement of impact sound insulation.

[C7] DIN EN ISO 10140-5:2010: Acoustics – Laboratory measurement of sound insulation of building elements – Part 5: Requirements for test facilities and equipment.

[C8] DIN 4109-1:2016: Sound insulation in buildings – Part 1: Minimum requierements. Beuth Verlag GmbH.

[C9] DIN 4109 BBl2:1989: Sound insulation in buildings – Guideline for planning and execution; Proposals for increased sound insulation; Recommendations for sound insulation in personal living and working areas. Beuth Verlag GmbH.

Silent Timber Build

The overall objectives of Silent Timber Build project are to develop prediction models for multi storey buildings using various wooden floor and wall assemblies in the structural elements.