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Hybrid joist floor constructions.
Evaluation of measurement results.

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ABSTRACT

Lightweight building systems in general suffer from limited sound insulation, especially at low frequencies. Furthermore, theoretical models have severe limitations regarding prediction of the impact sound insulation, and the design is to a high extent based upon experience and measurements. Recommendations in Norway includes the frequency range down to 50 Hz, which means to include the spectrum adaptation term $C_{I,50\text{-}2500}$ and $C_{50\text{-}5000}$. One possible solution to improve the properties at low frequencies is to add mass and increase the stiffness of the construction. We refer to lightweight building systems combining wood and cement-based materials as hybrid constructions.

The paper will present analysis of relevant measurement results of hybrid wood joist floor constructions from laboratory and field objects. The paper will discuss possible improvements of such floor constructions. From the "Silent Timber Build project", some relevant laboratory measurement data exist. Due to the impact sound insulation focus, some apartments with hybrid joist floors have been built and data collected. This paper is a part of a project at SINTEF Building & Infrastructure aiming to develop robust solutions also involving HVAC components inside the partition structure. Further progress in this project will include new laboratory measurements and a fire test.

Keywords: Impact sound insulation, floor, hybrid joist constructions

1. INTRODUCTION

Lightweight building systems generally suffer from limited sound insulation properties, especially in the low frequency range. A number of research studies and investigations confirm the lack of correlation between perceived impact sound insulation and standard measurement objective $L'_{n,w}$ for lightweight systems, see [1] and [2]. The necessity of including low frequency evaluation in the objectives and national requirements is conspicuously. The acceptability of lightweight wood frame residential buildings is at risk if low frequencies aspects neither are formally integrated in building codes with more specific acoustic requirements, nor made largely available in building design guides. The lack of requirement seems also to prevent a more rapid development of lightweight solutions including low frequency terms.

The process of developing new solutions could be more rapid up if reliable calculation tools was available. Some development of mathematical models and numerical simulations predicting the impact sound pressure level of the floor element is published, see for instance [3], but due to the complexity of such solutions, the development still need to be based upon experience and measurements more than "pure" mathematical models. In addition, the lack of tools to calculate the contribution from flanking transmission is even more limited. Therefore, the development of new or improved solutions need to include both theoretical investigations, measurements in the laboratory and field- or prototype testing.

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The paper is focusing on the impact sound insulation and the low frequency properties in special. When the final solution include some floor covering or parquet layer on an interlayer, the single number rating will always be determined by frequencies below 400 Hz. Therefore, the measurement spectra presented in this paper limits the frequency range upwards to 500 Hz.

2. OBJECTS

Traditional lightweight wood frame based buildings involves generally rigidly connected elements for floors and walls except the ceiling and the top floor solutions. In Norway, the ceiling is normally elastic suspended to the joists, more seldom completely separated. Concerning the floor covering, floating floor solution (rigid topping on a resilient layer) are also commonly implemented. Over the past years, many research projects and studies in different countries has been conducted; quite a large number of laboratory measurements are now available, see for instance [4] or [5]. Results covering hybrid joist floor solutions with resilient or independent ceiling solutions is more seldom. The presentation in this paper is therefore a first step on our work on this specific item.

Relevant alternatives for the top floor solution we divide into two main groups:

- added Mass Below the Resilient layer, named MBR
- added Mass Above the Resilient layer, named MAR

Figure 1 shows a sketch of the two principal solutions of the top floor. For the MBR solution, lightweight materials will be used above the resilient layer. For the MAR solution, we normally have some additional floor covering or parquet product. In addition, we divide the resilient layer into two groups, for simplicity:

- Product with dynamic stiffness below 15 MN/m^3, coded LDS
- Products with dynamic stiffness above 30 MN/m^3, coded HDS

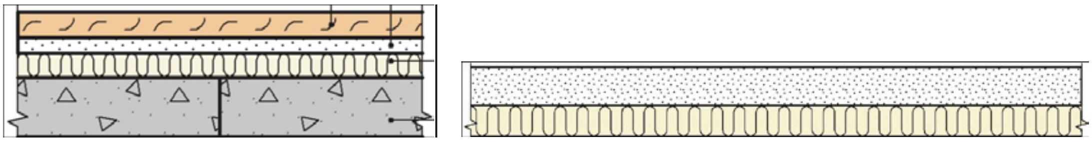

Figure 1 – Sketch of the MBR (left) and MAR (right) top floor solution

So far, the prioritizing in the project limits the added mass solutions to concrete products or some kind of wet screed. In this presentation, the concrete or wet screed have been installed without (stiffening) connectors between the mass and the wooden floor below.

3. LABORATORY MEASUREMENTS

In the following, results from a number of laboratory measurements of hybrid wood joist floor solutions will be presented. Some of the measurement were performed in the sound transmission laboratory at SINTEF Building and Infrastructure in Oslo. Other measurements have been performed at other European laboratories, collected within the Silent Timber Build project and published, see [4]. In all cases, the measurements have been conducted in accordance with NS-EN ISO 10140, part 3, see [6] and evaluated according to NS-EN ISO 717-1, see [7]. So far, there are a limited number of hybrid floor solutions including resilient suspended ceiling available for our study. Among available results, some of the most interesting data are presented in the following. The goal of this presentation is to quantify the effect of different hybrid floor solutions and secondly to present data relevant for verification of calculation tools. Table 1 shows an overview of relevant laboratory measurement objects, and figure 2 shows the frequency spectrum of the normalized, impact sound pressure level.

Table 1 – Overview, laboratory measurement objects

Main group	Resilient layer	Total mass pr. unit area, kg/m^2	$L_{n,w} + C_{I,50-2500}$, dB
MAR	LDS	135	54
MAR	LDS	166	55
MBR	HDS	180	46 1)
MBR	HDS	187	52
MBR	LDS	192	52
MAR	LDS	224	51

1) High transverse stiffness of the joist system, see [4] or [8]

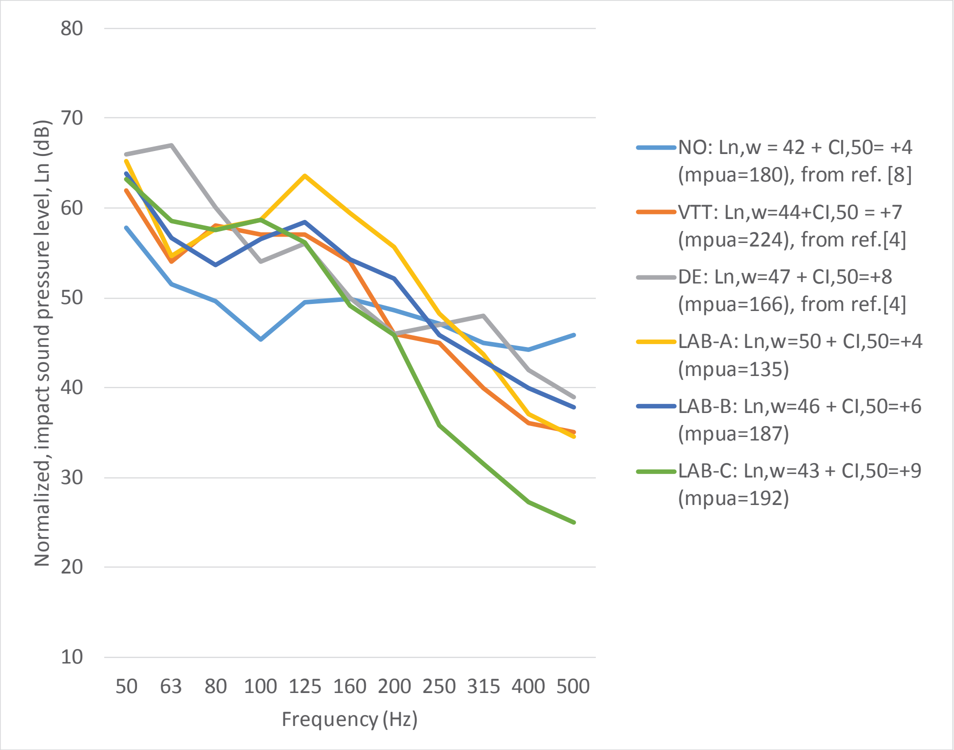

Figure 2 – Normalized impact sound level of laboratory measurement objects

Results presented in figure 2 shows a relatively large spreading, both with respect to single number rating and the normalized impact sound level in the frequency range. Not unexpected, the two MBR objects shows relatively low spectrum adaptation term, $C_{I,50-2500}$ due to high dynamic stiffness of the resilient layer. For the MAR objects it is in general the opposite. The NO object differs significantly from the other, probably due to the increased transverse stiffening of the joist floor.

A comment to the collection of results is that we have not data available for the combination of MAR and HDS resilient products and solutions combining MBR and LDS resilient products.

4. FIELD MEASUREMENTS

Despite the fact that hybrid joist floor solution is relatively seldom, a number of field measurements has been performed the last years. The purpose has been to study the effect of additional mass for improving the impact sound insulation due to arguments presented in chapter 1. Collected data include a number of relevant solutions and results. But collected data also include solutions not relevant for further use and solutions without significant effect on the impact sound insulation properties. Such data is not a part of the presentation below. All measurements carried out by SINTEF Building & Infrastructure have been performed according to NS-EN ISO 16283 [9], from 2017 also including low frequency procedure of small receiving room volumes, Some measurements have been performed by consultancy companies, reported according to [9], but without the low frequency procedure given for small receiving room volumes. Therefore, small receiving room volumes have been excluded in this paper.

Table 2 shows an overview of relevant objects, and figure 3 shows the frequency spectrum of the normalized, impact sound pressure level. All of them with large receiving room volumes. Two examples are from specific, field measurements, while the two others are from averaging of numbers of results from almost equal solutions.

Table 2 – Overview, field measurement objects

Main group	Resilient layer	Total mass pr. unit area, kg/m^2	$L_{n,w} + C_{I,50\text{-}2500}$, dB
MAR	LDS	109-124	55
MAR	LDS	124	53
MAR	HDS	125-140	57
MAR	HDS	148	59

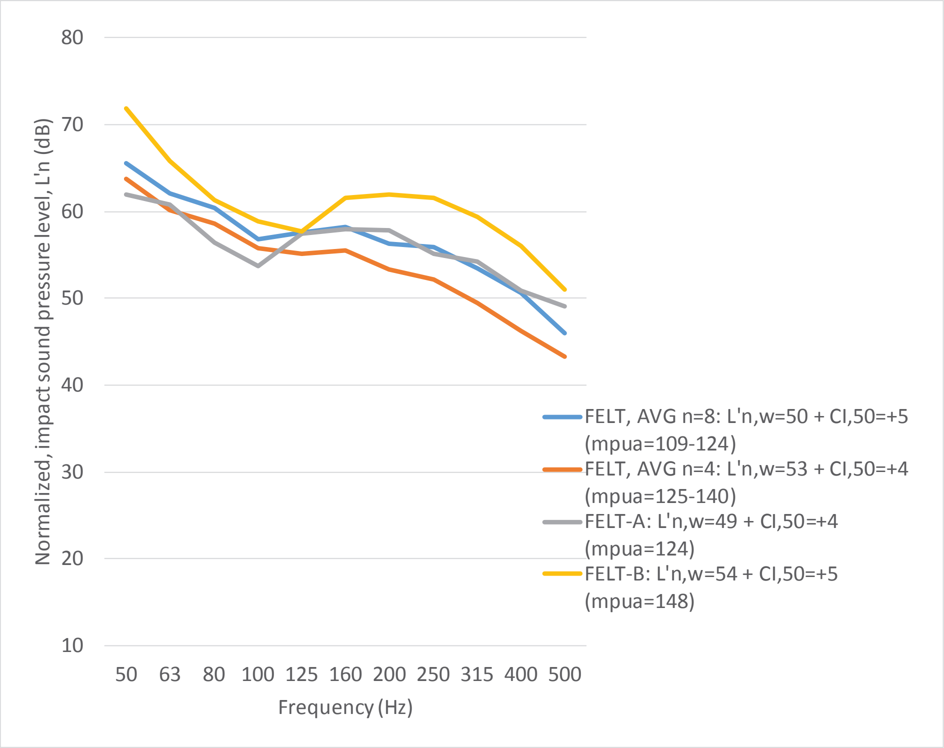

Figure 3– Normalized impact sound level of field measurement objects

Results presented in figure 3 shows a 6 dB spreading of the single number rating, $L'_{n,w} + C_{I,50\text{-}2500}$, and relatively large spreading of the normalized impact sound level in the frequency range. All results show spectrum adaptation term, $C_{I,50\text{-}2500}$ in the range 4 to 5 dB, positively influenced by large receiving room volumes. All constructions fulfill national minimum requirements (sound class C) of $L'_{n,w} \leq 53$ dB. Except one construction, the example object don't fulfil recommended limit of $L'_{n,w}+C_{I,50\text{-}2500} \leq 53$ dB or the stricter requirements for sound class B according to present Norwegian requirements in NS 8175:2012.

A comment to the collection of results, is that we have not field measurement results available for the combination of MBR independent of the type of resilient layer.

5. DELTA ACOUSTIC CALCULATIONS

Predicting the impact sound insulation improvement by a floating floor is not an easy task. It is necessary to take into account both forced and resonant transmission. The resonant transmission will depend on the boundary conditions for the floating as well as for the primary floor. Theoretical calculation of the impact sound insulation improvements has been studied by several researchers. The most well-known work dealing with floating floor constructions was performed by Cremer, see reference [10]. From reference [11], the following equation from this work regarding continuously elastic layer will be used.

$$\Delta L_n = 40 \cdot log\left(\frac{f}{f_o}\right) + 20 \cdot log\left|1 + \frac{j \cdot 2\pi \cdot f \cdot m_h}{Z_1}\right| \tag{1}$$

Simple, one-dimensional theory based on mechanical impedance also ends up with the same frequency dependent improvement above the resilient floor resonance frequency, f_o. Theory presented in [10] especially developed for lightweight floating floors also give a similar slope of the improvement according to equation (2). Below the f_o frequency, the improvement will be set to 0 dB.

$$\Delta L_n = 40 \cdot log\left(\frac{f}{f_o}\right) + 20 \cdot log\left|1 + \left(\frac{f}{f_z}\right)^2\right| \tag{2}$$

$$f_z = \frac{4\sqrt{B_1 \cdot m_1}}{\pi \cdot m_h}$$

The textbook also conclude that it is not possible to fulfil some important assumptions, and the measured improvement may therefore differ from the calculated one. Improvements achieved from measurement objects in LAB and FIELD will be compared with results from these equations.

6. COMPARISON OF MEASURED AND CALCULATED IMPROVEMENT

Calculation of the impact sound insulation improvement will be compared with measured improvements due to different top floor solution added to a basic structure. The basic structure consists of a traditionally wooden joist floor with resilient suspended ceiling with data from the basic structure of the LAB measurement series. It means that the comparison should be reliable for the other LAB-examples if we assume a low influence on the modal behavior of the floor due to the added top floor. The comparison with improvements measured from field objects may of course be less accurate due to obviously different modal behavior. Table 3 shows an overview of essential data for comparison between calculations and measurements. Exact data of the dynamic stiffness of the resilient layer is not available, but from general information 10 MN/m^3 have been used for the LDS layers and 40 MN/m^3 for the HDS layers.

Table 3 – Objects for comparison between calculations and measurements

Object	Main group	Resilient layer	Mass above/below resilient layer, kg/m^2	Calculated f_o (Hz)
LAB-A 7	MAR	LDS	86 / 49	~ 90
LAB-B 3	MBR	HDS	30 / 157	~ 202
LAB-C 8	MBR	LDS	38 / 154	~ 91
FIELD-A B	MAR	LDS	86 / 38	~ 98
FIELD-B E	MAR	HDS	102 / 46	~ 179

In figure 4, comparison between measured and calculated improvement of LAB example objects are presented. Figure 4a shows the result for the solution with the mass above the resilient layer, while figure 4b show the result when the added mass is positioned below the resilient layer. In figure 5, comparison between measured and calculated improvement of FIELD example objects are presented, both with mass above the resilient layer.

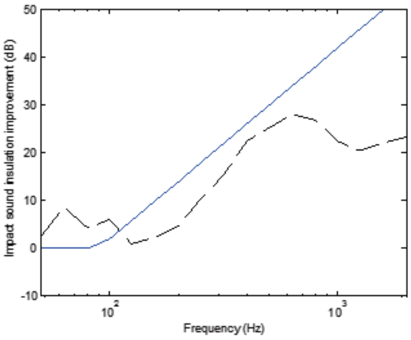

Figure 4a – Comparison of calculated and measured improvement of object LAB-A

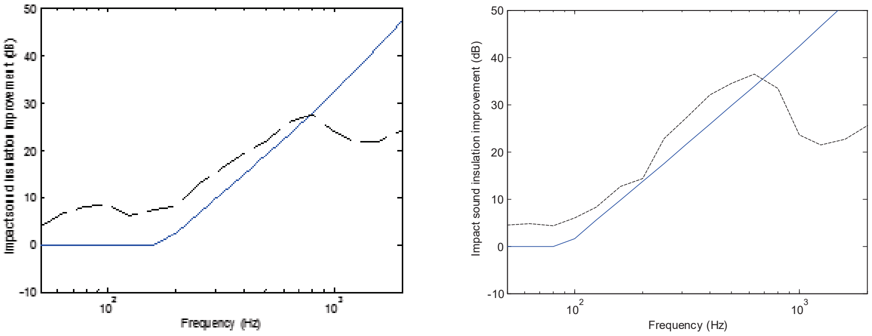

Figure 4b – Comparison of calculated and measured improvement of object LAB-B and LAB-C

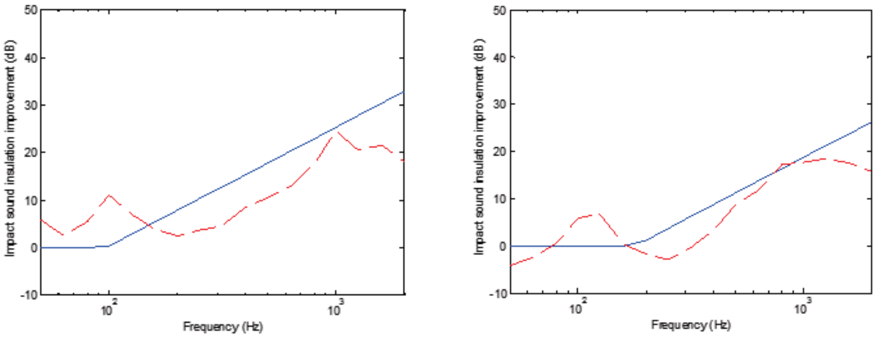

Figure 5 – Comparison of calculated and measured improvement of object FIELD A and FIELD-B

Results presented in figure 4a show that the calculated improvement is overestimated for the MAR example influenced by the low f_0 value from the calculations. Results presented in figure 4b show that the calculated improvement is slightly underestimated for the MBR examples, and the resonance frequencies, f_0 coincide to a high degree. Results presented in figure 5 show that the calculated improvement is overestimated for both MAR examples, influenced by the low f_0 value from the calculations. Generally, the improvement slope coincides relatively well except the FIELD-B example.

The comparison also, partly shows an improvement at low frequencies, which deviate from the general assumption of zero improvement in this frequency range. The modal behavior plays obviously a role in this frequency range, together with effects of the field object solutions and may be flanking transmission. The overestimation for all MAR examples is probably caused by vibration transmission because of low impedance of the basic structure compared with the top floor impedance. Too low impedance of the basic structure gives additional or increased resonance frequencies of the system, compared to the calculated f_o value.

7. CONCLUSIONS

Different hybrid floor solutions have been measured experimentally with $L_{n,w} + C_{I,50\text{-}2500}$ results between 46 and 55 dB. Three of those solutions may perform sufficient for the recommended impact sound insulation level in residential housing of $L_{n,w} + C_{I,50\text{-}2500} \leq 53$ dB.

Object with increased transverse stiffening of the joist solution perform significantly better than other objects at low frequencies. Until now, object measured in ejected buildings have more uniform solutions, but still the results varies between 53 and 59 dB. Only one of those example objects fulfil the recommended impact sound insulation level. Therefore, other solutions need to be developed and tested. Both analyses and further development of solutions is a part of the ongoing research project "Hybrid joist floors with integrated ducts".

From a laboratory setup recently measured, we had an option to analyse measurement data of the basic floor and with additional hybrid solutions on top. Different combinations of the position of the resilient layer and added weight was a part of this. Data from the basic floor have also been used for comparison with field measurement results with hybrid top floor solutions.

Results from the measured improvement have been compared to calculation according to well known analytical equations. Results from this comparison show that the prediction of MAR solutions overestimate the improvement, mainly due to the low f_o value from the calculations. The reason for this deviation is obviously uncomplete prediction tools. Results from the comparison show that the prediction of MBR solutions slightly underestimate the improvement, but the resonance frequencies, f_o coincide to a high degree in these cases.

Generally, the improvement slope coincides relatively well except one object. From these studies, we so far conclude that a positioning of the mass below the resilient layer is beneficial, at least when the basic floor has relatively low stiffness in the transverse direction.

Results presented in this paper shows that more research need to be done regarding theoretical calculations of such timber floor constructions. Up to now, too little focus has been put into the impact sound insulation of hybrid floor solutions, partly due to the complexity on modelling and partly due to experimental costs.

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