Abstract

During the last years, there has been an increasing interest of cross-laminated timber constructions among project owners, architects and producers. A more extensive use of wood in buildings is also of strategic interest in the wood industry. Design solutions to fulfil sound insulation requirements between apartments have been an issue on earlier work beside research work on flanking transmission with CLT elements. Recently we recognize an increased interest on CLT solutions used in other building categories, for instance student apartments and schools. Development and verification of floor constructions is of course important also for such applications. The paper will present a collection of results from SINTEF Building & Infrastructure combined with some preliminary research work running in the "Silent Timber Build" project within the WoodWisdom-Net program. The paper will focus on impact sound insulation properties of hybrid solutions with CLT and concrete. Results from both laboratory and field measurements will be given. In addition, calculations based on analytical methods have been carried out. A preliminary comparison between calculation and measurement results of the impact sound insulation will therefore be given in the paper. It is possible to fulfil the main impact sound requirement in Norway based on optimization of such hybrid solutions.

Keywords: Impact sound insulation, cross-laminated floor, measurement, prediction
Hybrid cross-laminated timber floors. Comparison of measurements and calculations

1 Introduction

During the last years, cross-laminated timber (CLT) floor constructions have been more common in Norway and other countries in north of Europe. Much focus have been on constructions for apartment buildings but also for internal use in apartments and single-family houses. However, the sound insulation properties of the CLT floor itself is limited due to low mass and relatively low stiffness. To fulfill some level of sound insulation requirements it is therefore necessary with an additional construction above the CLT element, an additional ceiling or both measures. Results from research conducted at SINTEF Building & Infrastructure the last decade have been published, see [1] to [3]. In these studies on vibration properties and sound insulation properties, the focus have mainly been on additional lightweight materials and solutions. German-speaking countries have developed the hybrid cross-laminated timber floors. Such solutions is also highly interesting for different kind of building categories due to increased mass and stiffness contribution.

Within the "Silent Timber Build", project work is going on regarding verification and prediction of such floor assemblies. A collection of laboratory measurement data is in progress, and this paper will present some preliminary results from this work limited to hybrid types of cross-laminated timber floors. It have also been an opportunity to investigate how ordinary analytical calculation tools correlate with the measurement results. The heavy, concrete part of hybrid timber floors can be installed in various ways. One possibility is of course complete, static connection between the CLT element and the concrete. This is a relevant solution with respect to acoustical properties and vibration behaviour but an obvious challenge with respect to shrinkage deformations. An acoustically decoupled solution is to install the heavy part on a soft, elastic interlayer. In between those solutions, different kind of more or less stiff interlayers could be an opportunity. This paper will present measurement results from three different types of floor assemblies and calculation results from two of them. The presentation also includes results from measurements and calculations of an in situ object see [8].

2 Measurement objects

In the following chapter, three examples of CLT floor assemblies for relevant building categories will be presented. As the impact sound insulation tends to be the most significant problem for the wooden floor construction building technique, such measurements are in focus. Impact sound insulation of cross laminated wooden floor constructions has been studied in different experiment set up both in laboratory and field objects during the last decade.

Figure 1 show a drawing of a hybrid floor construction with concrete poured directly on CLT. The mass per unit area (mpua) of the concrete-CLT part of this floor is approximately 230 kg/m². Laboratory measurement result of this object A is presented in chapter 3, figure 4.
Figure 1. Object A: Hybrid floor construction with concrete poured directly on CLT

Figure 2 show a drawing of a hybrid floor construction with concrete on an elastic interlayer on CLT. The mass per unit area (mpua) of this floor is approximately 190 kg/m². Laboratory measurement result of this object B is presented in chapter 3, figure 5.

Figure 2. Object B: Laboratory measurement of floor with concrete on an elastic interlayer on CLT

Figure 3 show a drawing of a hybrid floor construction with concrete on a semi-rigid interlayer on CLT. The mass per unit area (mpua) of this floor is approximately 240 kg/m². Field measurement result of this object C is presented in chapter 3, figure 6. Sound transmission through flanking elements has a limited influence on the measurement result in this case.

Figure 3. Object C: Field measurement of floor with concrete on a semi-rigid interlayer on CLT
3 Measurement results

3.1 Measurement method and data
The impact sound insulation measurements were carried out according to ISO 140-6 standard, versions valid at the time of measurements (now replaced by ISO 10140-3). Major number of measurements realized after 1995 has been carried out including the low frequency range, i.e. starting at 50 Hz. The measured normalised, impact sound pressure levels in the frequency range 50 – 5000 Hz are presented as graphs in the following sections. From these results, different single-number quantities for rating the impact sound insulation were calculated, i.e. $L_{n,w}$ (alternatively $L'_{n,w}$), the spectrum adaptation term, $C_{1,50-2500}$ and the sum of these, $L_{n,w}+C_{1,50-2500}$ (alternatively $L_{n,w}+C_{1,50-2500}$) see EN-ISO 717-2 [4].

3.2 Concrete poured directly on CLT
Laboratory measurement results from [5] of the hybrid floor construction with concrete poured directly on CLT, object A are presented in figure 4. The figure show results with and without a lightweight top floor on a continuously elastic layer.

![Figure 4. Laboratory measurement of object A with concrete poured directly on CLT](image)

3.3 Concrete and elastic interlayer on CLT
Laboratory measurement results of the hybrid floor construction with concrete and elastic interlayer on CLT, object B are presented in figure 5. The figure show results with two different dynamic stiffness properties of the elastic interlayer, respectively from [6] and [7].
3.4 Concrete with semi-rigid interlayer on CLT

Field measurement results from [8] of the hybrid floor construction of concrete with semi-rigid interlayer on CLT are presented in figure 6. The figure show results with and without an additional elastic interlayer for sport gym activities at the top floor.

Figure 5. Laboratory measurement of object B with concrete on an elastic interlayer on CLT

Figure 6. Laboratory measurement of object C with concrete on a semi-rigid interlayer on CLT
4 Analytical calculations

4.1 Calculation of massive floor

The principle of calculating the impact sound transmission of massive floor construction is given in NS-EN 12354-2, see [9]. This theory is applied in this case because of the concrete part of the floor construction. We assume that the layer of concrete will entail sound transmission properties similar to pure massive floor constructions. The normalized, impact sound pressure level, $L_n$, has been calculated according to the following equation:

$$L_n \approx 155 - 30 \cdot \log m + 10 \cdot \log T_s + 10 \cdot \log \frac{f}{f_{\text{ref}}} \ (dB)$$

where:
- $m$ = mass per unit area (kg/m$^2$)
- $T_s$ = structural reverberation time (sec)
- $\sigma$ = radiation factor for free bending waves
- $f_{\text{ref}} = 1000$ Hz

Calculation of the sound radiation factor, $\sigma$ and the damping properties represented by the structural reverberation time, $T_s$, is difficult to determine correctly for such floor assemblies. Regarding the sound radiation factor, the equations given in annex B of [10] have been used. But it is difficult to be sure of the accuracy of this expression in our case with the combination of concrete and CLT element. The shape of the sound radiation factor have been based on the coincidence frequency of the concrete part of the floor assembly. Regarding the structural reverberation time, the following equation given in annex C of [10] will be used:

$$T_s = \frac{2.2}{f \cdot \eta_{\text{tot}}} \ (\text{sec})$$

The internal loss factor in the laboratory case is calculated as:

$$\eta_{\text{int,lab}} = \eta_{\text{int}} + \frac{m}{485 \cdot \sqrt{f}}$$

The internal loss factor in the field case is calculated as:

$$\eta_{\text{int,field}} = \eta_{\text{int}} + \frac{c_o}{\pi^2 \cdot S \cdot \sqrt{f / f_c}} \cdot \sum_{k=1}^{4} l_k \cdot \alpha_k$$

where:
- $\eta_{\text{int}}$ = internal loss factor
- $S$ = area of element (m$^2$)
- $c_o$ = critical frequency (Hz)
- $l_k$ = length of the junction at the perimeter (m)
- $\alpha_k$ = absorption coefficient for bending waves at the perimeter

For the laboratory measurement case, the total loss factor has been determined according to equation (3) above. Relevant input data from the field measurement case have been used to evaluate equation (4). The result show small influence of the input parameters and equation (3) has been used also for the predictions of the floor assembly in figure 3, object C. Calculation results of hybrid floor constructions of object A is presented in figure 7. The effect of a floor covering is not included.
The difference between the curves actually represents the difference of mass per unit area (mpua). In the frequency range above the coincidence frequency, the impact sound pressure level highly depends on the damping properties of the floor assembly. In this case increased structural damping more or less balance the contribution due to increased frequency, see formulae (1). The accuracy of the calculation results is close coupled to the accuracy of the input parameters. It is also of course difficult to generalize the results because minor changes of the construction details significantly can change the calculated values.

### 4.2 Calculation of impact sound insulation improvement

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 calculations of the impact sound insulation improvement have been studied by several researchers. The most well-known work dealing with floating floor constructions was performed by Cremer, see reference [11]. From reference [12], the following equation from this work regarding continuously elastic layer will be used:

\[
\Delta L_n = 40 \cdot \log \left( \frac{f}{f_0} \right) + 20 \cdot \log \left| 1 + \frac{j2\pi f}{z_1} \right| \quad \text{for } f > f_0
\]  

(5)

Simple, one-dimensional theory based on mechanical impedance also ends up with the same frequency dependent improvement above the resilient floor resonance frequency, \( f_0 \). Theory presented in [12] especially developed for lightweight floating floors also give a similar slope of the improvement according to equation (6).

\[
\Delta L_n = 40 \cdot \log \left( \frac{f}{f_c} \right) + 10 \cdot \log \left| 1 + \left( \frac{f}{f_z} \right)^2 \right|
\]

(6)

\[
f_z = \frac{4\sqrt{mB}}{\pi m}
\]

(7)

The textbook also conclude that it is not possible to fulfil some important assumptions, and the improvement may be lower than 12 dB per octave. Improvements achieved from measurement of object A with an additional lightweight top floor will be compared with calculations according to these equations.

Evaluation of methods to calculate the improvement with a concrete layer on a continuously elastic layer, for instance object B are in progress. Results from this work and comparison with measurement results will be presented in future articles.

### 5 Comparison of measurements and calculations

Figure 7 and 8 shows the measured and calculated impact sound insulation pressure level in the frequency domain of object A. Figure 7 present the results regarding the bare floor structure. Figure 8 present the result when an additional lightweight floor on elastic interlayer have been installed.
Results from figure 7 show that it is possible to achieve high correlation between measured results and common analytical calculation methods in the low and medium frequency range. Calculations according to formulae (1) to (3). The deviation in the higher frequency range have at least two reasons: The impact sound level depends to a high degree of the surface roughness of the concrete surface. The second reason is the assumption and choice of input data regarding the loss factor of the floor construction. However, when installing a more or less soft floor covering, the properties in the high frequency range will be of minor importance, see figure 8 and 9.
Results from figure 8 show that it is possible to achieve high correlation between measurement results and common calculation methods in a broad frequency range. Calculations according to formula (6) and (7). The deviation at higher frequencies depends mainly of the softness and elastic properties of the floor covering installed. With respect to single number quantity $L_{n,w}$, the deviation between measured and calculated results is within 1 dB in this case.

Figure 9 shows the measured and calculated impact sound insulation pressure level in the frequency domain of object C including floor covering. The exact type of floor covering from the field object is not known. The type of floor covering used in the calculations have been based on a similar type measured in the laboratory.

![Figure 9. Comparison of measured and calculated floor construction, object C with concrete on semi-rigid interlayer on CLT](image)

Results from figure 9 show that it is possible to achieve high correlation between measurement results and common calculation methods in a broad frequency range. Calculations according to formula (1) to (3). The deviation in the higher frequency range depends of the elastic properties of the floor covering installed and the input data regarding the loss factor of the floor construction as mentioned previously. With respect to single number quantity $L'_{n,w}$, the deviation between measured and calculated results is also within 1 dB in this case.

6 Conclusions

This paper presents the results of some well-controlled impact sound insulation measurements of hybrid cross-laminated timber floors. The measurement data have been compared with calculations based on analytical equations given in well-known textbooks. The prediction and comparison cover both the basic structure of the hybrid floor and the improvement due to an additional lightweight floor on elastic interlayer. Calculation of the basic structure have been
based on stiff connection between the concrete layer and the CLT element for the object with a semi-rigid interlayer. Results presented show that it is possible to achieve high correlation between measured results and common analytical calculation methods in the low and medium frequency range. The deviation in the higher frequency range depends on the elastic properties of the floor covering installed and the input data regarding the loss factor of the floor construction. Including impact sound insulation improvement due to common soft floor covering, the deviation between measurements and calculations are limited with respect to the single number quantity, $L_{n,w}$.

Acknowledgments
The research presented in this paper is a part of the WoodWisdomNet+ project Silent Timber Build with funding from each country participating in the project consortium representing the following countries: Sweden, France, Germany, Austria, Norway and Switzerland.

References