The Optimization of a Wooden Floor Design Based on Validated Finite Element Models

Jeffrey MAHN[1]; Carl HOPKINS[2]; Marios FILIPPOUPOLITIS[2];

Ulrich SCHANDA[3]; Raphael VÖLTL[3]; Luboš KRAJČI[4]

[1] National Research Council Canada

[2] Acoustics Research Unit, University of Liverpool, Liverpool, UK

[3] Rosenheim University of Applied Sciences, Germany

[4] Soundtherm Ltd., Im Brüel 15, Elgg, Switzerland

ABSTRACT

This paper describes a research project to develop a dowelled joist floor design which has a similar thickness to typical concrete floor constrictions in Switzerland but with better environmental life cycle impact and impact sound insulation below 200 Hz. The dynamic properties of the floor designs were evaluated using a systematic process of developing and then elaborating on initially simple finite element models which were validated based on experimentally determined material properties. This approach was successful with close agreement in both the mode frequencies and the MAC values. Results from the finite element analysis are presented as are the results from impact testing of full scale floor designs.

Keywords: Lightweight Timber, Sound Transmission, Impact Noise
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1. INTRODUCTION

This program was conducted as part of a project funded by Swiss National Science Foundation through the National Research Program (NRP 66) Resource Wood to develop dowelled joist floor designs with improved impact sound performance below 200 Hz. The floor design was to incorporate the use of Swiss hardwoods. The significant challenge for accomplishing these goals was that at the start of the project, very little was understood about the performance of dowelled joist floor designs or the material properties of Swiss hardwoods. Therefore, the evaluation of the floor design and materials involved extensive characterization of both spruce and beech as materials and the design of the assemblies used for the floor constructions. The characterization was important to the industrial partner for the project not just in terms of understanding the acoustic performance of the materials and floor design, but also in terms of their structural capabilities. Once the materials were characterized, the results were used to validate finite element models of the floor constructions. The validated models could then be used to optimize the floor design. The measurements and models have progressed the state of the art concerning dowelled joist floors and the use of Swiss hardwoods in floor designs to a point where improvements in the design to reduce low frequency impact noise can be systematically evaluated.

[1] jeffreymahn@jeffreymahn.com

2. ANALYSIS

2.1 Characterization

Early work in the project focused on the characterization of the material properties of the dowelled joist floors. This was done by building small assemblies of doweled joists and measuring the material properties experimentally. Assemblies made of beech and spruce were included in the evaluation. Beech is a denser material than spruce, which results in a higher modulus of elasticity and bending stiffness. Beech was also found to have a higher internal loss factor than spruce at the first three natural frequencies. The values of the modulus of elasticity determined from the quasi-longitudinal wave speed were found to be higher than those determined from modal analysis data. The difference in the values measured using different measurement techniques may have been due to timber being an anisotropic solid. Further details of the characterization were reported in an earlier paper [1].

2.2 Dynamic performance

Once the materials were characterized, finite element models were developed for a solid timber floor formed from dowel-connected joists. These models were validated through comparison with the results of an experimental modal analysis that was carried out on the floor assemblies. Finite element models were developed and validated for three individual assemblies and for a complete floor formed from three assemblies. A sequence of finite element models of increasing complexity were assessed, resulting in the use of spring connections at the dowel positions combined with precise modeling of the boundary conditions (supports) at the two ends of the assemblies. This approach was successful for all three assemblies and for the complete floor as there was close agreement in both the mode frequencies and the MAC values as shown in Figure 1.

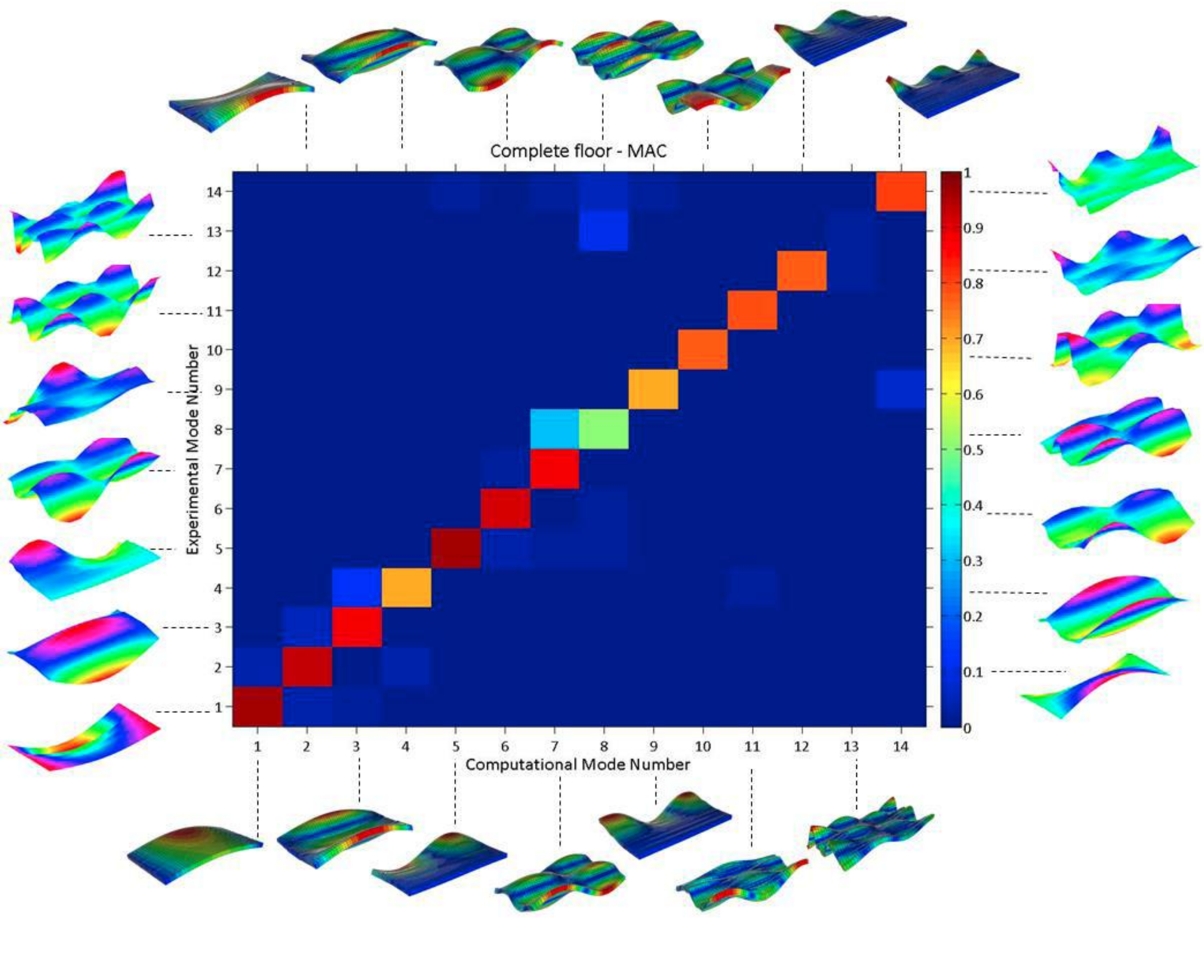

Figure 1 – Modal Assurance Criterion (MAC) for the modes from the experimental modal analysis and finite element model.

Further details about the finite element models were presented at the Forum Acusticum conference in September, 2014 [2].

2.3 Impact sound insulation

The impact sound insulation values of the dowelled joist floor design was measured at the University for Applied Sciences in Rosenheim. The impact sound insulation (L_n) is plotted in 1/3 octave bands in Figure 2.

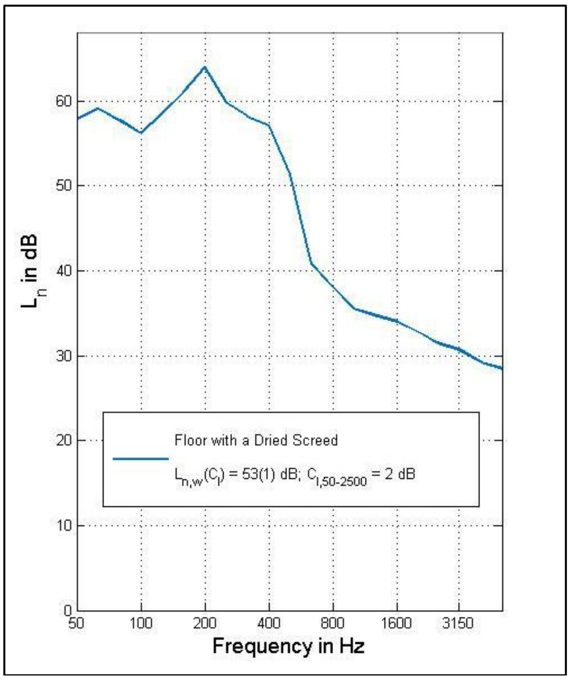

Figure 2 – Impact sound insulation of the doweled joist floor with a dried screed topping.

The design using a dry, lightweight floating floor with an absorption layer of 60 mm wood fiber in the cavity and a decoupled suspended ceiling had a weighted impact sound level $(L_{n,w})$ of 53 dB. Due to the floor design, it is expected to be feasible to achieve the same quality of decoupling from other building elements when the floor is implemented in practice as was achieved in the laboratory. Therefore it is expected that the impact sound insulation will not be significantly decreased by flanking sound transmission through other building elements in the mid- and high-frequency ranges.

The results shown in the figure above 1250 Hz were unexpected since timber constructions typically show a much steeper decline of the impact sound levels in this frequency range. Experience suggests that the shallow slope shown in the figure was due to the influence of the flanking transmission from the base floor to the suspended ceiling due to the construction of the test rig in the laboratory compared to the actual floor. This transmission through the test rig requires further investigation.

The peak shown in the impact sound levels in the frequency range from 200 Hz to 630 Hz was unexpected and the peak dominated the single number rating value of the impact sound level. If this peak could be decreased, the $L_{n,w}$ value would be reduced. This response in the mid-frequency range is not typical for timber floor constructions. The most probable reason for this behavior is the enhanced radiation of the suspended ceiling which will be addressed in the next phase of the study.

The impact sound insulation of the floor is compared to that of several other floor constructions in Figure 3.

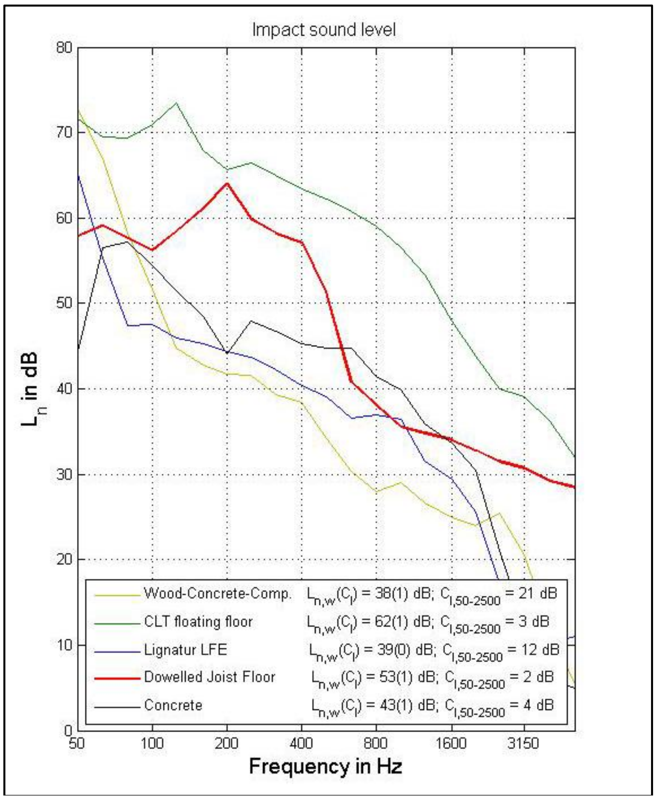

Figure 3 – Comparison between the impact sound insulation of the dowelled joist floor with a dried screed toping and the impact sound insulation of other floor constructions.

The impact sound insulation of the doweled joist floor is shown to be lower than the comparable CLT floating floor with a screed construction by over 10 dB below 100 Hz and lower than the wood-concrete composite floor below 80 Hz. The difference between the values of the impact sound insulation of the doweled joist floor and the comparable CLT float floor shows the great potential for the doweled joist floor design. Also shown in the figure is a commercial Swiss timber construction, Lignature LFE. This floor is equipped with a heavy floating floor and additional mass layers. The heavy suspended ceiling of the dowelled joist floor is advantageous at 50 Hz when compared to the Lignature LFE floor. Fortunately the industrial partner intends to use a heavy floating floor on top of the doweled joist floor which will help to reduce the higher impact sound levels in the mid-frequency range. Once the mid-frequency impact sound levels are reduced, it should be feasible to achieve the impact sound insulation performance of a standard concrete construction across the building acoustics frequency range.

3. DISCUSSION

The goal of the initial project to develop a dowelled joist floor construction with superior impact sound insulation in the low frequency range has been met. However there are a number of other goals to be met before the floor can be considered to be commercially viable. The proposed floor design has excellent impact sound insulation at the low frequencies, but shows a peak in the 200 Hz to 630 Hz 1/3 octave bands. The source of the peak has been investigated and a solution has been proposed, but further work is required for the solution to be evaluated and implemented. In addition, structure-borne noise which is transmitted from the floor to the surrounding walls needs to be quantified so that the flanking transmission can be estimated. A second phase to the program has been submitted which will address these characteristics to ensure that the industrial partner has the confidence to implement the design.

4. CONCLUSIONS

Recent work to develop a lightweight timber floor system which make use of Swiss hardwoods has proposed a dowelled joist floor design. The dynamic properties of the floor designs were evaluated using a systematic process of developing and then elaborating on initially simple finite element models which were validated based on experimentally determined material properties. This approach was successful with close agreement in both the mode frequencies and the MAC values. Although the goal of the initial project to develop a floor with superior impact sound insulation to concrete floors in the low frequency range has been met, the measured impact sound insulation had an unexpected peak in the impact sound levels between 200 Hz to 630 Hz. Further work will therefore need to investigate design changes that could be used to improve the performance in this frequency range.

ACKNOWLEDGEMENTS

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