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SOUND INSULATION IN LIGHT WEIGHT BUILDING STRUCTURES, A) DEVELOPMENT OF A FULL-SCALE TEST HOUSE AND A STEEL BEAM FLOOR, B) IMPROVED MODEL FOR IMPACT SOUND PREDICTIONS

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ABSTRACT
The paper presents an ongoing research with the objective to design a light weight floor based on steel profiles that fulfil high sound insulation as well as dynamic demands. A full scale three room test building has been constructed. In the work a complete characterisation of the vibro-acoustic properties will be carried out, including FEM-modelling, modal analysis, mobility measurements, airborne sound insulation, impact sound levels, flanking transmission and subjective evaluations. The paper also presents some new results from an improved simplified impact sound prediction model, with prediction results that are very good.

1 - INTRODUCTION
Light-weight floor constructions for apartments are in Scandinavia traditionally built with timber joists or with hard-board beams. Heavy steel beams have mainly been used for industrial plants and offices and light-weight steel beams have not been so common. There has during the last decade been a growing interest from steel industry to take part of the growing light-weight building market. Therefore, a couple of both national and European projects have started during the last years. At Lulea University of Technology work is in progress together with a local construction company with the aim to develop a new design for a light-weight steel beam floor that fulfils high sound insulation, vibration and production demands. The work is partly covered by a confidentiality contract, final results and all details are therefore at this stage not allowed to be presented. This paper will therefore give an overview of the ongoing work and also show the resent development of the simplified prediction model that was presented at INTER NOISE 99, [1].

2 - THE STEEL JOIST FLOOR
One of the main problems with light weight floors is the low frequency behaviour. From an acoustical point of view the frequencies of main interest for timber floors is 20 to 125 Hz, where measurement standards put the lower limit at 50Hz. From the perspective of vibrations and booming caused by walking and heal dropping, also lower frequencies than that are of interest. With the span lengths that are in question the lowest eigenmodes of the floors may be found as low as at 7 Hz. It is essential to have a strong damping at these low frequencies, both of subjective vibration reasons and to avoid low frequency booming.
In order to find the low frequency modes and determine the damping, mobility measurements have been carried out on floors of 3m, 5m and 7m length. Various supports have been tested, with solutions such as the floor freely supported on beams, fig 1, bolted to beams, resiliently supported on beams and resiliently supported in a sound insulation laboratory. Finally, experiments were conducted in the test building. Detailed information about the damping was found, generally it was found that the boundary damping was of very high significance. The new light weight floor is based on thin steel beams. The goal is to

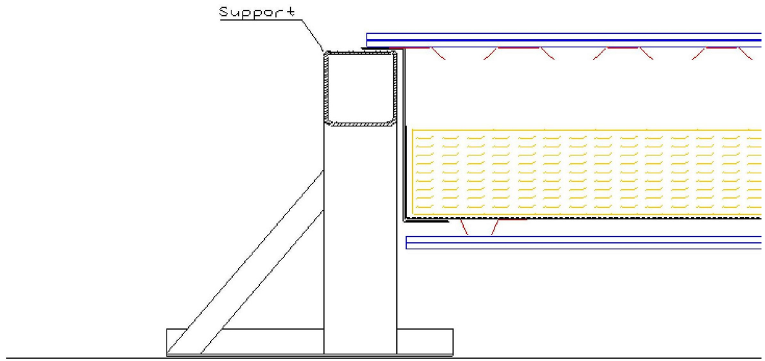

Figure 1: Example of test support for mobility measurements − freely supported.

make it pass class A certification for dwellings and to make it suitable for up to 6 m lengths. The work so far is very promising with high stiffness and reasonable damping figures.

3 - THE TEST BUILDING

A problem when developing new building structures in a laboratory environment is to include factors related to the building application, like correct boundary damping and flanking transmission. In order to overcome this limit a test house was built at the factory plant. In order to make the building complete, a prototype wall element based on steel beams was also designed. The test house is built in three rooms, fig 2.

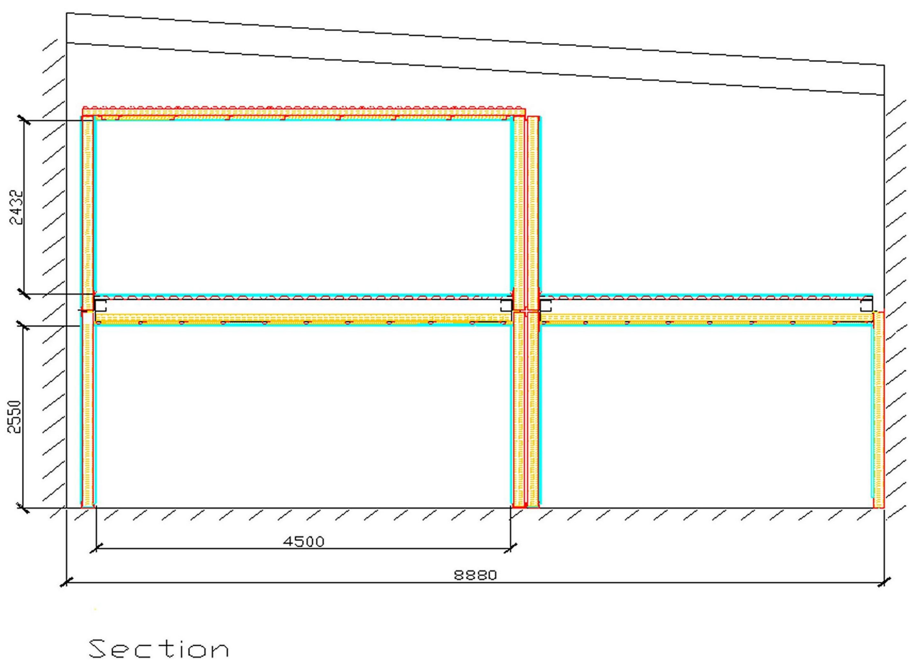

Figure 2: Full scale three room test facility for sound and vibration evaluations.

The test facility gives possibilities to measure under controlled circumstances a number of parameters like; 1) airborne sound insulation horizontally, 2) airborne sound insulation vertically, 3) impact sound insulation through the floor, 4) airborne sound insulation diagonally, 5) impact sound diagonally 6) flanking transmission, 7) damping, 8) subjective evaluations, 9) vibration evaluations and 10) impact sound from door slamming.

4 - MODELLING OF LOW FREQUENCY VIBRATIONS

In order to understand the physical behaviour at low frequencies a simple mass-spring model and a FEM beam model are being developed. Modelling the shapes and frequencies of the lowest modes has not been a big problem. The largest problem has been to estimate internal and boundary damping. Therefore damping figures have so far been estimated from mobility measurements on the floors. The damping figures varied largely between the different applications between 0.1 and 0.4. Another result that can be mentioned is the complex dynamic behaviour around the resonance frequency of a resiliently mounted ceiling. This behaviour will be reported at a later occasion.

5 - PREDICTION OF IMPACT SOUND INSULATION

In /1/ a prediction model for impact sound levels of light weight floors was presented. The model applies a homogeneous plate prediction model to determine the normalised impact sound insulation of timber joist floors. An equivalent method was used to obtain basic floor parameters in order to replace the composite floor with an equivalent homogeneous single plate. The normalised impact sound insulation of a timber joist floor was calculated in third octave bands from 31.5 Hz to 3150 Hz, and was compared with measured data.

The radiated sound power from one side of the equivalent homogeneous plate is in the model simplified as the resonant field of bending vibrations to be of pre-dominant importance [5]. The driving point impedance of the common floor is assumed to be large compared with the impedance of the standard tapping machine. Then the model yields for the radiated sound power

$$L_{\Pi} = 10\text{log}F_{rms}^2 + 10\text{log}\rho_0 c_0 \sigma - 10\text{lo g}\omega m' \eta Z + 120\ dB$$

where F_{rms} = rms impact force, ρ_s = mass/unit length, σ = radiation efficiency for free bending waves, S= radiation area, m' = mass/unit area, η = total loss factor, Z = driving point impedance.

If the simplified assumption of reverberant conditions in the receiving room is made, the normalised impact sound pressure level inside the receiving room can be determined as

$$L_n = 10\text{log}F_{rms}^2 + 10\text{log}\rho_0 c_0 \sigma - 10\text{log}5\pi f m' \eta Z + 120\ dB$$

The effect of the resilient layers, the soft surface, the floating floor and the suspended ceiling is modelled as low-pass filters. Traditionally in literature, the layers are treated as simple filter models with 40logf/f_c for locally reacting floating floors, [4] and 30logf/f_c, for resonantly reacting floating floors [6] and a slope of 40logf/f_c, [3], for a suspended ceiling. We have observed other behaviors for light weight floors. One thing that can be seen when comparing measured and estimated ceiling isolation is that the isolation effect does not start where expected from the calculated mass-spring resonance, but from a frequency about 2-3 times above the calculated frequency. The reason for this is at present under investigation and is at this stage assumed to be due to breakup modes of the ceiling plates.

Another observation is that in practice, the impact sound insulation improvement by the resilient layer, the floating floor and the suspended ceiling give good prediction results with traditional estimations when the frequency is less than three or four times the characteristic frequency [7]. But, there are many measurement results that show improvements in sound insulation at a rate of around 20dB when the frequency is three or four times higher than the characteristic frequency. The lower insulation rate at higher frequencies may be explained by mechanical damping at the layer boundaries, by wave propagation over the layer or the z-beam suspension, by the resonant field of the plates or by non-linearity. Therefore, in this model the slope of the reduction is approximated to 40dB/octave at $f_0 < f < 3f_0$ and 20dB/octave at higher frequencies.

One of the most important and limiting simplifications that is included in the model, is that it is assumed that the influences of the orthotropic character of the timber floor can be neglected with this type of model. A composite floor like the one described above is by definition orthotropic while a homogenous single plate is isotropic. Orthotropic behaviour will be found in a joist floor in many ways. One orthotropic behaviour that probably has the greatest influence on the sound insulation is caused by the joist design. Another effect in the orthotropic plate is that the differences in bending stiffness in the stiffest and weakest directions will give different critical frequencies. These discrepancies compared to an isotropic behaviour will be suppressed if the construction is strongly damped and if an analysis is carried out in third octave bands. The sound radiation from the floors is estimated as frequency-averaged radiation efficiency, [7]. It was assumed that a resonant field of bending vibrations is of predominant importance. The model was in /1/ verified on one type of floor of limited sizes. Some limiting simplifications were also seen in that model. One topic that could be criticised was that the radiation of the floor was assumed to be controlled by the coincidence frequency related to the equivalent plate stiffness of the whole floor. The physically realistic radiation of the floor is that the radiation is controlled by that behaviour at frequencies where the whole floor vibrates in global modes. This can, due to an expected forced motion caused by the floor on the ceiling, be expected to be in the frequency range up to approximately where the inner height of the floor is larger than l/4-1/2 of the wavelength. That is for the timber floor case around 300-600 Hz. Above these frequencies the ceiling plates can be expected to be more or less locally vibrating. Thus, the radiation efficiency at high frequencies should be related to the coincidence frequency of the ceiling plates. In the improved model the radiation efficiency is assumed to be controlled by the whole construction as an equivalent plate up to 1/3 octave band below the coincidence frequency of the ceiling plate. Above this frequency the radiation efficiency is assumed to be controlled by the ceiling plates according to Maidanik. The results of this change can be seen as a small peak around 2kHz, both in the predicted curves and in many of the measured ones.

6 - VERIFICATION EXAMPLES

In /1/ the model was verified on a typical Scandinavian timber joist construction. The construction was built up around timber joists with an upper part of two layers of particle board with a layer of cork granule board in between and a layer of mineral wool resting on a layer of spaced panels. A lower part consisted of two layers of plasterboard suspended in a resilient steel section. The original timber construction has now been predicted with the improved model, fig 3.

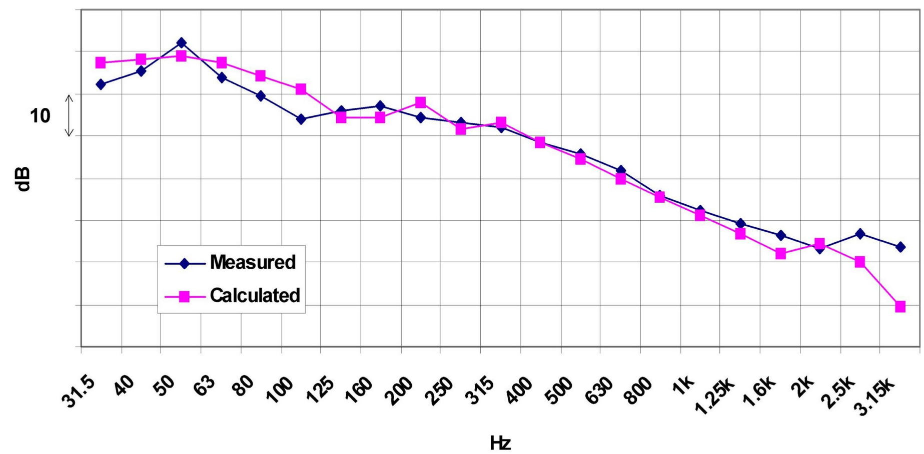

Figure 3: Example comparing predicted and field measured timber floor impact sound levels; the floor area is 3.45×3.45 m^2.

Additional to the timber floor models, predictions have also been conducted on the steel joist floor in two sizes, figs 4, 5 and 6. Verified predictions have shown good agreement both for lab and a field conditions.

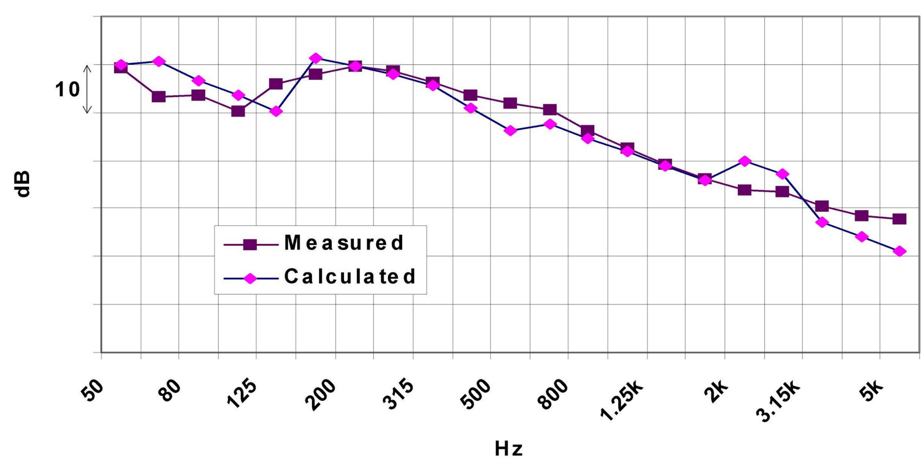

Figure 4: Laboratory measured and predicted impact sound pressure level from 3m span lightweight steel framing floor with carpet.

7 - CONCLUSIONS

A prototype steel beam floor that shows promising vibroacoustic results has been developed. A test building comprising light weight structures has been built, where a multitude of acoustical experiments

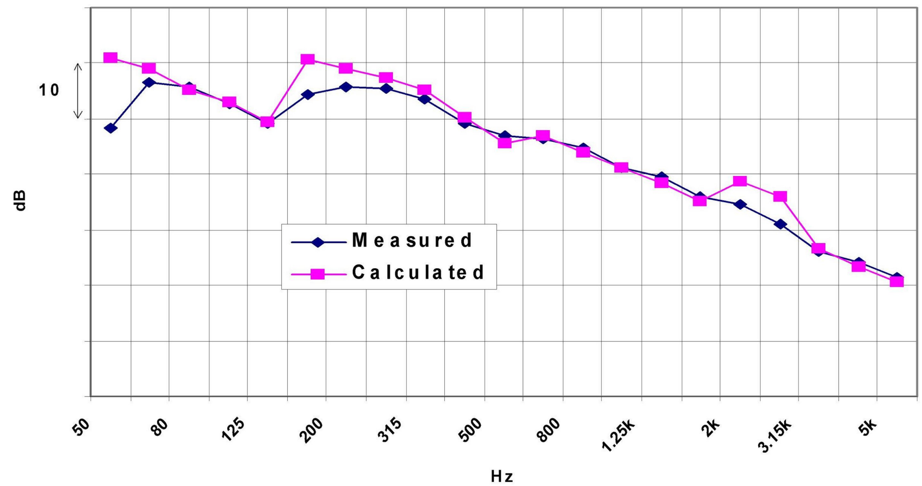

Figure 5: Laboratory measured and predicted impact sound pressure level from 3m span lightweight steel framing floor with carpet.

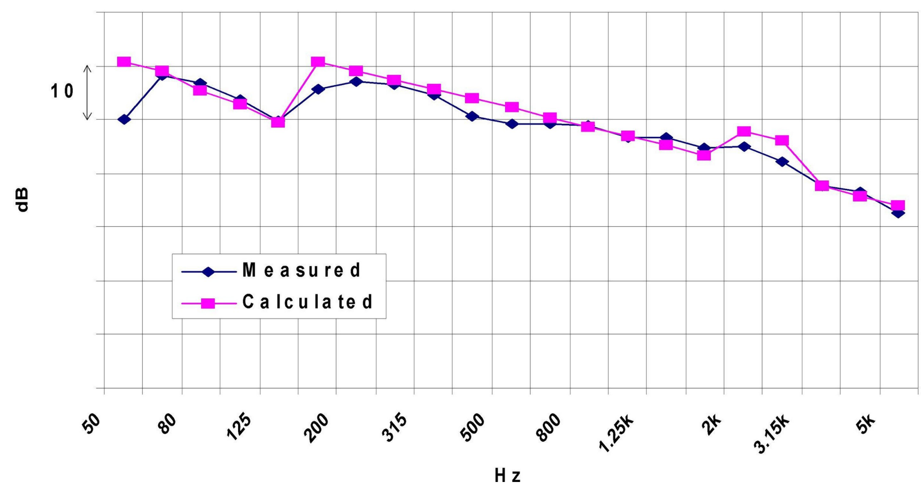

Figure 6: Measured and predicted impact sound pressure level from a 4.5m span lightweight steel framing floor with carpet and mounted in the test building.

are being conducted. Examples to be mentioned are horizontal, vertical and diagonal airborne and impact sound tests as well as vibration and flanking transmission tests.
A simplified prediction model presented earlier has been further improved and verified. Additional to earlier verifications, there is added a new light weight floor of two sizes and both at laboratory and field conditions. The model shows very good tendency predictions.
Further work will be conducted on the steel beam floors where detailed results will be presented as soon as allowed by the project manager. The prediction model will also be further developed.

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