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Lightweight floor/ceiling systems with improved impact sound insulation

Hyuck Chung (1), Colin Fox (2), George Dodd (3) and Grant Emms (4)

(1) School of Computing and Mathematical Sciences, Auckland University of Technology, New Zealand
(2) Department of Physics, University of Otago, New Zealand
(3) Shool of Architecture, University of Auckland, New Zealand
(4) SCION Research, Rotorua, New Zealand

ABSTRACT

Contrary to common belief, a relatively simple and practical lightweight timber based floor/ceiling can have impact sound insulation superior to that of concrete slab based systems. This paper presents examples of such systems that include vibration isolation/damping features, such as rubber ceiling batten clips, glass fibre wool, and a sand-sawdust mixture layer. We give enough details to reproduce our experiments and build the proposed lightweight systems.

INTRODUCTION

A room with good heat and sound insulation can make us feel secure and comfortable. Our interest in this paper is in sound insulation that can be achieved using lightweight floor/ceiling systems or lightweight timber-framed systems (LTFS). In general, the more money and time one spends, the higher sound insulation performance one can achieve. In the past, thick and heavy, e.g., concrete slabs, has been a well-accepted method to achieve good sound insulation. However, timber-based lightweight construction methods are more favourable in countries, such as New Zealand, Canada, and Scandinavian countries where timber is more economical and environmentally sustainable. In this paper we present several examples of lightweight timber based floor/ceiling systems that have higher sound insulation performances than the concrete slab based systems.

As the popularity of LTFS grows, the systems weakness in sound insulation in the low- to mid-frequency range has become apparent. The lightness of the system, which is an advantage in terms of construction, is in this case a main reason for the poor performance. Our objective is then to improve the low to mid-frequency sound insulation without increasing the total weight of the system. In this article we describe how the theory and the experiments have been used together to come up with novel designs of the lightweight floor/ceiling systems. In 2006 the authors produced a technical report [3] for Forest & Wood Products Australia (formerly Forest and Wood Products Research and Development). This article gives *structural vibration* and *subjective listening test* parts of the report.

During the project, 26 variations of LTFS were built. The designs were made incrementally complex. At each step of design changes, a theoretical model and architectural practicalities contributed to choose which component and how to change it. The theoretical model was built to predict the low-frequency vibrations of the floor and the ceiling surfaces when damping, stiffness, or sizes of various components were changed. Thus it kept us from wasting our time on building clearly inferior designs.

The designs we present were also evaluated in listening tests [3]. These verified that in realistic settings the lightweight floor/ceiling systems can have better sound insulation than a 150mm thick concrete slab with suspended ceiling panels. The use of a *sand and sawdust* mixture in the upper layer of the system improves the performances significantly. This debunks the widely held belief (e.g. [2]) that LTFS cannot perform as well as their concrete counterpart.

In the following sections we will present:

1. Detailed measurements of the surface motion using a laser-vibrometer.
2. Recording and recreating the impact sound from the structure.
3. Listening tests to assess the performance of the systems.

Design specifications of selected experimental floor/ceiling systems will also be given. Material properties and details of proprietarily products are given in the appendix.

EXPERIMENTAL SETUPS

Two series of experiments were conducted to assess the performance of each floor/ceiling design. First, detailed vibration measurements of the ceiling and floor surfaces gave us the low-frequency behaviour of the structure, such as resonance frequencies and modal shapes. Second, we recorded the sound from each structure resulting from various impact sources on the floor surface. The recordings were then played back to human subjects, who graded the LTFS.

Figure 1. An electrodynamic shaker (top) and setups of the laser vibrometer to measure the ceiling (bottom).

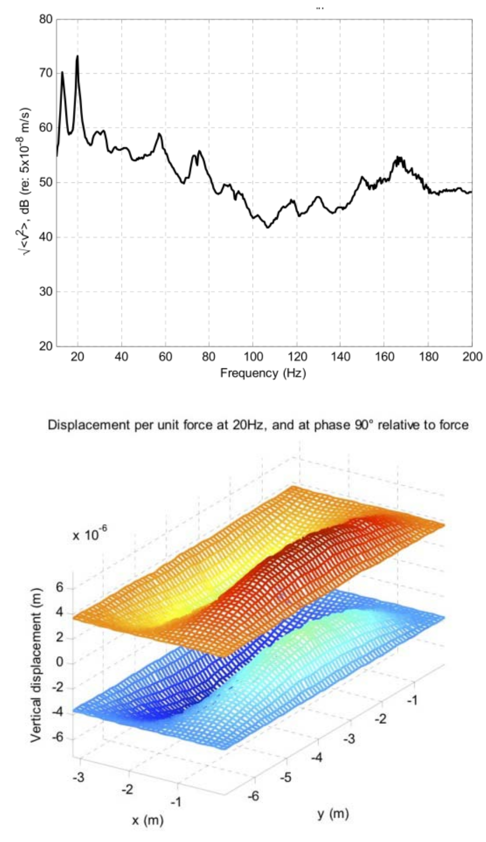

Figure 2. Top: the RMS velocity of the ceiling, as a function of frequency. Bottom: a mesh plot of the amplitude of vertical displacement of the ceiling and floor for the second resonant mode (at about 20Hz).

Vibration of the floor and the ceilings

Each design was constructed and tested in a purpose-built test rig (see Figure 1). An electrodynamic shaker provided a localized vertical force on the upper surface, connected through a wire stinger and a reference force transducer. The force transducer measured how much force was applied to to the floor. The shaker body was mounted on a beam resting on supports, which sat on the concrete collar surrounding the floor, and the beam itself was isolated from the concrete collar by very resilient pads made of polyester fibre infill. A pseudo-random signal was used as excitation, with a bandwidth from 10Hz to 500Hz, for a duration of 2 seconds (to achieve a frequency resolution of 0.5Hz).

We used a scanning laser vibrometer (Polytec PSV 300) to measure the velocity normal to the surface of the floor and ceiling for each of the test designs. A grid with a spatial resolution of 10-14cm was obtained to map the surface velocity of the floor and ceiling relative to the input force. Both amplitude and phase information were recorded at each frequency. Figure 1 shows the laser-vibrometer setup for measuring floor and ceiling vibrations. The scanning vibrometer can capture fine details of the surface motion as shown in Figure 2. The overall vibration response was measured in terms of the root-mean-square (RMS) velocity in dB (also shown in Figure 2), as this gives a measure of average radiated sound power at each frequency.

Recording impact sounds and listening tests

Experimental floor/ceiling systems were constructed in the ceiling opening (7m by 3.2m) of a purpose-built concrete block reverberation chamber. In total 26 systems were built and tested according to ISO 140-6. We made near-field recordings underneath the ceilings (70mm from the ceiling) at 4 microphone positions spaced across a diagonal of the chamber of a sequence of impact excitations of each floor/ceiling construction. These excitations comprised –

1. the standard tapping machine at a central floor position
2. heavy tyre drops at 4 positions along a diagonal (above the mic positions)
3. a 72Kg male walking along the diagonal
4. the same male running along the same diagonal
5. light impact ball drops at the 4 diagonal positions

In each case simultaneous recordings were made from the 4 near-field microphones. The RT (Reverberation time) of the chamber was reduced for these recordings by laying out a complete floor covering of thick polyester sound absorber. The aim was to reduce reverberant sound picked up by the near-field microphones. The recordings were played back in a simulated living room that conforming to IEC 268-13. The room itself was equipped with 4.2 loudspeaker reproduction system (4 loudspeakers in the ceiling cavity and 2 subwoofers in the room). Our approach was novel in the following ways:

1. The listening room (Figure 3) was furnished to look and feel like a domestic environment
2. The hidden loudspeakers provided directional realism for the impact sound
3. The system was equalized to provide a flat frequency response down to 16Hz (see Figure 4)

The individual loudspeakers in the ceiling of the listening room were each fed with one channel of the recordings. The 2 woofer loudspeakers were fed an average mix of the low frequency signals from the 4 microphones. The levels at the subject's listening position were adjusted to account for differences in RT between the reverberation chamber and the listening room based on the ISO 140 impact measurement spectra.

31 subjects were invited to participate as assessors for the initial experiment. They were chosen to provide a group spanning a wide age range (mean age 31 years, maximum 61 years) and between males and females. Also they were only included if, based on the subjects' own reporting, they were free from any hearing impairment. Each participant was asked to complete profiling questionnaires to collect information on their listening habits, noise sensitivity, and privacy rating.

The impact insulation performance of a concrete slab floor (150mm thick) with a suspended plasterboard ceiling was taken as a reference and the LTF floor recordings were paired with the equivalent recording from the concrete slab and presented in an A/B comparison for assessment of (a) preference and (b) difference. A selection was made of 8 floors considered most relevant to the overall project. This, together with 4 impact types (walking on bare floor, walking on carpeted floor, tapping machine and ball drop), gave 32-paired assessments for each subject.

Figure 3. Listening room simulating an average living room with common furniture settings.

The preference question took the form of a 2-Alternative-Forced-Choice experiment with no ties allowed [5] and for this the subjects were asked to imagine they were going to live in an apartment where they had to choose a floor/ceiling construction to separate them from the apartment above. The presented sounds in each pair being the typical sounds they might hear from 2 alternative floor/ceiling constructions. In each case one of the pair was the sound from the concrete reference floor although this was not communicated to the subjects.

The *difference* question took the form of asking the subjects to mark on a continuous semantic differential scale how different the pair of sounds seemed. The extremes of the scale were marked *Not significantly different* and *Markedly different* and the mid point was marked *Noticeably different*.

DESIGNS AND PERFORMANCES

Figure 5 shows the design of a common joist floor, which has a plywood upper layer, supporting timber joists, and a suspended ceiling panel underneath. All other designs we present are developments on this basic configuration. We made three kinds of changes to the top layer: variation of its mass, its stiffness, and its damping. Our experiments have shown that increasing damping between components, rather than increasing the mass or the stiffness, is most effective at reducing the vibration response of this type of floor.

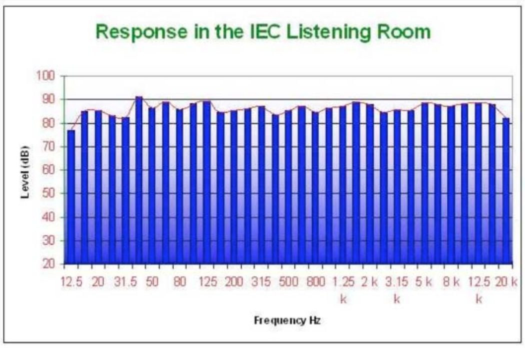

Figure 4. Listening room sound level across the frequency range.

Multiple plaster board top layer

Adding multiple layers of plaster board (see Figure 6 increases the mass and stiffness of the top layer, and moves the first an second resonant frequencies. However the increased mass and stiffness did not lower the vibration level.

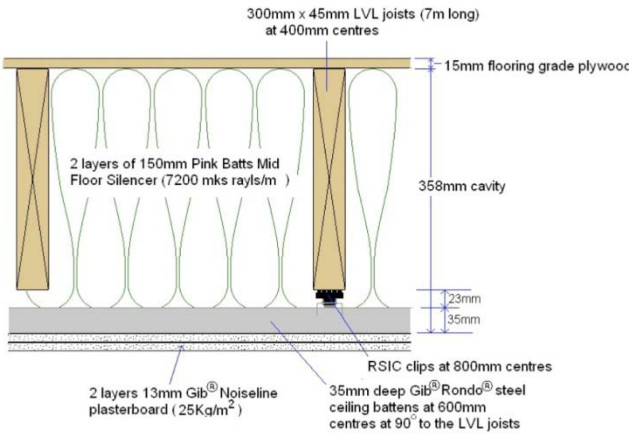

Figure 5. Cutaway schematics of a floor/ceiling system with a single plywood upper layer. The descriptions of the commercial products are given in Appendix.

Sand-sawdust upper layer

The design shown in Figure 7 gave the best performance in terms of the sound insulation perceived by listeners, based on listening experiments using recordings in the room below the floor of impacts on the floor. We tested this design with sand only, and with various sand and sawdust mixtures. Figure 8 shows the positive effects of including sawdust in mixture in the top layer, by comparison with a sand-only damping layer. Above 80Hz, the vibration and radiated sound is significantly damped more by mixing in sawdust. The best mixture we tested had 80% sand and 20% sawdust, by loose volume.

Aerated concrete top layer

We also tested the basic design built with aerated concrete (Hebel) panels as the upper layer. These have comparable mass density to the sand fill, so provide a direct test of whether it is the mass or the damping in the sand-sawdust that is giving good performance. Figure 9 shows the system, and the performance of the system, with the sand-sawdust system results for comparison. The comparison shows that the dampingcontributed by the sand-sawdust cannot be replicated by simply adding equivalent mass. The sand-sawdust fill dampens the vibration above 60Hz more effectively than the aerated concrete upper layer. It should be noted that timber I-beams were used for joists in this system, however our numerical modelling showed that the same result would have been achieved with standard timber joists.

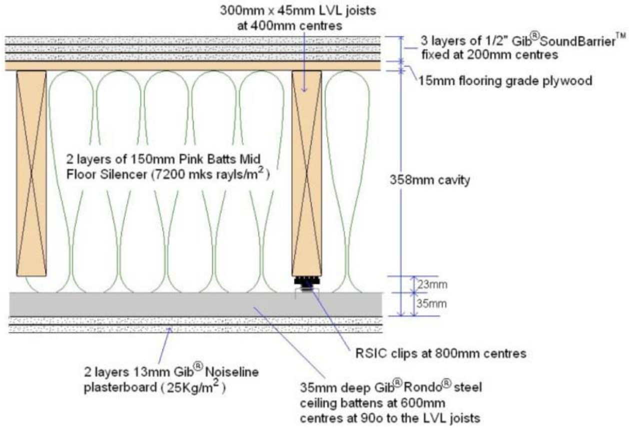

Figure 6. Cutaway schematics of a floor/ceiling system with three plaster boards as the upper layer.

Figure10 shows numerical simulations of the effect of using various values of stiffness and mass density in the upper layer [1]. The mass density and the stiffness were varied in order to confirm that the damping by the sand-sawdust could not be achieved by replacing it with layers that provide only mass and stiffness. That is, we want to confirm and extend the conclusion reached from the comparison in Figure 9. Both simulations in Figure 10 show that an increase in mass and stiffness certainly lowers the vibration level above 80Hz. However the vibration level is still highly varying with frequency compared to the near flat response of the sand-sawdust floor. Furthermore, it takes an impractical amount of mass and stiffness to achieve a performance comparable to that achieved with a sand-sawdust layer.

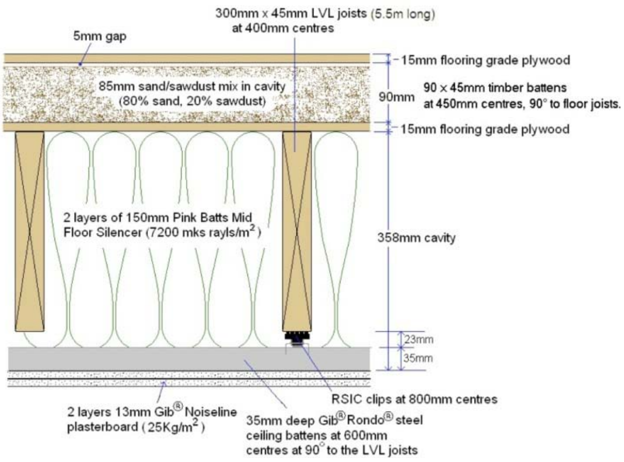

Figure 7. Cutaway schematics of a floor/ceiling system with a sand-sawdust damping layer.

Transverse stiffening

In order to stiffen the floor perpendicular to the joists, we tried transverse stiffening as shown in Figure 11. The addition of transverse stiffeners was found to increase the fundamental frequency of the floor, and therefore to make it potentially noticeable to human hearing. This is particularly the case if the floor is relatively narrow. Thus, transverse stiffeners should not be installed between the floor edge and the next joist. As a consequence though, this introduces a rotational vibration mode in the floor, which depends on the bending stiffness of the upper layer. However, since it is an odd type mode (and hence having a tendency for canceling for radiated sound) the sound radiation efficiency would be low.

The effect of the stiffeners was to produce little change at frequencies below100Hz, but a poorer performance for frequencies above 100Hz. Transverse stiffeners made from I-beam sections were also added to the Hebel floor and their effect was again insignificant. Thus we conclude that transverse stiffeners in floor designs provide little acoustical benefit.

Table 1. Standard single figure ratings of the various floor/ceiling systems.

Top layer	*IIC*	*Ln,w*	C_I	$Ln,w+C_I$
Concrete slab	37	69	-12	57
Single plywood	49	61	-1	60
3 plaster boards	61	45	1	46
Hebel panel	35	72	-10	62
Sand-sawdust	62	48	-2	46

Tapping machine results

Table 1 shows the results of tapping machine experiments. A standard tapping machine was used on the bare floor surface to measure the standard single figure ratings. We did not use any additional surface cover (e.g. carpet) in order to create the most demanding condition, and because it is common to have bare floors or parquet directly on top of concrete. The overall *Ln,w* rating of each floor was obtained using the relevant part of ISO 140 and ISO 717-2. The table shows *IIC* ratings in accordance with ASTM E989 (Standard Classification for Determination of Impact Insulation Class) and spectrum adaptation terms $Ln,w+ C_I$. Note that $Ln,w+C_I$ tends to have mid-frequency emphasis. The worst performing floors for high-frequency impact insulation as indicated by a high *Ln,w* values are the systems with a 150mm concrete slab, and with aerated concrete panels. Although these systems would meet the Australian building code requirements $(Ln,w+C_I \leq 62)$, they would not meet the New Zealand building code requirements ($IIC \geq 55$).

Listening test results

Table 2. Rankings by Preference and Subjective Difference scores. Although many more LTFS were ranked, we only show the LTFS mentioned in this paper.

Top layer	Tapping machine	Ball drop	Walking
Concrete slab	5th	1st	3rd
Single plywood	4th	5th	5th
3 plaster boards	2nd	4th	2nd
Hebel panel	3rd	3rd	4th
Sand-sawdust	1st	2nd	1st

The intention was to use the *difference* judgements to provide a ranking of the different floor constructions relative to one another. It became evident, however, that subjects approached their judgement in two differing ways. This difficulty has prompted a repeat stage of experimentation but the results from the 2AFC question do in general support the rankings found by the difference method (see Table 2).

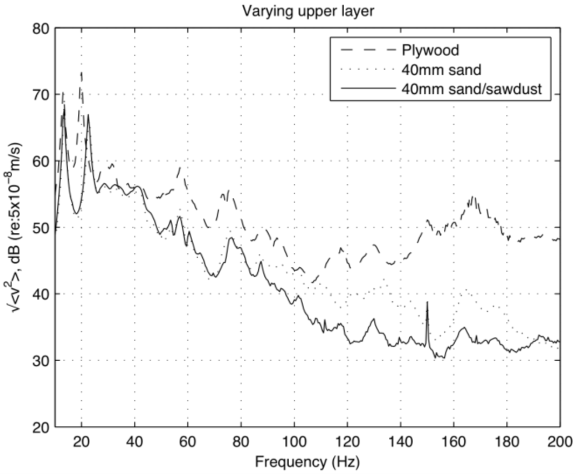

Figure 8. Top: RMS velocity comparison between sand-sawdust and sand-only upper layer. Bottom: Photo of sand-sawdust layer before it is covered by plywood.

The cohort of subjects was too small to allow any clear indications of differences between subjects of significantly different Noise Sensitivity or Privacy Rating. When the subjects were divided into Low, Average and High groups for Noise Sensitivity and Privacy Rating the results showed no consistent trend, - but with such small numbers of subjects in the extreme groups (e.g.~the High Noise Sensitivity and Low Privacy Rating groups each comprised only 3 subjects) this cannot be relied on as indicating no dependency.

When divided by sex a small but consistent difference between men and women was evident (e.g. an average of 0.32 for the tapping machine and 0.53 for the Ball drop - these values being distances on the continuous scale of length 10) with women judging differences overall to be slightly smaller.

When the subjects were divided into two age groups first those aged <30 (n=14) and those aged >40 (n=10) the judgements were not different for the tapping machine sounds but for the Ball drops the younger subjects consistently judged the differences larger by an average of 1.2.

Apart from providing a direct indication of the relative satisfaction to occupants of LTFS and standard concrete floor constructions we hoped that the subjective experiment results would help clarify if existing objective measures are adequate for ranking occupant preference. The issue here is that the standard building insulation measures [4] – even with the ISO low frequency extensions [6] – do not cover the full bandwidth used in this experiment. However, Loudness (in Sones) and A-weighted SPL are both standardised measures and can be extended to include all the low frequencies (see [3] for the Loudness calculation). The correlations between Loudness and the subjective preference scores are given in [3], and the results show surprisingly good correlations for both the A-weighted SPL (Leq 10s) and Loudness with the subjective judgements.

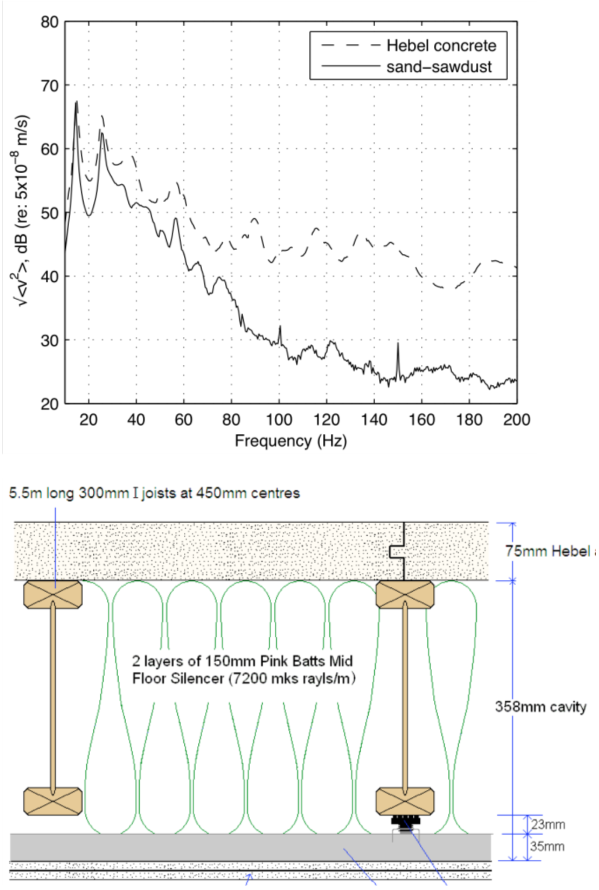

Figure 9. Top: RMS velocity comparison between the structures with sand-sawdust and equivalently weighted upper layers. Bottom: A cutaway schematics of the floor/ceiling system with aerated concrete upper layer and timber I-beams for the joists.

The rankings consistently show sand-sawdust system as either close to, or better than, the concrete reference construction whatever the impact source or floor covering. The critical condition is when the floor is subjected to heavy impact where the Loudness and A-weighted SPL results and the subjective preferences do distinguish the floors as different. We note that *Ln'w* and *IIC* values are not helpful here because the tapping machine has such a different excitation spectrum.

Guidance can be found from the way in which *semantic difference scale* processing has been carried out in other research on subjective judgements. We processed our scale with a resolution of 1% but others divide their scales into categories with a much coarser resolution. For example in the most recent work (see [9] and [10]) it is recommended to use a scale divided into only 5 categories. This would imply that subjective differences less than 2 in our results put the sounds in the same category of acoustic perception and the associated floors into the same class of acoustic comfort. This is clearly the case for sand-sawdust system in the case of the ball drop where, although the mean preferences indicates a bias for the concrete slab floor, the subjective difference is less than 2 (i.e. 1.61 for the Ball drop).

Further guidance is found in the acoustic quality categories and classes of acoustical comfort that are used in Europe (e.g. in the Nordic countries and Germany). Typically different categories or classes span a range of 5 - 7dB, and so impact levels that differ by less than 5dB would be regarded as being subjectively in the same category. This is consistent with the 5dB increments that are used in audiometry in order to create level changes, which are just noticeable to the average listener. The A-weighted SPL (Leq 10s) values for sand-sawdust system and the reference concrete system in the above situation, in fact differ by less than 1dB.

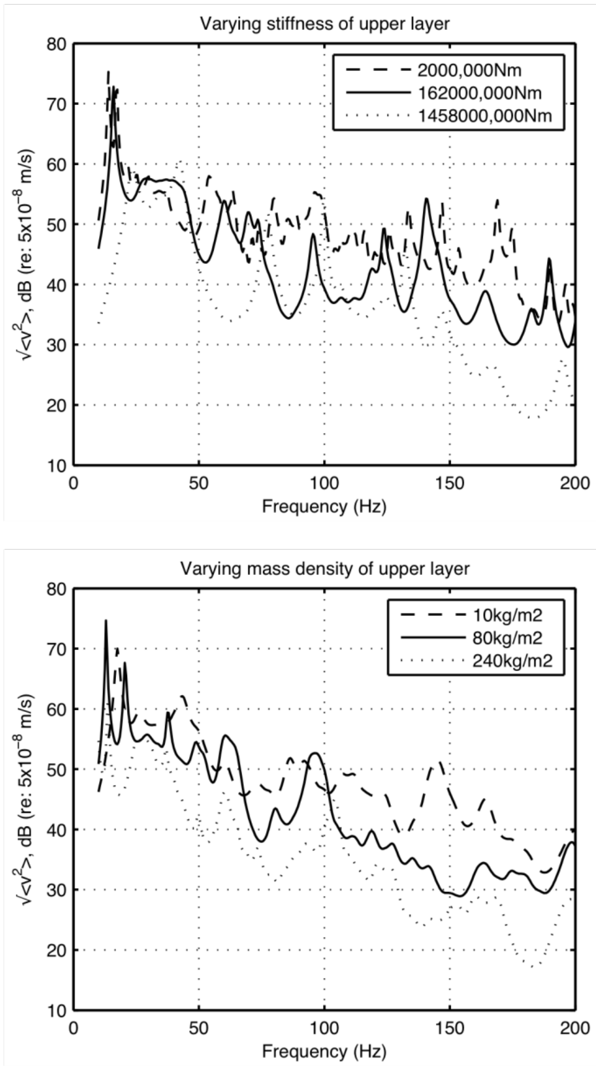

Figure 10. Numerical simulations with various upper layer stiffness (top) and mass density (bottom).

It therefore seems a valid conclusion from this experiment that sand-sawdust system – and any similarly performing LTFS – provides a subjectively perceived performance, which is at least as acceptable as that of the 150mm concrete reference floor. This is true, at least, for the range of normal impacts represented by the sources used in this experiment, but, as the reproduction system did not adequately reproduce the very lowest frequencies, confirmation is necessary from the next stage of planned subjective testing.

CONCLUSIONS

A lightweight floor/ceiling system requires a range of components to achieve effective isolation of the ceiling layer from vibration induced in the floor surface above. The inclusion of a sand-sawdust mixture layer has been found to provide effective vibration damping of the whole composite structure over a wide frequency range. In fact, a sand-sawdust layer results in a performance which is superior to the addition of mass or stiffeners to the upper layer. A notable advantage of the sand-sawdust design is that the bottom and top plywood panels in the upper layer are directly connected through the separating battens (see Figure 7), which makes the system robust to building mistakes. Another advantage of such a highly damped system is that flanking transmission is well attenuated.

Figure 11. Sytem with the transverse stiffeners.

The ultimate aim of research on the insulation provided by floor/ceiling systems must be to determine what is required to render impact noises completely non-problematic. In this project we have addressed an interim goal of demonstrating that LTFS can be designed to match, or exceed, the insulation achieved by a concrete-based floor (interpreted as 150 mm slab with a plasterboard suspended ceiling). In addition we have demonstrated that a Loudness calculation suitably extended to include the very low frequencies provides a reasonably acceptable means for rank order LTFS for their ability to insulate against heavy and light impacts.

AKNOWLEDGEMENT

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