Novel Design of a Lightweight Floor/Ceiling System with Improved Impact Sound Insulation

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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. We present examples of such designs that include vibration isolation/damping features, such as rubber ceiling batten clips, glass fibre wool, and a sand-sawdust mixture layer. This article gives enough details to reproduce our experiments and build the proposed lightweight systems.

Introduction

Most residential buildings can be classified as either concrete-based or lightweight timber-based constructions. The lightweight systems have become popular because timber is a renewable resource and a primary industry that is commercially important to New Zealand. However, where timber constructions are designed solely to meet structural requirements they typically have a noticeable weakness in sound insulation in the low-frequency range. In this article we describe how theory and experiments have been used together to come up with novel designs for lightweight floor/ceiling systems that have excellent sound insulation, particularly for low frequencies. In 2006 the authors produced a technical report [3] for Forest & Wood Products Australia (formerly Forest and Wood Products Research and Development Corporation). This article describes the designs and experiments in the structural vibration aspects of the report.

The designs we present were also evaluated in listening tests [3]. These verified the vibration results we present here, that in realistic settings the lightweight floor/ceiling systems can have better sound insulation than a 150mm thick concrete slab with carpet and 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. Blazier and DuPree [2]) that lightweight floor/ceiling systems cannot perform as well as their concrete counterpart.

Experimental setup

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

Figure 1: An electrodynamic shaker (left) and setups of the laser vibrometer to measure the floor (Centre) and Ceiling (Right)

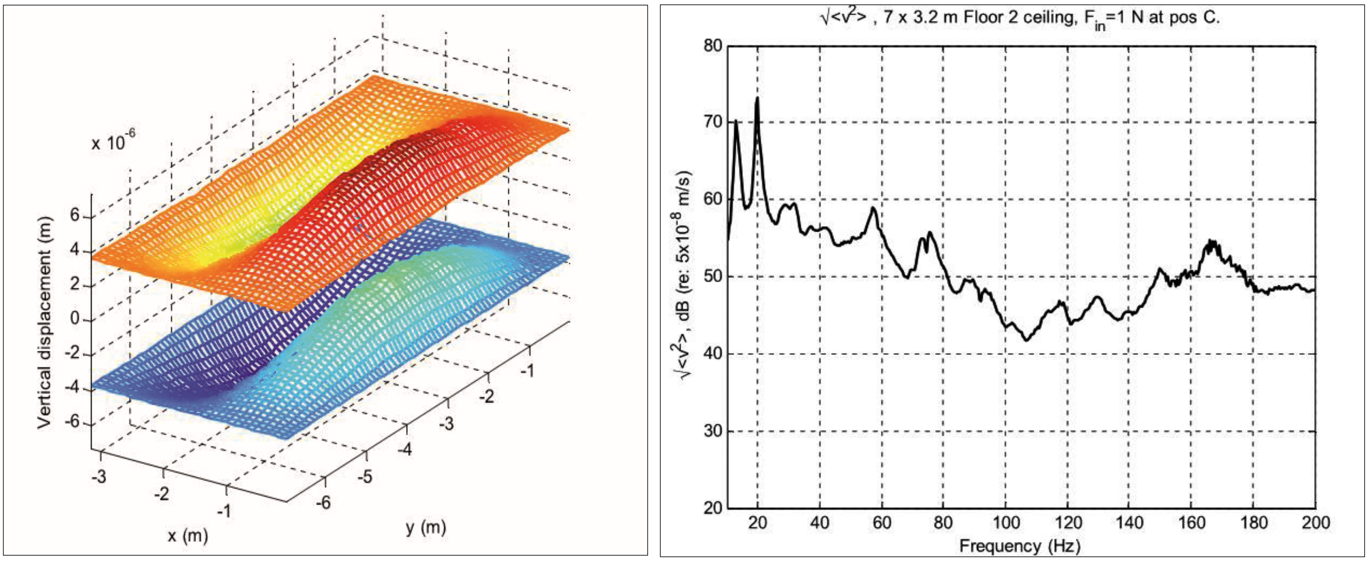

Figure 2: An example of experimental results for one design. Left: the RMS velocity of the ceiling, as a function of frequency. Right: a mesh plot of the amplitude of vertical displacement of the ceiling and floor for the second resonant mode (at about 20 Hz)

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.

Designs and Performances

Figure 3 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. Descriptions of the commercial products

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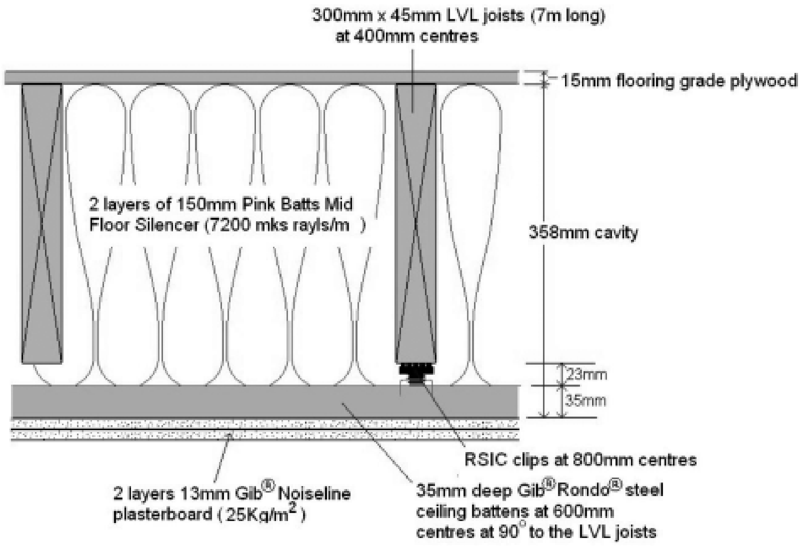

Figure 3: Cutaway schematic of a floor/ceiling system with a single plywood upper layer

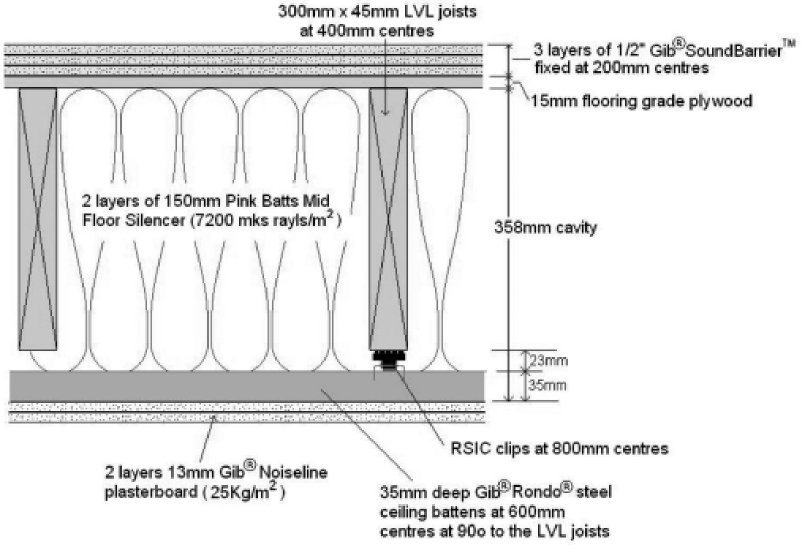

Figure 4: Cutaway schematic of a floor/ceiling system with three layers of plaster boards as the top layer.

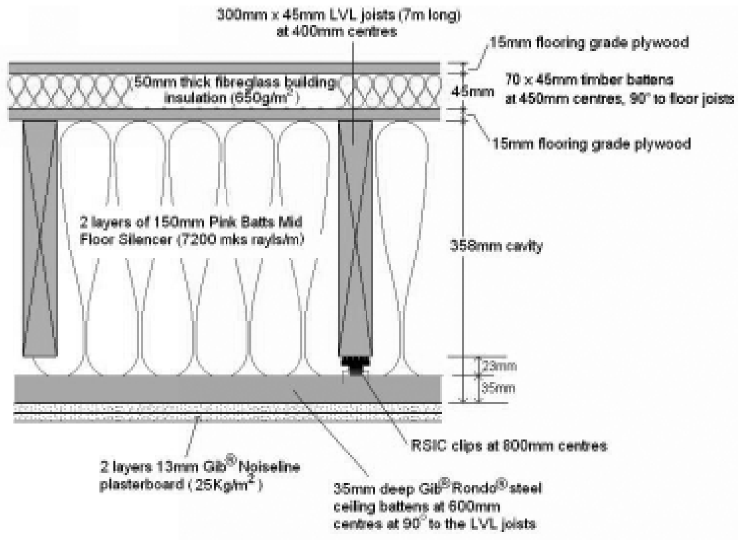

Figure 5: Cutaway schematic of a floor/ceiling system with fibreglass wool in the upper layer

used in our experiments are given in the appendix. 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 construction.

Multiple layers of plaster board on the top layer

Adding multiple layers of plaster board (see figure 4) increases the mass and stiffness of the top layer, and moves the first and second resonant frequencies. However the increased mass and stiffness did not lower the vibration level.

Multiple Layers of Plaster Board on the Top Layer

We tested the basic design with a layer of fibreglass wool added to the top layer, to increase acoustic damping. This had little effect on vibration, except through the increased the stiffness of the upper layer provided by the double-leaf plate.

Sand-Sawdust Upper Layer

The design shown in figure 6 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 7 shows the value 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 (shown in figure 8) 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 damping contributed by the sand-sawdust cannot be replicated by simply adding equivalent mass. The sand-sawdust fill dampens the vibration above

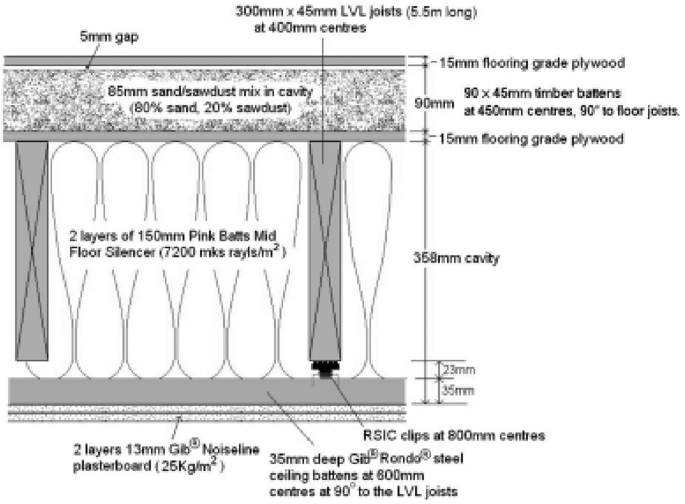

Figure 6: Cutaway schematic of the floor ceiling system with a sand-sawdust damping layer.

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.

Mass and Stiffness versus Sand-Sawdust

Figure 10 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 cannot 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.

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 model (and hence having a tendency for cancelling for radiated sound) the sound radiation efficiency would be low.

The effect of the stiffeners was to produce little change at frequencies below 100Hz, but a poorer performance for frequencies above 100Hz. Transverse stiffeners made from I-beam sections were also added to the Hebel floor and


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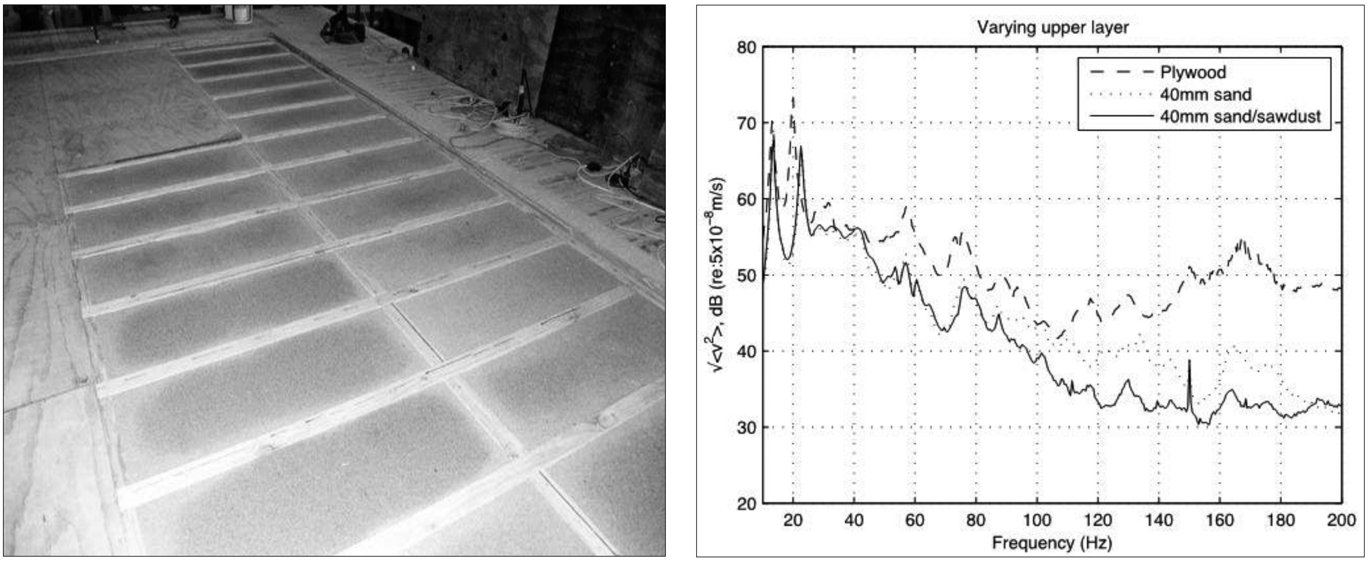

Figure 7: Left: RMS surface velocity for the design with sand-sawdust and sand-only upper layer. Right: Photo of sand-sawdust layer before it is covered by plywood

their effect was again insignificant. Thus we conclude that transverse stiffeners in floor designs provide little acoustical benefit.

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. The overall $L_{n,w}$ rating of each floor was obtained using the relevant part of ISO 140 and ISO717-2. The table shows IIC ratings in accordance with ASTM E989 (Standard Classification for Determination of Impact Insulation Class) and spectrum adaptation terms

Figure 8 Aerated concrete panel used for the top layer.

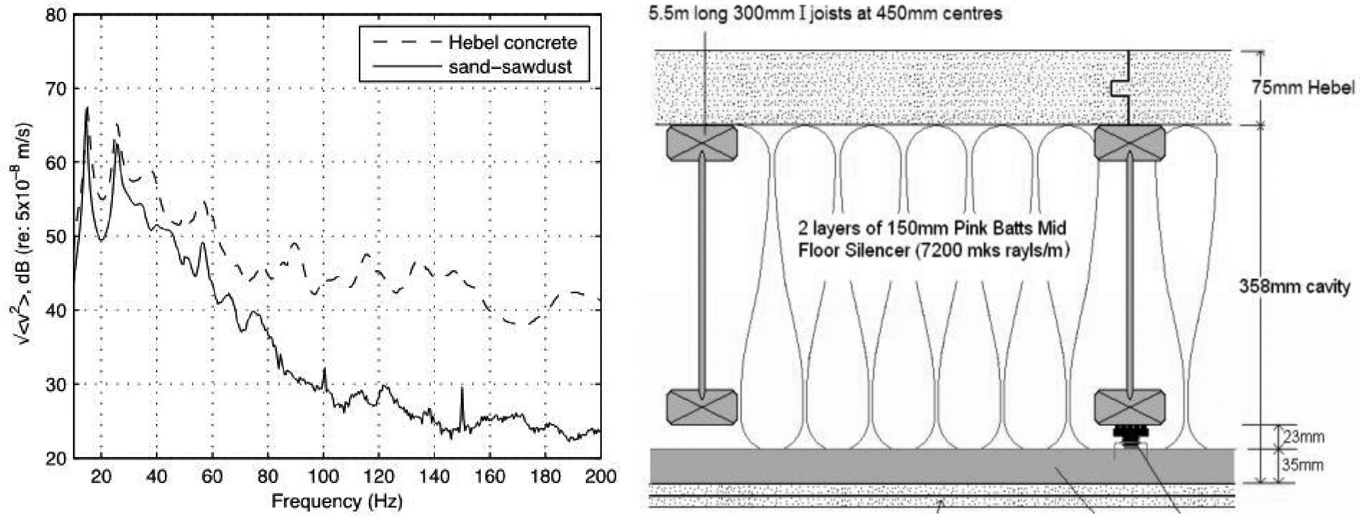

Figure 9: Left: Comparison of the performance of structures with sand-sawdust and equivilently weighted aerated concrete upper layer. Right: A cutaway schematic of the floor/ceiling with aerated concrete upper layer and timber I beams for joists.

TOP LAYER	*IIC*	$L_{n,w}$	C_I	$L_{n,w} + C_I$
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

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

$L_{n,w} + C_I$. Note that $L_{n,w}+C_I$ tends to have mid-frequency emphasis. The worst performing floors for high-frequency impact insulation as indicated by a high $L_{n,w}$ values are the systems with a 150mm concrete slab, and with aerated concrete panels.

Although these systems would meet the Australian building code requirements ($L_{n,w} + C_I <= 62$), they would not meet the New Zealand building code requirements (IIC >= 55).

Summary

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 than 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.

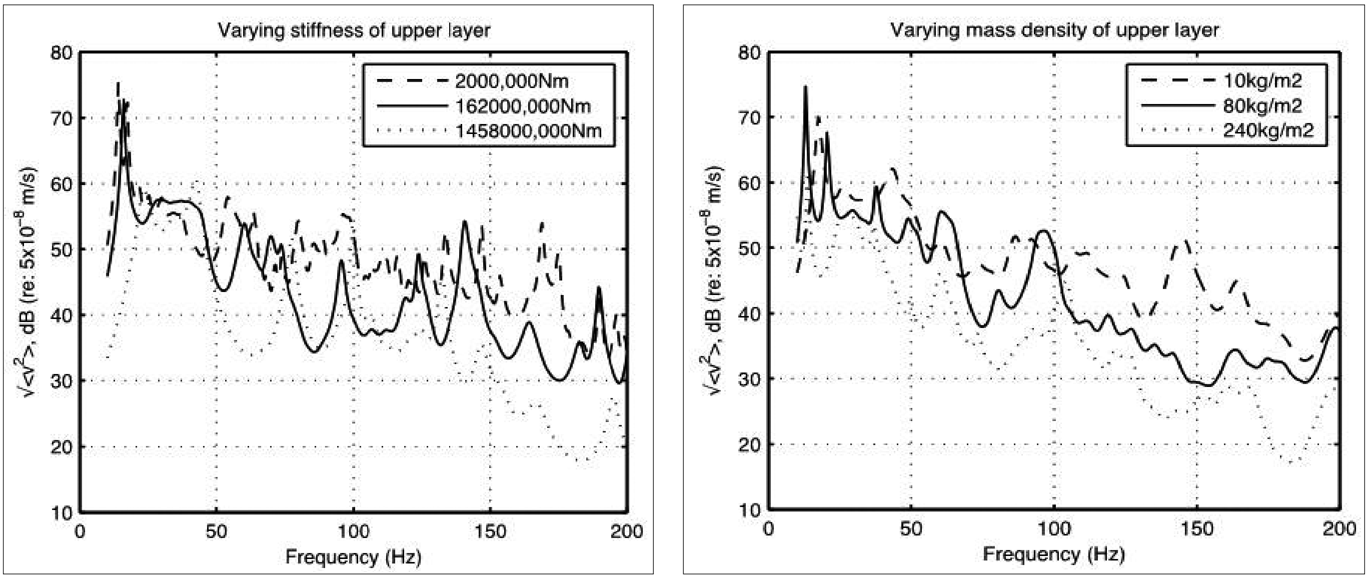

Figure 10: Numerical simulations showing RMS surface velocity for various upper layer stiffness (left) and mass density (right), as a function of frequency.

Figure 11: Transverse stiffeners.

Appendix: Material parameters

1. Panel products

- 15mm 5-ply Ecoply F11 plywood: Manufacturer's nominal Density = 560kg/m3, nominal static bending stiffness 2360Nm2 along face grain, 684Nm2 perpendicular to face grain assuming 10.5GPa along-grain wood stiffness. Dynamic measurements from one sample showed that along-grain wood stiffness was 13GPa. Apparent measured dynamic bending stiffness along face grain (from floor measurements) is equivalent to homogeneous material with Young's modulus from 12 to 14GPa. Vibration loss factor of material assumed to be 0.03.
- 13mm GIB Noiseline (gypsum) plasterboard: Manufacturer's nominal density = 962 kg/m3. Dynamic bending stiffness = 3.7GPa. Measured vibration loss factor = 0.013. Supplied by Winstone Wallboards Ltd.
- 75mm Hebel Floor panels: Lightweight autoclaved aerated concrete. Density with nominal moisture content = 690Kg/m3. Manufacturer's Static Young's modulus = 1.715GPa Vibration loss factor of material = 0.02.

2. Joists

- CHH (Carter-Holt-Harvey) Hyspan LVL (laminated veneer lumber): Manufacturer's nominal density = 620kg/m3, nominal static Youngs modulus = 13.2GPa. Apparent dynamic Young's modulus from measurements = 14.5GPa to 15.5GPa. Assumed vibration loss factor= 0.03.
- 300mm CHH Hybeam I-beam (HJ300-63): Manufacturer's nominal linear density = 4.4kg/m,nominal static bending stiness = 1.1106Nm2. Assumed vibration loss factor = 0.03.3.

3. Infill materials

- 150mm Tasman Insulation Mid-floor Silencer: Measured sample flow resistivity = 7227Rayls/m. Density = 12kg/m3.4. 4.

4. Ceiling fixtures

- RSIC clip: Dynamic Stiffness at 20Hz under 130N load (approx equiv to 25kg/m2 ceiling surface density) = 220000N/m. Loss factor = 0.1.
- Gib Rondo Batten: Estimated (from measurements) bending stiness when attached to plasterboard = 11000Nm2.

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