Improving the Impact Insulation of Light Timber Floors

Grant Emms (1), Hyuck Chung (2), Ken McGunnigle (3) and George Dodd (4)

(1) Sustainable Consumer Products, Scion, Rotorua, New Zealand. (grant.emms@scionresearch.com)
(2) Mathematics Department, University of Auckland, New Zealand.
(3)McGunnigle Ltd, Auckland, New Zealand.
(4) Acoustics Research Centre, University of Auckland, New Zealand.

ABSTRACT

One of the major problems with the impact insulation of lightweight floors is that they are lightweight, giving problems with impact insulation in the low-frequency region. This paper outlines the results of a New Zealand and Australian project which has been looking at which techniques may be useful in reducing the above problem in lightweight floors, particularly light timber-framed floor systems. Floor designs were produced, incorporating techniques from around the world, and then evaluated in a laboratory setting. The particular emphasis has been to produce floor designs which can be easily built in New Zealand and Australia.

INTRODUCTION.

Current occupier perception of timber inter-tenancy floor/ceiling systems used in Australasia is that they do not perform acoustically as well as heavy masonry building systems, particularly in terms of impact sound transmission from the floor above. This perception has resulted in a limit in growth of multi-residential timber apartments in Australasia. Concern for this problem and an expectance of a growth in medium-rise apartment construction has resulted in increased Australasian research into this problem. This concern is not unique to Australasia, and as a result, a number of other countries with an interest in timber housing construction have also been researching this problem. A team of New Zealand building acoustics researchers and Australasian companies and associations (NZPMA, CSR, Gib, CHH, Tenon) formed a consortium to tackle this project with part funding from the FWPRDC of Australia. This project essentially consisted of progressing existing Australasian and overseas research into this problem with a view to produce floor/ceiling system design recommendations for floors having acoustic properties which are comparable with concrete floor constructions, while also meeting the proposed Australian and New Zealand building code requirements, and being cost effective and buildable using existing construction industry skills.

The members of the team consist of acoustic professionals and researchers, mathematicians, construction experts, structural engineers, and people expert in the area of bringing new construction ideas and techniques to the market place. In some instances the researchers have both acoustic and practical building experience. It is this breadth of knowledge of the research team which tends to set this team apart from others, giving a practical grounding to the development of their ideas.

This paper is an overview of the project. More details can be found in the complete report 'Maximising impact sound resistance of timber framed floor/ceiling systems' – FWPRDC project PN04.2005. This report can be downloaded from the FWPRDC's website: www.fwprdc.org.au.

OVERVIEW OF THE ISSUES.

The aim of the project.

The aim or brief of the project can be divided into two aspects:-

- Achieving the appropriate mid to high frequency floor impact insulation performance.
- Achieving the appropriate low-frequency floor impact insulation performance.

Aspect (1) concerns the frequency range from about 100Hz to 3150Hz, and can be reasonably well determined and rated by standard impact insulation measurement techniques (e.g. following standard ISO 140) and the resulting single figure ratings (e.g. following standard ISO 717). According to the BCA Acoustic Regulations (which have subsequently come into force) a floor's mid to high-frequency performance should be such that $L_{n,w}+C_I$ is less than or equal to 62 dB. As far as almost any type of inter-tenancy floor is concerned this is relatively easily achieved by putting the appropriate resilient surface or underlay on the subfloor. It is often the case that timber floors, due to their inherently softer materials, have a head start here over concrete floors.

Aspect (2) concerns the frequency range below about 100 to 200Hz. It is in this low-frequency range that problems arise in a number of areas. For one thing, this is the area that lightweight floor systems have problems compared to heavy floor systems due to, well, their light weight and perhaps their lower stiffness. It has been found by experience over the world that inter-tenancy lightweight floors tend to be regarded as poor performers by occupiers in the neighbouring tenancy (usually the tenancy below). This poor performance is often expressed by occupiers as the hearing of 'bumps and thumps' from above and is due to poorer low-frequency impact insulation. In part, this has presumed to have been caused by people walking or otherwise moving around on the floor above. Another contribution to these low-frequency 'bumps and thumps' can be things such as doors closing or heavier objects being dropped. On the other hand, heavy masonry systems, from experience, appear to perform 'acceptably' in this area of low-frequency impact insulation.

Another problem with low-frequency impact insulation of floors is that it is difficult to measure and rate. It is difficult to measure the low-frequency performance of a floor due to the fact that the room connected to the floor has a significant contribution to the floors' performance and it is difficult to remove this effect for low-frequencies. It is also difficult to rate the low-frequency performance of a floor because we don't really understand how objective measurements relate to people's perceptions of the low-frequency impact insulation of a floor.

Due to the uncertainty surrounding how one can express and rate low-frequency performance, and because of the appreciation that heavy masonry floors seem to perform acceptably in the minds of occupiers, the measure of acceptable low-frequency performance is to make such performance comparable to a 150mm dense concrete slab floor (as stated in the objective).

Note that in the above paragraphs on low-frequency floor performance, only lightweight floors were mentioned, rather that lightweight timber floors specifically. This is simply because the problem is not specific to timber floors, and is suffered by other lightweight systems, even thin, lightweight or hollow-core concrete slabs.

Both low and high frequency aspects of impact insulation are important. However, the problem of low-frequency impact insulation is the one which is most challenging to solve for lightweight floor systems, and hence will received the most attention in this project. This is not to say that the high-frequency impact insulation of a floor is not important, but it is something which is relatively easy to deal with and measure, having received much attention from researchers and industry.

Summary of the Problems.

The problem of the impact insulation performance of floors can be divided into a number of factors which influence the overall result; these are illustrated in Figure 1.

The first factor is the impact source itself. The issue here is to know which impact sources represent activities that happen in apartments, or at least, ultimately produce a result which ranks floors according to the occupiers' opinions.

The second factor is the reaction of the floor to impact forces imposed on it. The reaction we are primarily concerned with is how the ceiling of the floor vibrates in response to the impact forces. The issue here is to produce floor designs which minimise the ceiling vibrations which produce offending sounds for the impacts that typically occur in apartments.

The third factor is the influence of the room on the sound generated by the ceiling vibrations. It is important to realise that the so-called receiving room itself is a highly influential factor in sounds that are produced by the ceiling vibrations. This is particularly so for low-frequency sounds.

The fourth factor is the psychoacoustic response of the occupants in the receiving room below the floor. This factor is how the occupiers react to the sounds that are produced in the receiving room. This subjective aspect of the problem is important to determine how well floors and sounds generated by impacts on them perform against each other and against some reference (i.e. how they can be ranked). This is possibly the most important factor of the problem, but is also possibly the most nebulous.

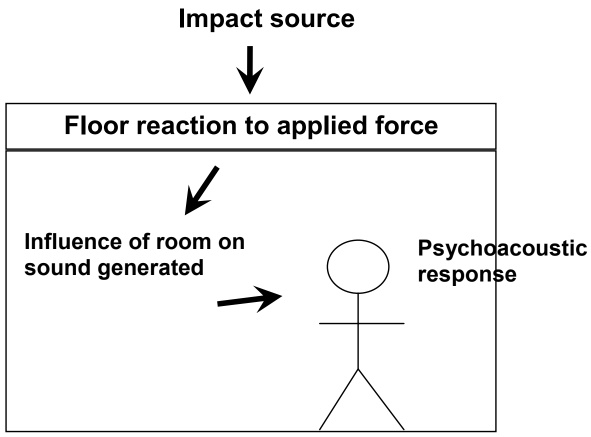


Figure 1. Diagram illustrating the breakdown of the problem into factors influencing the outcome.

OVERVIEW OF EXISTING KNOWLEDGE.

The problem of low-frequency impact sound insulation in light-weight timber floors has been an issue for a long time. In recent years, research and anecdotal evidence have identified the problem as being of major concern for customers. In particular, the increased acceptance and use of light timber-framed construction in various parts of the world has highlighted the issues in certain countries (for example, in the US Blazier and DuPree (1994) highlighted increased customer perception of low-frequency impact sounds). As a result, a number of research projects have looked into this issue. Probably the most significant research project into this area was done in Scandinavia, by Finland, Sweden, Norway and Denmark. As part of the so-called Nordic R&D project "Multistorey timber frame buildings", the project consisted of each contributing country selecting a number of suitable floors (after some experimental development), and then installing these floors into real building developments with occupants. This project spanned 5 years and finished in 1999. A number of summary papers have been completed by the main researchers into this project, a good one being that produced by Hveem (1998), the principal researcher of this project.

Existing Low-frequency Performance understanding.

The results of the Nordic R&D project resulted in a number of conclusions and desires for further work. It is worth summarising their conclusions here, because they seem to be a set of effective conclusions about the problem – echoing conclusions of other research projects.

Hveem (1998) produced these conclusions:-

- There is a trend against stiffer joist construction in the form of deeper joists, i.e. the fundamental frequency shouldn't be too high. This echoed by Blazier and DuPree (1994).
- Lightweight floating floor systems (e.g. a couple of layers of particleboard on 20mm mineral wood board) don't improve impact insulation below 160Hz. Even heavyweight floating floor systems (e.g. 50mm dense concrete on 20mm mineral wool board) won't improve low-frequency performance below 50Hz, at best.
- The elastic suspended ceiling systems they used perform well, but have a resonance frequency of about 30Hz, and hence have limitations.
- Completely filling (or, even overfilling) the cavity with mineral wool has a positive effect on performance, especially for the cavity depths found in floors.

- For the low-frequency range it is important to separate the most dominating natural frequencies in the floor system from the modes in the room, given by typical dimensions.
- The peak energy of a footfall occurs in the frequencies below 50Hz.

Sipari (2000), the leader of the Finnish contribution to the acoustic aspect of the Nordic R&D project, concluded that the way forward is to increase mass and stiffness of the floor and floor parts. They found in their testing that a composite floor consisting of concrete slab bound to joists, so that they structurally work together, is an effective solution. They also concluded that a floor with a mass greater than 200 kg/m^2 acts satisfactorily in most cases. This possibly presents an issue since, at such masses, floors can't be regarded as lightweight elements; bearing in mind that a dense concrete slab floor 150mm thick would be about 350kg/m^2. This would be especially of concern for seismic considerations, where we may find that different bracing schemes are required. However, Sipari (2000) also suggested that lightweight floors full of mineral wool in the airspace could be developed to satisfy occupants, based on their results; it is not said how, 'though. Sipari also produced a figure (reproduced in Figure 2) showing where timber floors perform poorly against concrete floors and in what frequency range certain resilient components in a floor improve performance.

In the previous summaries no comment has been made of vibration damping. Work by Walk and Keller (2001) emphasised the importance of considering vibration damping in floor performance, since they believed that a lightweight floor will not have enough mass to perform well without extra damping.

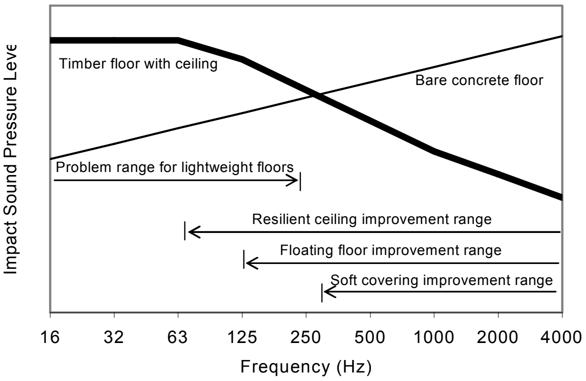


Figure 2. Impact sound insulation of a timber floor compared to a concrete floor and areas where certain resilient aspects of the floor design will change its performance (after P. Sipari). The soft covering and floating floor improvement range can start at lower frequencies than shown; it depends on the type of system (e.g. heavy floating floor systems or carpet on underlay can show significant improvements starting at approximately 100Hz).

Existing High-Frequency Performance understanding.

Although this project is focused on improving the low-frequency performance of timber-framed floors, the high-frequency performance (above 200Hz) is a critical aspect of a floors performance too. It is often the case that if there are high-frequency problems, they overshadow low-frequency issues. Having said this, it is easier to deal with high-frequency than with low-frequency problems in lightweight floor systems. One of the reasons for this is that it is easier and more meaningful to measure and rate the high-frequency impact insulation performance of a floor using standard methods, and so it has been easier to develop solutions.

In the case of lightweight timber floors, the issue of high-frequency impact (and airborne) insulation comes down to one of resilience and disconnection between masses:-

- To reduce high-frequency vibration being transmitted into the floor, the upper surface should be soft, or if hard, floating on a resilient layer.
- For vibration that has entered the floor, to prevent it from being transmitted to the ceiling and then radiated into the space below the floor, there should be good decoupling of vibration to the ceiling by use of resilient ceiling connections or separate ceiling joists mounted on resilient supports. There should also be good airborne sound decoupling between the floor and the ceiling in the form of a cavity with fibrous infill.

Guidance for reducing high-frequency impact sound transmission through lightweight floors is available in a number of text books on building acoustics. Recent work by Warnock and Birta (1998), where 190 floor systems were tested for sound insulation performance, did result in a number of observations for guidance on the matter of impact insulation of lightweight floor systems, as well as a empirical, regression-based formulation to predict the Impact Insulation Class of a floor system.

As far as this project was concerned, we were only concerned with keeping a weather eye on the high-frequency performance; in the sense of noting whether particular designs are better or worse for high-frequency impact sound insulation performance, as well as doing standard tapping machine tests on all floor systems.

THE STRUCTURE OF THE RESEARCH PROJECT.

The research project was structured in order to respond to the factors influencing the problem of the low-frequency impact insulation of timber floors. With relatively minor attention being paid to the issue of the higher frequency impact insulation of timber floors. The project was divided into these three areas:-

- Low-frequency theoretical modelling of timber floors and receiving rooms.
- Experimental measurements of the impact insulation of floors for both low and high frequencies.
- Subjective assessment of the floors.

Obviously these areas are not independent of each other, and the results of one area influences the progress and decisions made in other areas.

Theoretical modelling.

Theoretical modelling is important to enable deeper understanding of what is happening and to enable predictions without having to build numerous floors to test to produce empirical results. It also enables the testing of ideal or extreme situations to illustrate concepts. In this project a low-frequency theoretical model of a joist floor was developed, as well as a low-frequency model of a receiving room.

Once developed, tested against measurement, and refined, the theoretical modelling was used to perform a trend analysis on parameters of the floors.

Experimental measurements.

A series of experimental floors were built in a laboratory and tested for both low and high frequency performance. The procedure used to test the low-frequency performance consisting of directly measuring the vibration of the floor using a shaker to excite the floor and a scanning laser vibrometer to measure the vibrations that resulted in the floor. Standard tapping machine measurements were also made on the experimental floors.

Subjective analysis.

As mentioned before, a critical aspect of the impact insulation performance is how occupiers might react to the sounds of impacts on various floor designs. For this subjective aspect of the project, recordings of various types of impacts were made on the experimental floors, and played back to test subjects in a listening room. The feedback from these test subjects was then used to compare a selection of the experimental floors and to give information which would allow the generation of a suitable low-frequency assessment rating system for a floor.

CONCLUSIONS OF THE ANALYSES.

Theoretical Analysis Conclusions.

In this section we offer some conclusions from the analysis of the theoretical model which was developed. These are divided into particular regions of the floor. The descriptions of the trends of the theoretical analysis relate to changes from a ‘basic’ inter-tenancy floor, illustrated in Figure 3.

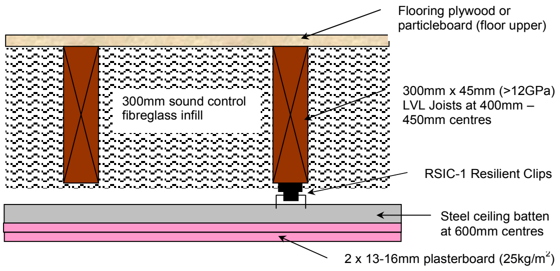


Figure 3. Illustration of the 'basic' inter-tenancy floor.

Joists.

- It would appear that massively increasing the stiffness of the joists substantially improves performance. However, at least a four-fold increase in bending stiffness of the joists from the ‘basic’ floor is required for a significant gain.
- Increasing the damping of the joists does improve results by reducing the resonance peaks, especially the fundamental.
- The addition of transverse stiffeners made from blocking and tie rods can show some improvement by increasing the spacing between resonances. The improvement is not very great however, especially for wider floors where much greater transverse stiffness is required to achieve significant results. Such a feature may be best used for very narrow floors.

Floor upper (section of floor on the joists).

- It is no surprise that increasing the surface density of the floor upper does improve the performance, but after about 100kg/m2 it would appear that minimal gains are to be had, unless unreasonable surface densities are used.
- Increasing the bending stiffness of the upper only offers slight gains.
- Increasing the damping of the upper offers some significant gains in the performance in terms of reducing the resonance peaks. However, the performance as indicated by the loudness of the low-frequency impacts is limited by the first horizontal resonance in the room. In some cases, a resonance in the floor might coincide with that in the room, and in such cases damping would be obviously beneficial.

Floor cavity.

- The major conclusion from the floor cavity results is that for cavity depths greater than about 200mm the resilient rubber ceiling clips are the dominant sound transmission path. It is clear that very significant gains could be had by reducing the stiffness of the ceiling clips, or by using independent ceiling joists. However, independent ceiling joists can be prone to flanking transmission issues in a similar way to staggered stud walls.
- It is interesting to observe the effect increasing the damping of the ceiling clips has on performance. This appears to be due to the fact that, since the ceiling clips are a dominant transmission path, increasing the ceiling clip damping reduces the mass-spring-mass resonance of the floor system at around 30-40Hz. We also see an improvement in other low-frequency resonances.

Ceiling.

- Increasing the surface density of the ceiling improves the performance significantly. It would seem that, for a given amount of mass in the floor system, having about half the mass on the floor upper and half in the ceiling produces best results. This result relates well to the fact that airborne sound reduction in double-leafed constructions performs best for a given amount of mass when an equal amount of mass is to be found on each leaf.
- Greatly increasing the stiffness of the ceiling can have a detrimental effect whereas increasing the damping has a positive effect. Both of these results are probably related to the fact that the dominant sound path to the ceiling is through the ceiling clips.

Floor and room dimensions.

- Increasing the span of the floor tends to improve performance up to a point. In part, this effect appears to be due to the movement of the fundamental resonance along the longest length of the room to a different frequency which might start to coincide with resonances in the floor.
- Changing the width of the floor does affect the results, but produces no trend as such, apart from increasing the size of the receiving room and hence the overall sound absorption.
- Changing the height of the receiving room only changes the results above the first vertical mode of the room (at around 60-80Hz, depending on the height). As a result, there is little influence on the loudness ratings, particularly for footstep sounds, since the energy is mostly concentrated below 80Hz.

Experimental Analysis Conclusions.

In this section the conclusions from the experimental impact insulation results are presented.

Low-frequency conclusions.

The conclusions drawn from the low-frequency testing on the floors tend to be the same as those found in the theoretical model analysis, although what was experimentally tested was a subset of the analysis that could be done theoretically.

In summary, the conclusions are:-

- The addition of transverse stiffeners did show the ability to reduce the density of resonance frequencies in the low frequency region.
- The addition of mass and stiffness in the floor upper improves low-frequency performance.
- The addition of damping in the floor upper improves low-frequency performance.
- The use of a sand/sawdust mix as an infill in a battened cavity in the floor upper provides good results, by way of adding mass, adding a lot more damping, and adding some floor upper stiffness.
- Extra ceiling layers improve low-frequency performance.
- Independent ceiling joists can improve the low-frequency performance if care is taken to isolate them and the ceiling from vibration from the edge of the floor. This shows that the ceiling clips (even the rubber RSIC clips used) are the dominant sound transmission path. When care was not taken to isolate the ceiling joists and the ceiling, they performed as well as the RSIC clips. An obvious application for independent ceiling joists would be when using timber floors hung on masonry walls.

High-frequency conclusions.

Although the focus of the project was not exactly on high frequency impact insulation, we did make standard tapping machine measurements on the floors and did find some interesting results:-

- The addition of transverse stiffeners in a floor significantly improved the high-frequency impact insulation (by 5dB in the floors tested) for the case when the floor upper was thin with little stiffness (e.g. one layer of plywood).
- Extra ceiling layers did not improve the high-frequency impact insulation.
- The span of the floor did not affect the high-frequency results.

Subjective Analysis Conclusions.

A number of timber floor designs (nine in total) were subjectively tested using impacts that consisted of a standard Japanese impact ball, walking, and the tapping machine. These timber floors were compared against a reference 150mm concrete floor with an added suspended ceiling so that it met the Australian building code ($L_{n,w} + C_I \leq 62$). One conclusion from the subjective analysis was that a floor design consisting of 85mm of sand in the floor upper, as shown in Figure 4, performed as well as the reference concrete floor for the low-frequency impacts (viz. the ball drop and the walking. Another conclusion was that the subjective results correlated well with loudness measures of the impact sounds, enabling such rating methods to be used for further analysis.

Buildability Conclusions.

Buildability issues were discussed with Australian housing developers. As a result of this discussion and through the existing knowledge of members and companies of the project team, some buildability issues did come out as being important and are listed:–

- The overall depth of the floor is an issue, however, the view was expressed that it is not a critical factor: designs can be adjusted to accommodate deeper floors, if necessary. In fact, it is good to have deeper joists (300mm) to accommodate air conditioning services, and to achieve greater spans.
- The total weight of a floor is an issue, for seismic concerns in New Zealand, but a weight of about 150kg/m2 is acceptable if standard LTF bracing systems and methods are to be used.
- The use of wet trades is an important factor. The delay and project management issues they bring to the job are very important. One major advantage of timber construction is that they lack wet trades in the construction. This would seem to rule out the use of concrete screeds.
- Cutting and laying of multiple layers of sheeting material is time consuming. To overcome this, the inter-tenancy floor for a whole tenancy could be completed and then infill walls added later.

Other Considerations.

There are some other, miscellaneous considerations which are worth noting:-

- Another issue is concern about the embodied energy of a building. Timber is seen as a material with a low embodied energy (as well as being a carbon store), and other materials used should have similar qualities, including being available locally (to reduce transportation energy requirements).
- It is important that the floor not have noticeable felt vibrations. It is often stated that this requirement is met by ensuring the fundamental frequency of the floor is above 8Hz.
- It has been observed by a number of people that a floor which feels solid is good (e.g. Pitts (2000)). People have a tendency to like concrete screeds on timber subfloors for this reason. Since subjective opinions are complicated, this could a contributing factor for reports that thick concrete screeds are effective.

SUCCESSFUL FLOOR DESIGNS.

The preceding analysis has led us to develop floor designs which are deemed to be successful in the eyes of the requirements of the brief. We therefore define a successful floor to be one which, according to subjective testing we have done, has similar performance to a 150mm concrete floor. We also require that the floor be buildable with skills that exist in the market, and that there be few proprietary products in the floor system. We also would like the floor to be a dry construction to retain one major advantage of LTF construction.

Floor design A.

The initial testing phase of the project and the theoretical modelling showed that a floor consisting of an upper with a deep layer of sand/sawdust mix could provide a solution. Subsequent subjective analysis showed it to be about as effective as a 150mm thick concrete floor. This tested solution design is shown in Figure 4. In the testing programme this floor was designated ‘Floor 9’. The standard tapping machine (ISO 140,717) results of this floor are $L_{n,w}$=48 dB, C_I=-2 dB, $C_{I,50\text{-}2500}$=9 dB.

The cost of this floor has been estimated by a qualified quantity surveyor to be \$A 63 more per m^2 than the ‘Basic floor’ of Figure 3 for construction in Sydney or Melbourne. The depth of the floor is 504mm, and weighs 156 kg/m^2 (113 kg/m^2 for the floor upper, 25 kg/m^2 for the ceiling). The joist span of this design tested was 5.5m which gave a fundamental resonance of 14.5Hz.

Possible alterations to the shown floor design.

To avoid felt vibration problems it is recommended that the fundamental frequency be above 8Hz. For vibration control, a span of 6.5m could therefore be attained with the joists used, subject to other structural considerations. The more rigorous analysis in this project may allow designers extra span depending on what limits have been applied in previous evaluations for span tables.

A joist spacing of 400mm is shown; this could be changed to 450mm, without undue effects, since such a small overall change in stiffness has an insignificant effect on results.

The floor is quite deep overall; however theoretical results do show that with the RSIC clips used, the cavity depth could be significantly less without much change to the results. The problem would be making the joists stiff enough to carry the weight. A possibility here is to re-orient the battens so that they are parallel to and on top of the less deep joists, and screw the battens into the joists resulting in a composite action.

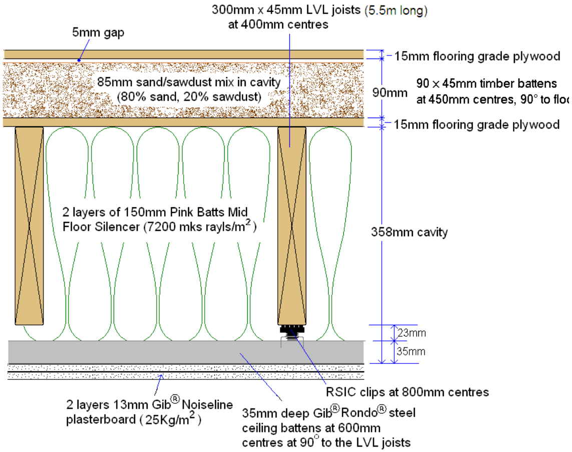
The cavity is shown full of fibreglass infill of high flow-resistivity. Theoretical modelling has shown that with the use of RSIC clips, using less infill with less flow-resistivity makes little difference to the low-frequency performance.

The ceiling is shown as being two layers of 13mm plasterboard. The critical aspect of the ceiling for low-frequency impact performance is that it has a surface density of 25 kg/m^2; 2 layers of 16mm plasterboard with the same or greater overall surface density would be acceptable (if this were needed for fire performance).

The ceiling battens don't appear to be a critical element with the RSIC clips used; they could be replaced by different battens.

Floor 9. Upper: 1 x Plywood, battens/sand-sawdust, 1 x Plywood

SECTION FIGURE 1. **Typical section across joists**



Notes: 1) Floor size 5.5 x 3.2m. Perimeter of flooring to test rig junction filled airtight with acoustical sealant.
2) One end of floor joists simply supported on 100x50mm timber grounds with solid blocking between ends of joists, other end on joist hangers off cross beam
3) For construction detail at perimeter of ceiling refer to note 3 on Floor 2, Section Figure 1

Figure 4. Design of floor tested in subjective testing and shown to have similar low-frequency performance to a 150mm concrete floor. (Known as Floor 9 in the experimental testing programme).

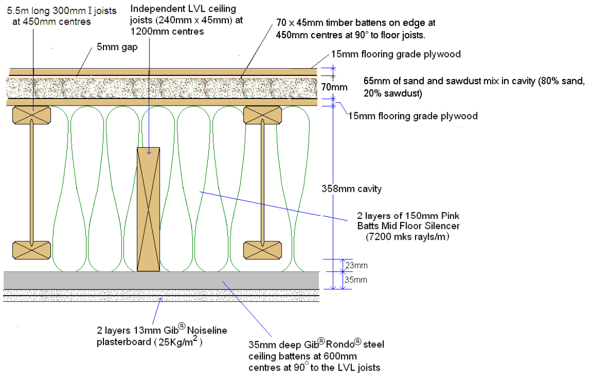
Floor design B.

The previous floor design (A) seemed to be an effective solution for producing a floor which is comparable to a concrete floor in performance, particularly for low-frequency performance. It does, however, use RSIC resilient clips to suspend the ceiling from the joists; whereas results from theoretical analyses did show that these clips are a major sound transmission path, even though the RSIC clips are very resilient when compared to other resilient clips or rails. There is opportunity to test a floor which uses independent ceiling joists to improve performance. However, as has been shown from experimental testing, such a system can be sensitive to how the ceiling joists are mounted, and how the ceiling edges are fixed. Nevertheless, assuming there is reasonable isolation from such flanking problems, if we use a ceiling supported by independent ceiling joists, we can expect better low-frequency performance from the ceiling system.

If we use such a ceiling with independent ceiling joists, we can then reduce the amount of material used in the floor upper. We use the same principal of adding mass and damping to the floor upper by creating a cavity filled with sand and sawdust. However, with the added performance of the ceiling system we are able to reduce the size of the battens to 70mm and hence the nominal thickness of the sand/sawdust layer to be 65mm.This floor design (which is also known as Floor 25 in the test series) is shown in Figure 5. The independent ceiling joists used are made of LVL to prevent distortion of the ceiling from warping of timber; it would be possible to use I-beams instead. Steel ceiling battens are fixed to the underside of the independent ceiling joists to offer a cheap, easy and stable system to fix the ceiling to. In order to prevent flanking problems, the ceiling joist ends are supported on rubber vibration isolation pads, and the ends of the battens do not connect to the wall (a separation of 10mm is used).

Floor 25. Upper: 1 x Plywood, battens / sand & sawdust, 1 x Plywood. Mid: ceiling joists: Lower: ceiling isolated.

SECTION FIGURE 1. **Typical section across joists**



Notes: 1) Floor size 5.5 x 3.2m. Perimeter of flooring to test rig junction filled airtight with acoustical sealant.
2) One end of floor joists simply supported on 100x50mm timber grounds with solid blocking between ends of joists, other end on joist hangers off cross beam
3) Ends of ceiling joists supported on 100 x 50 x 10.5mm thick Shearflex rubber pads.
4) At perimeter of ceiling, steel ceiling battens and ceiling linings were cut to provide a 5 to 10mm gap adjacent the timber ground on the blockwork with acoustical sealant in gap.

Figure 5. Design 'B' of floor tested and shown to have similar low-frequency performance to floor design A. (Known as Floor 25 in the experimental testing programme).

The spatially-averaged, low-frequency ceiling vibration measurements of the floor for the shaker excitation point at one position are shown in Figure 6 with a comparison made against the results of floor design 'A' (a.k.a. Floor 9). We see from these results that the performance up to 100Hz is about the same as floor design 'A', with a bit more variation above 100Hz. The standard tapping machine (ISO 140,717) results of this floor are $L_{n,w}$=48 dB, C_I=-2 dB, $C_{I,50\text{-}2500}$=10 dB. From these two results we can conclude that floor design 'B' has similar performance to floor design 'A', and therefore also has similar performance to a 150mm concrete floor.

The cost of this floor has been estimated by a qualified quantity surveyor to be $A61 more per m^2 than the 'Basic floor' of Figure 3 for construction in Sydney or Melbourne. The depth of the floor is 484mm, and weighs 131 kg/m^2 (90 kg/m^2 for the floor upper, 25 kg/m^2 for the ceiling). The joist span of this tested design was 5.5m which gave a fundamental resonance of 13Hz.

Additional tapping machine tests were done on ceramic tiles adhered to a substrate of 10mm Gib gypsum fibreboard

“Sound Barrier’, which was screwed to the floor. The results of this were $L_{n,w}$=53 dB, C_I=-4 dB, $C_{I,50\text{-}2500}$=3 dB.

Possible alterations to the shown floor design.

To avoid felt vibration problems it is recommended that the fundamental frequency be above 8Hz. For vibration control, a span of 6.0m could therefore be attained with the joists used, subject to other structural considerations. The more rigorous analysis in this project may allow designers extra span depending on what limits have been applied in previous evaluations for span tables.

The ceiling is shown as being two layers of 13mm plasterboard. The critical aspect of the ceiling for low-frequency impact performance is that it has a surface density of 25 kg/m^2; 2 layers of 16mm plasterboard with the same or greater overall surface density would be acceptable (if this were needed for fire performance).

The ceiling battens don’t appear to be a critical element; they could be replaced by different battens.

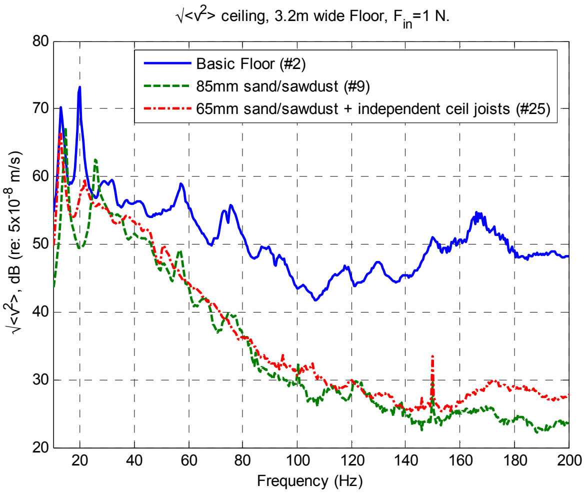


Figure 6. Ceiling surface average measured velocity results for floor design ‘A’ (Floor 9) as compared to floor design ‘B’ (Floor 25). The results for the ‘basic floor’ (Floor 2) are also shown for comparison.

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