METHOD OF WOODEN FLOOR CONSTRUCTION FOR MINIMIZING LEVELS OF VIBRATION

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Abstract

Occupants in residential houses are occasionally disturbed by the vibrations in wooden floors resulting from human activities. The recently revised allowable joist spans in the National Building Code of Canada incorporate empirical allowance for vibrational serviceability and are expected to reduce the number of unsatisfactory wooden floors. Further reduction can be achieved by adopting construction details which minimize vibration levels in addition to using appropriate spans. This project was undertaken to investigate how changes in certain construction details can affect vibrational performance of wooden floors.

Vibration tests were carried out on full size wooden floors in the laboratory. These tests were designed to identify the characteristics which influence human sensitivity to floor vibrations. For each floor size a reference floor constructed by normal practices was tested. Different construction details were introduced sequentially and the modified floors retested. Comparison of results from modified floors with those for the reference yielded both positive or, in some cases, negative impacts of changes in construction details. A total of twelve modified systems covering two floor sizes were tested. The results demonstrated that adding between-joists bridging and supports of edge joists improve overall vibrational performance of a floor. A method of evaluating the effectiveness of different forms of between-joists bridging was developed. The method was used to evaluate several forms of bridging. One form of bridging consisting of solid blockings glued to the underside of flooring and a mild steel strap nailed to the underside of blockings and joists was found to be more effective than either wood or steel cross bridging with the same bottom strap. It was found that using damping materials or a stiff flooring with a low density can have a detrimental effect on performance. Also no real advantage was achieved using elastomeric glue, in lieu of nailing in flooring-to-joist connections.

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EXECUTIVE SUMMARY

Wooden floor systems in residential houses have occasionally been found to produce excessive vibration under in-service dynamic loadings, such as those due to human footsteps. This project was initiated to investigate the types of detailing which can lead to better vibrational performance through testing a series of floors. The tests were conducted in two stages. The first stage identified the better details. Limited tests were conducted in the second stage using a different floor size to ensure that the conclusions reached in stage 1 can be extrapolated to at least another floor size.

In stage 1 a reference floor was constructed and tested in the laboratory. The floor span and width were 4.06m and 4.2m respectively. The joists were 38mm x 235mm No.1 grade spruce-pine-fir lumber and spaced at 600mm centres. The flooring was 18.5mm thick tongued and grooved grade 0-1 Oriented Strandboard (OSB). The flooring was attached to the joists using 50mm common nails. Different construction details were sequentially incorporated into the floor and the modified systems retested. Nine modified systems were tested. In stage 2, a reference floor of size 3.18m (span) by 3.6m (width) was tested. The joists were 38mm x 184mm No. 1 spruce-pine-fir spaced at 600mm centres. The same flooring material as in stage 1 was used. Three modified systems were tested in stage 2. All systems were tested by the impact vibration approach to determine their vibration characteristics such as natural frequencies and damping ratios. In addition static weights equivalent to 0.478 kN/m^2 (10 lb/ft^2) were distributed on the floor surface and vibration levels generated by dropping a 15 kg sandbag from a 50mm height onto the floors were measured. The sandbag impact device was fabricated to produce a consistent impact on all floor systems.

Comparison of performances between the reference floor and the modified systems was mainly based on the measured natural frequencies and frequency-weighted root-mean-square acceleration (a parameter which has been found to correlate with human response).

The construction details studied included: between-joists cross bridging, edge joist support, artificial damping material, plywood flooring and glued flooring-to-joist connection. In addition, an effective form of bridging was devised. This form of bridging consisted of solid blockings glued to underside of flooring and a continuous light gauge steel strap nailed to the undersides of blocking pieces and joists. This form of bridging was adopted after screening a few forms of between-joists bridging details using a technique developed in this study.

It was found that the use of the new form of bridging greatly improved floor performance. Supporting edge joists was also found to be beneficial. The uses of damping materials and stiffer flooring (plywood) were observed to lead to a deterioration in performance. No real advantage was obtained with a glued flooring-to-joist connection in lieu of a nailed one.

RÉSUMÉ

Méthodes de construction des planchers de bois
permettant de minimiser les vibrations

Soumis à la surcharge dynamique du pas des humains, les planchers de bois des maisons sont parfois reconnus pour produire de fortes vibrations. La présente étude a été lancée dans le but de déterminer, en mettant à l'épreuve une série de planchers, quels modes d'exécution réduisent le plus les vibrations. Les essais ont été menés en deux étapes. Dans un premier temps, il s'agissait de cerner les techniques de construction les plus efficaces. Dans un deuxième temps, des essais limités ont été conduits sur des planchers de dimensions différentes afin de vérifier si les résultats obtenus à la première étape pouvaient être reproduits.

Pour la première étape, un plancher de référence a été construit dans un laboratoire puis mis à l'essai. La portée et la largeur de ce plancher étaient de 4,06 m et de 4,2 m respectivement. Les solives, en bois appartenant au groupe d'essences pin-sapin-épinette de qualité n° 1, disposées à entraxe de 600 mm, mesuraient chacune 38 mm sur 235 mm. Le support de revêtement de sol, d'une épaisseur de 18,5 mm, était constitué de panneaux de copeaux orientés, bouvetés, de qualité 0-1, fixés aux solives par des clous ordinaires de 50 mm. Différents détails de construction ont tour à tour été mis à contribution, le plancher ainsi modifié étant chaque fois éprouvé. Neuf planchers modifiés ont été mis à l'essai de cette façon. À la seconde étape, un plancher de référence de 3,18 m (portée) sur 3,6 m (largeur), constitué du même matériau de support ayant servi pour le plancher de la première étape, a été éprouvé. Les solives en pin-sapin-épinette de qualité n° 1, disposées à entraxe de 600 mm, mesuraient 38 mm sur 184 mm chacune. Trois planchers modifiés ont été examinés à la seconde étape. Tous ont été mis à l'essai selon la méthode de la vibration à l'impact en vue d'en déterminer les caractéristiques vibratoires telles que la fréquence de résonance et le rapport d'amortissement. De plus, des masses statiques équivalant à 0,478 kN/m^2 (10 lb/pi^2) ont été réparties sur la surface des planchers et les vibrations produites par un sac de sable de 15 kg tombant d'une hauteur de 50 mm ont été mesurées. Ce générateur d'impact à sac de sable a été conçu de telle sorte que l'impact créé soit uniforme sur tous les planchers.

La comparaison du comportement du plancher de référence avec ceux des planchers modifiés s'est basée principalement sur la mesure des fréquences de résonance et de l'accélération efficace pondérée en fréquence (paramètre qui s'est avéré compatible avec les réactions humaines).

L'étude a porté sur les détails de construction suivants : croix de Saint-André ou entretoises croisées entre les solives, support des solives de rive, matériau antivibratoire artificiel, support en contreplaqué et assemblage par collage du plancher et des solives. Par ailleurs, une forme efficace d'entretoisement a été mise au point. En effet, des cales solides ont été collées à la face inférieure du support de revêtement de sol et une série de liernes en acier de faible épaisseur ont été clouées à la sous-face des cales et des solives. Cette forme d'entretoisement a été adoptée après avoir éliminé d'autres types d'entretoises au moyen d'une technique élaborée dans le cadre de cette étude.

On a constaté que cette nouvelle forme d'entretoisement améliore considérablement le comportement des planchers. Le fait de supporter les solives de rive s'est également révélé avantageux. Par contre, l'utilisation de matériaux antivibratoires et de supports de revêtement de sol plus rigides (contreplaqué) s'est traduite par une détérioration du comportement. Aucun avantage réel n'a été obtenu en assemblant par collage le plancher et les solives au lieu de les clouer.

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1.0 INTRODUCTION

Light-weight structures are prone to producing high levels of vibration when excited dynamically, which may be disturbing to the occupants. Wooden floors built with lumber joists are an example of this type of structure.

The escalating costs of materials have led to more material-conscious and therefore lighter floor constructions in recent years. Consequently the likelihood of floors having unsatisfactory vibrational performance has been on the increase. Design of wooden floors has traditionally been based on their responses to static design loads. Recent experience with regards to vibrational performance has called for the additional need for designing against excessive floor vibration under normal service conditions. (Polensek 1970; Onysko 1975; Ohlsson 1982; Whale 1983; Chui et al 1985)

This need was recognised by the Associated Committee on the National Building Code of Canada. The span tables in the 1990 edition of the NBCC (NRC 1990) incorporate new design criteria derived by Forintek Canada Corporation (Onysko and Bellosillo 1978) for ensuring acceptable vibrational serviceability of wooden floors in residential houses. The Forintek design criteria are based on a deflection limit under a concentrated load of 100 kg applied at the centre of a span. The limit is given as a function of the span.

It is claimed that a floor having a span within the allowable value and with the prescribed construction details given in Part 9 of NBCC (NRC 1990) will have acceptable static and vibrational performances. Although most floors "designed" to Part 9 of NBCC will have satisfactory vibrational performance, there are other design and detailing methods which may lead to floors with even better vibrational performance (Smith and Chui, 1988).

The University of New Brunswick Wood Science and Technology Centre (WSTC) undertook a study, with financial support from Canada Housing and Mortgage Corporation, on vibrational performance of conventional wood-joisted floor systems. The objective of this study is to investigate how vibration response characteristics change with different details through testing a series of laboratory-built floors.

At the start of this project meetings were held with scientists from Forintek Canada Corporation and the National Research Council to discuss recent work which had been performed in those organizations. Appendix I contains a report on the visit to those organizations. The remaining part of this report discusses the test work performed by WSTC.

2.0 GENERAL DETAILS OF TEST FLOORS

The test programme was conducted in two stages with two floor sizes.

Stage 1 was the main part of the programme. It consisted of a reference floor with the following characteristics:

- Span : 4.06m
- Width : 4.2m
- Joists : 38mm x 235 mm No. 1 (NLGA 1987) Spruce-pine-fir spaced at 600mm centres
- Flooring : 18.5mm tongued and grooved (t & g) Grade O-1 (CSA 1985) Oriented Strandboard (OSB)
- Fastening : 50mm common nails spaced at 150mm at board edges and 300mm at intermediate supports.

The reference floor had only the edges containing joist ends supported and no between-joists bridging. It was tested to determine its vibrational characteristics. Construction details of the reference floor were then altered sequentially and the "modified" systems retested. In total, nine modified systems were built and tested. The same set of joists were used throughout this stage. Each modified system had the same plan dimensions as the reference floor. As each modified floor only differed from the reference floor by one construction variable, the effects of variables could be studied systematically. Table 1 lists the scope of the modifications introduced to the reference floor system. Details of each modification are given in Section 4.

Table 1 - Variables changed in modified systems, stage 1.

System	Modified variable
1	One line of between-joists cross bridging
2	Three lines of between-joists cross bridging
3	Five lines of between-joists cross bridging
4	One line of innovative form of bridging
5	All four edges of the floor supported
6	Damping material between flooring and joists
7	Damping material between joists and support
8	Plywood flooring with higher stiffness properties
9	Elastomeric glued flooring-to-joist connection

The benefit, or in some cases the negative effect, of incorporating each of the construction variables outlined in Table 1 was assessed.

A more limited but similar study using a different floor size was then conducted in stage 2 to ensure that findings can be extrapolated within reasonable limits. In stage 2 a reference floor was built and tested, with the following characteristics:

- Span : 3.18m
- Width : 3.6m
- Joists : 38mm x 184mm No. 1 (NLGA 1987) Spruce-pine-fir spaced at 600mm centres
- Flooring : 18.5mm t & g Grade O-1 (CSA 1985) OSB
- Fastening : 50mm common nails spaced at 150mm at board edges and 300mm at intermediate supports.

The span was based on the 1985 edition of the NBCC (NRC 1985), as was the span in stage 1. Three modified forms of the second reference system were tested as detailed in Table 2.

Table 2 - Variables changed in modified systems, stage 2.

System	Modified variable
10	All four edges of the floor supported
11	One line of innovative form of bridging
12	All edges supported and innovative bridging

The construction details of all test floors followed the details outlined in "Canadian Wood-Frame House Construction" (CMHC 1984). The joist ends were supported with 38mm x 89mm top and bottom timber bearing plates. The bearing plates were clamped to a steel I-beam using threaded rods and nuts as illustrated in Figure 1. The steel beams were anchored to a reinforced concrete floor slab cast over a solid sub-base. Thus results are free from the influence of any motion at supports.

The floor components (joists and flooring) were tested for their moduli of elasticity and densities. The moduli of elasticity were determined using a beam vibration approach described in Appendix II. Also given in Appendix II are the modulus of elasticity and density of each joist in the two stages. Table 6 in Section 4.5 presents the corresponding properties for the flooring materials.

3.0 TEST METHODS

Throughout this investigation, the impact excitation approach (see for example Ohlsson 1982; Chui 1986a) was used to characterise the vibration responses of the test floors. Typically an impact was applied at one position and the responses measured at various other locations on the floor surface. For ease of referencing the response and impact positions, coordinate systems outlined in Figures 2 and 3 were adopted for floors in stages 1 and 2 respectively.

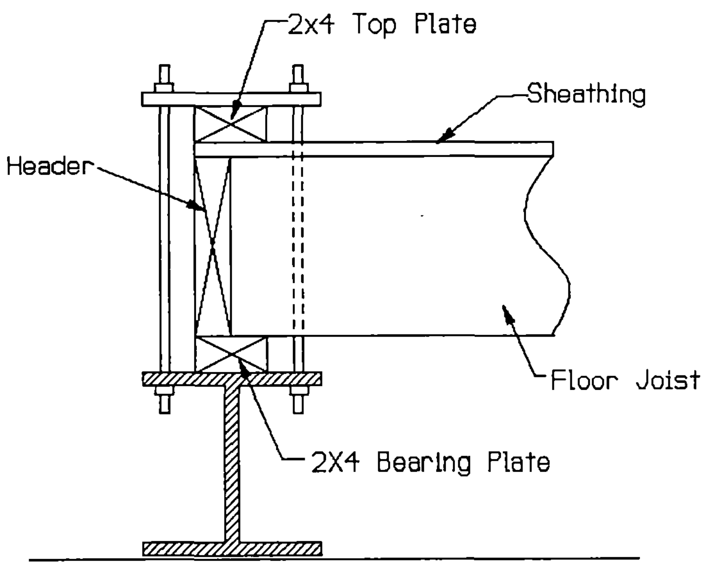

Figure 1 - End support details of joists

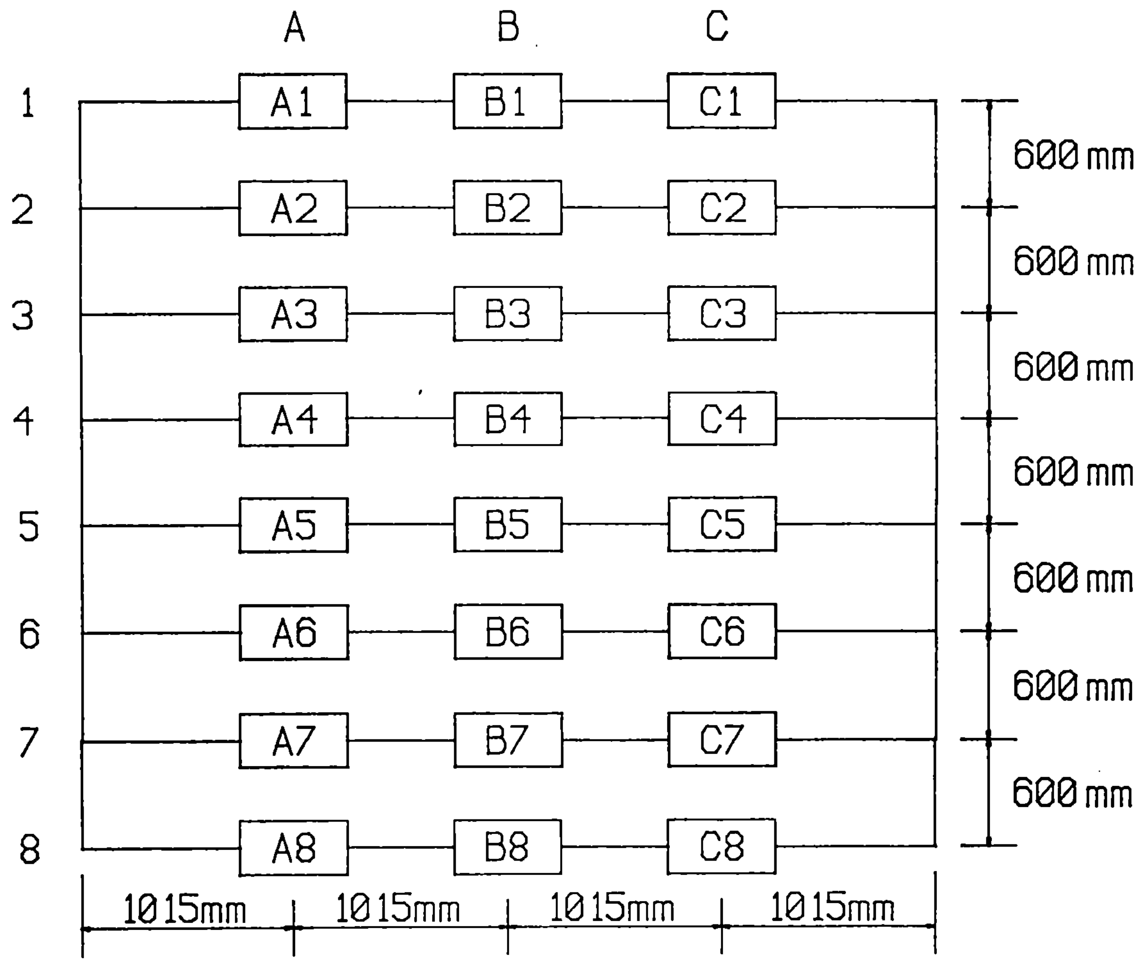

Figure 2 - Coordinate System For Floor In Stage 1

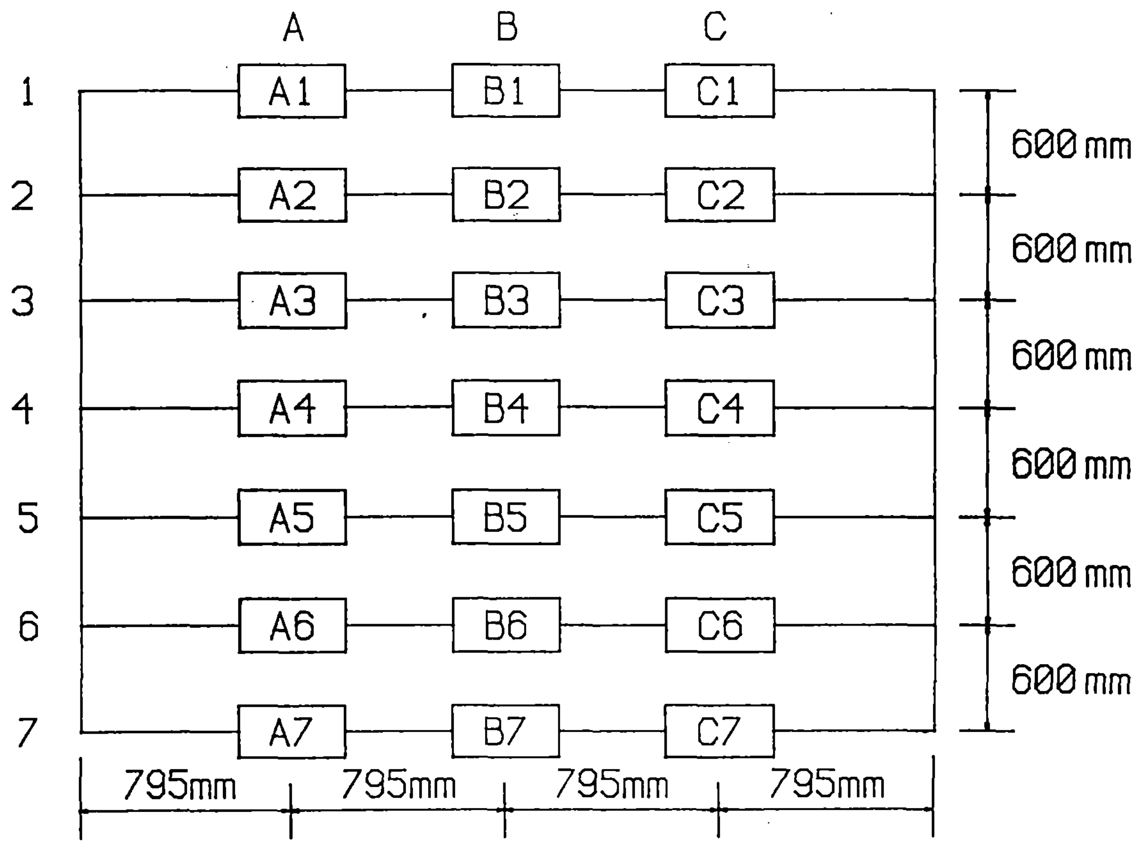

Figure 3 - Coordinate System For Floors In Stage 2

Two types of impact were applied on floor surfaces. The first type was by an instrumented hammer and the second by dropping a sandbag through a "standardized" distance.

3.1 Hammer impact tests

The hammer impact tests were performed on bare floors (no imposed loads) using an instrumented hammer. The instrumented hammer had a force transducer attached to its tip which enabled the impact force to be recorded. The hammer impact test is a simple and quick method of initiating a floor into free vibration motion and determining its natural frequencies (Ewins 1986). Generally any light tapping of the test structure with a hammer can achieve this objective. These impacts are usually not typical of those produced in service by human activities such as walking. However it provides a speedy means for determining the natural frequencies and damping characteristics of a structure.

On each floor system, the position of the impact was fixed and the response measurements were taken from the other numbered locations. In stage 1 the impact position was location A4, whilst in stage 2 the impact position was location A3. An accelerometer was placed sequentially at other locations to measure the vibration in the form of acceleration. A spectrum analyzer was used to record and analyze the impact and response signals. Both signals were analyzed using the Fast Fourier Transform (FFT) technique (Newland 1984) to calculate their spectra. The analysis yielded an experimental frequency response spectrum which was then curve-fitted to output the natural frequencies and damping ratios (Chui 1986a).

A sufficient number of response locations was required to ensure that all the vibration modes which were of interest, and hence their associated natural frequencies and damping ratios, were detected. In this investigation the first five vibration modes of each floor were evaluated.

3.2 "Sandbag" impact test

A sandbag impact test was developed to achieve impacts on floor surfaces that were similar in characteristics to typical human footfall impacts. This produced realistic levels of vibration, enabling a "standardised" evaluation of levels of responses for different floor constructions. This new test replaced the usual approach of initiating vibrations by the so-called heel-drop impacts (Ohlsson 1982; Chui 1986a). The heel-drop impacts produced by one person have been found to be fairly repeatable, but the measured responses are still far from being uniform (Chui 1986a). A sandbag impact device was developed to give more consistent impacts than are attainable with heel-drop impacts.

Figure 4 shows the details of the device. In each test the 15 kg sandbag was raised to a height of 50 mm from the floor surface, then the rope holding the sandbag was released. After the impact the sandbag stayed on the floor surface until the floor system returned to rest. The particular weight and drop height combination was adopted after comparing acceleration response characteristics produced by a sandbag with that by an 80kg male heel-impacting on the surface of the reference floor (stage 1).

Static masses equivalent to a 0.478 kN/m^2 (10 lb/ft^2) imposed load were distributed on a floor surface when sandbag tests were conducted. This magnitude was chosen to simulate the effect of typical in-service static loading (Harris and Bova 1981) such as furniture. In each floor two impact locations were selected. For floors in stage 1 the positions were B4 and A6 while in stage 2 they were B4 and A5 (Figures 2 and 3).

The response signals picked up by an accelerometer were recorded with a spectrum analyzer. The acceleration signals were then transferred to a micro-computer for storage and data analyses. Each signal was analyzed using a program developed by Chui (1986b) to determine the frequency-weighted root-mean-square (rms) acceleration (A_r) of the vibration.

The frequency-weighted rms acceleration has been postulated as a suitable parameter for evaluating human response to building vibrations (ISO 1978; BSI 1984) and found to be a reliable parameter for evaluating vibrations in wooden floors (Chui 1986b). The basis of its choice is that it accounts for all factors, such as frequency components, rate of decay and levels of a vibration, to which humans are sensitive. The concept of frequency-weighted rms acceleration is described in Appendix III.

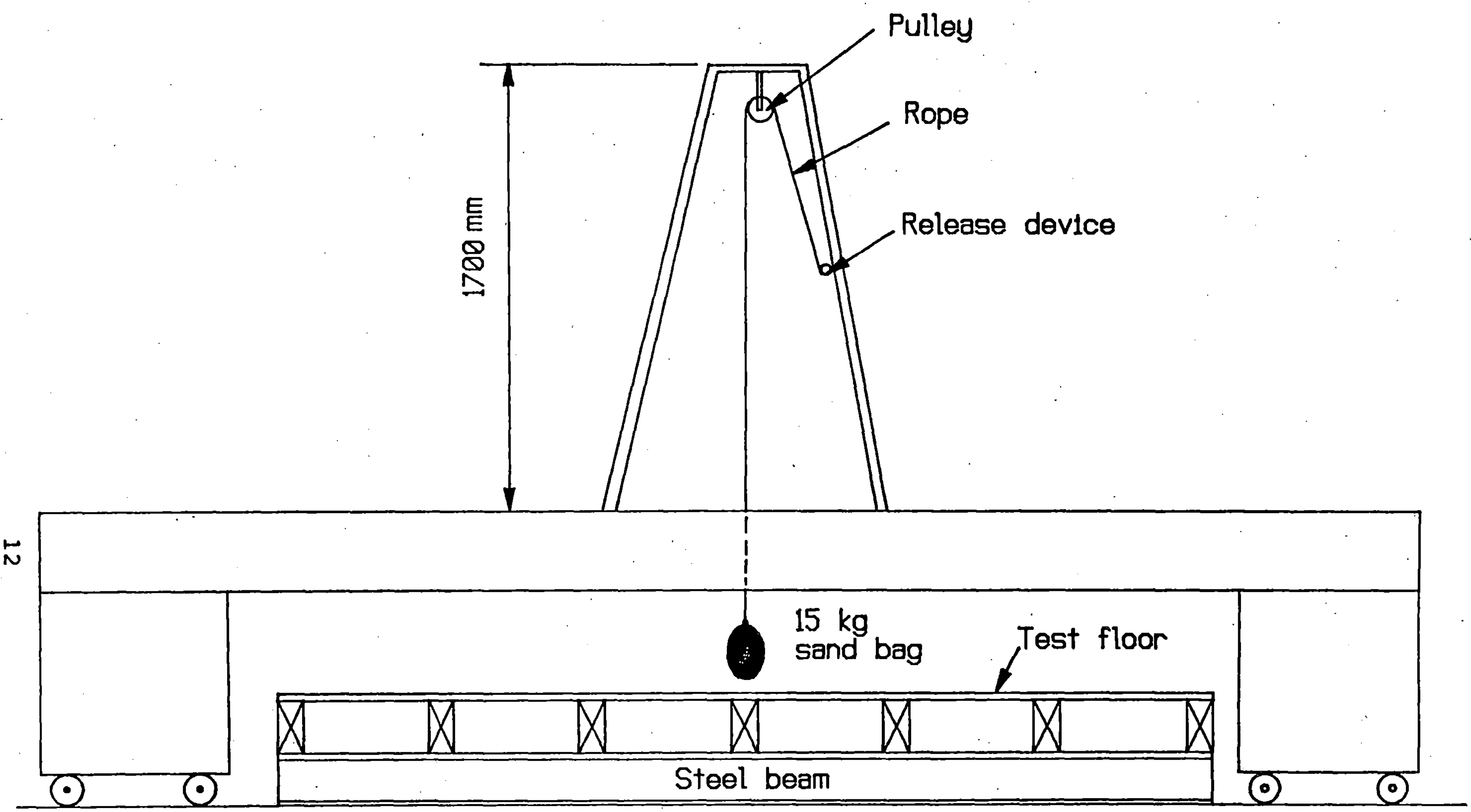

Figure 4 - Details Of Sand Bag
Impact Device

4.0 RESULTS AND DISCUSSION

Broadly speaking, this test study enabled an experimental evaluation of the effects of the following variables:

- Between-joists bridging
- Supporting all edges of floor vs. only joist ends
- Artificial damping material
- Flexural rigidity of flooring
- Elastomeric glued vs. nailed flooring to joist connections.

Each of the above variables will be discussed below. A summary of the results is given in Tables 3 and 4 for stages 1 and 2 respectively. These tables give the first five natural frequencies, their associated viscous damping ratios, and the frequency-weighted rms accelerations for loaded floors (averaged over the locations used for measuring response).

4.1 Reference floors

In each modified system it was assumed that the characteristics of "not modified" components remained unchanged compared with the reference floor. To ensure that this was the case, construction details of the test floor were returned to those of the reference floor and hammer impact tests performed to detect any changes in natural frequencies of the unloaded system after modified systems 3 and 8 in stage 1. The measured natural frequency values in Table 3 proved that there were negligible changes in the reference response with the repeated working of the floor components. Based on

Table 3 - Summary of test results for stage 1

System	Natural frequency (H_z) and Damping ratio (%)					A_r - Impact B4[1] (m/s^2)			A_r - Impact A6[2] (m/s^2)			Note
						Along Joist	Across Joist	Quarter Edge	Centre	Across Joist	Along Joist	
Ref	16.8 (2.7%)	21.6 (2.1%)	26.1 (1.7%)	30.4 (3.2%)	34.2 (1.4%)	0.928	0.460	0.321	0.406	0.484	0.844	Reference
1	15.4 (3.5%)	20.1 (2.0%)	25.1 (2.2%)	31.1 (2.7%)	39.1 (2.2%)	0.668	0.556	0.342	0.371	0.423	0.646	1 cross bridging
2	15.8 (3.7%)	20.5 (2.0%)	26.1 (1.9%)	33.8 (1.9%)	43.2 (1.6%)	0.633	0.589	0.340	0.378	0.298	0.560	3 cross bridging
3	15.5 (3.7%)	20.0 (2.3%)	25.4 (2.2%)	33.3 (1.8%)	44.8 (1.8%)	0.603	0.569	0.334	0.356	0.305	0.456	5 cross bridging
Ref*	16.2 (3.4%)	21.0 (1.7%)	27.3 (2.5%)	30.4 (1.5%)	34.5 (2.2%)							Retest with hammer impact
4	16.0 (3.3%)	20.6 (1.8%)	25.7 (2.9%)	41.7 (1.7%)	55.7 (1.8%)	0.576	0.493	0.285	0.329	0.305	0.361	1 new bridging
New Ref.	15.8 (3.7%)	20.8 (2.1%)	24.6 (2.1%)	28.6 (2.3%)	34.3 (2.2%)	0.826	0.525	0.349	0.405	0.371	0.691	New reference floor
5	12.9 (8.6%)	22.7 (2.2%)	27.2 (2.8%)	34.0 (1.6%)	46.3 (1.6%)	0.779	0.463	0.339	0.323	0.309	0.709	Edge joist support
6	15.7 (4.2%)	18.9 (2.2%)	21.9 (2.3%)	24.8 (1.7%)	30.3 (4.2%)	0.906	0.595	0.372	0.452	0.438	0.691	Damping material between flooring and joists
7	15.7 (4.2%)	19.6 (2.3%)	23.2 (2.6%)	26.4 (2.1%)	32.0 (2.2%)	0.865	0.618	0.351	0.485	0.342	0.901	Damping material between joists and support
New Ref*	15.5 (3.2%)	20.6 (1.9%)	25.0 (2.2%)	29.1 (2.7%)	34.4 (1.6%)							Retest with hammer impact
8	18.6 (3.5%)	25.2 (1.5%)	28.0 (2.2%)	31.5 (2.0%)	35.6 (1.6%)	0.899	0.638	0.367	0.410	0.351	0.809	Plywood flooring
9	15.6 (3.6%)	21.2 (2.3%)	24.3 (2.0%)	29.2 (1.6%)	34.4 (1.8%)	0.877	0.573	0.340	0.395	0.343	0.714	Glued connection

[1] Along - joist: Mean of A4 and C4
Across - joist: Mean of B3 and B5
Quarter - edge: Mean of A2, C2, A7 and C7

[2] Centre: Mean of B4 and B5
Across - joist: Mean of A5 and A7
Along - joist: Mean of B6 and C6

Table 4 - Summary of test results for stage 2												
System	Natural frequency (H_z) and Damping ratio (%)					A_r - Impact B4[1] (m/s²)			A_r - Impact A5[2] (m/s²)			Note
						Along Joist	Across Joist	Quarter Edge	Centre	Across Joist	Along Joist	
Ref	21.0 (3.7%)	28.2 (2.3%)	33.0 (2.7%)	39.3 (1.9%)	43.5 (2.8%)	0.940	0.634	0.396	0.565	0.435	1.122	Reference
10	15.7 (11.2%)	30.1 (2.8%)	40.1 (1.9%)	44.4 (2.0%)	58.4 (2.0%)	0.866	0.497	0.321	0.436	0.361	1.008	Edge support
11	21.1 (3.7%)	27.8 (1.9%)	36.2 (3.0%)	47.7 (2.5%)	61.1 (3.4%)	0.510	0.454	0.275	0.409	0.350	0.676	1 new bridging
12	17.0 (12.4%)	33.1 (2.9%)	48.0 (2.8%)	66.9 (2.8%)	76.6 (2.5%)	0.564	0.404	0.218	0.354	0.273	0.599	Combined bridging and edge support

[1] Along - joist: Mean of A4 and C4
Across - joist: Mean of B3 and B5
Quarter - edge: Mean of A2, C2, A6 and C6

[2] Centre: B4
Across - joist: Mean of A4 and A6
Along - joist: Mean of B5 and C5

the results in stage 1, no corresponding checking was thought to be necessary in stage 2 as there were only three modified systems.

In addition, it was found after testing modified system 4 (stage 1) that the repeated nailing and de-nailing of the OSB flooring had caused significant damage to the board edges and new flooring was needed for subsequent systems. Also, at that point joists were turned over to avoid excessive nailing holes in their top surfaces for latter floor systems in stage 1. Because this may have changed the floor response, the floor details were returned to those of the reference floor and the "full test" procedure performed. This defined the new reference responses indicated in Table 3, that apply to systems 5 to 9.

4.2 Between-joists bridging

Modified systems 1, 2 and 3 (stage 1) were tested to assess the benefits of increasing the number of lines of between-joists cross bridging. The cross bridging was nominal 1" x 3" (19mm x 64mm) S-P-F boards. One end of a board was connected to the top of a joist and the other end was connected to the bottom of an adjacent joist. Each connection was made with two 63mm common nails.

It can be noticed that the first few natural frequencies were lowered slightly with the addition of any cross bridging. This was due to the additional mass of the bridging material and the change in floor stiffness in the across-joists direction caused by the bridging. The higher natural frequencies (fourth and fifth modes) were raised due to the second factor.

When sandbag impacts were applied near floor centre (B4), significant reductions (improvements) in A_r were observed in other locations (A4 and C4) along the impacted joist. In the across joist direction however, A_r was seen to increase. This is an indication that cross bridging increases load-sharing capacity (or across-joists stiffness) of a floor system by causing more joists to resist the impact force. Thus, the general effect was a relatively large reduction in response level at the impacted joist but a small increase in other locations. When an impact was applied close to an edge (A6) there were reductions in A_r values for all positions.

Increasing the number of lines of bridging seemed to bring about an increase in higher natural frequencies and a decrease in A_r values, which improves vibrational performance of a floor. However, for the system in stage 1 most of the improvement occurred after one line of bridging was installed. This suggests that for solid joist wood floors of sizes similar to the test floors in stage 1 an extra benefit will not be readily achieved by installing more than one line of cross bridging.

It has previously been recognised that between-joists bridging is a cost-effective means of enhancing performance of a floor (Onysko and Jessome 1973;Ohlsson 1982). Traditional forms of bridging such as cross bridging and solid blockings have sometimes been observed to lose their effectiveness due to shrinkage of wood after a number of years in service and poor workmanship. Better forms of bridging which are less sensitive to these factors are desirable.

In this study, a floor (system 4) was tested using an "improved" form of bridging. To circumvent the expensive testing of full scale floor systems when searching for the "improved" bridging, a screening technique was developed. This technique involves the testing of a three-joist system with the bridging inserted between the joists. The span was 4.06m and the distance between adjacent joists was 600mm. The ends of joists were supported as detailed in Figure 1. The line of bridging was placed at mid-span. The hammer impact test was then performed on the system and its natural frequencies determined. This technique is based on the fact that a more effective bridging detail leads to higher stiffness in the across-joists direction which in turn produces greater spacing between adjacent natural frequencies. Thus examining the ratios of a higher natural frequency to that of the first natural frequency of these three-joist systems incorporating different forms of bridging gives a qualitative indication of the relative effectiveness of each form of bridging.

The following forms of bridging were "screened":

1. Wood cross bridging

These were nominal 1" x 3" boards nailed to joists as described before.

2. Wood cross bridging with light gauge steel bottom strap

Details are similar to 1 but with a 26 gauge mild steel bottom strap (0.6mm x 38mm) nailed to each joist with a 50mm common nail (Figure 5).

3. Light gauge steel cross bridging with a light gauge steel bottom strap.

Light gauge steel tension member[1] with one end nailed to the upper surface of a joist and the other end nailed to the underside of an adjacent joist, as illustrated in Figure 6, using 50mm common nails.

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[1] *TB30 tension bridging manufactured by Simpson Strong-Tie Company Inc.*

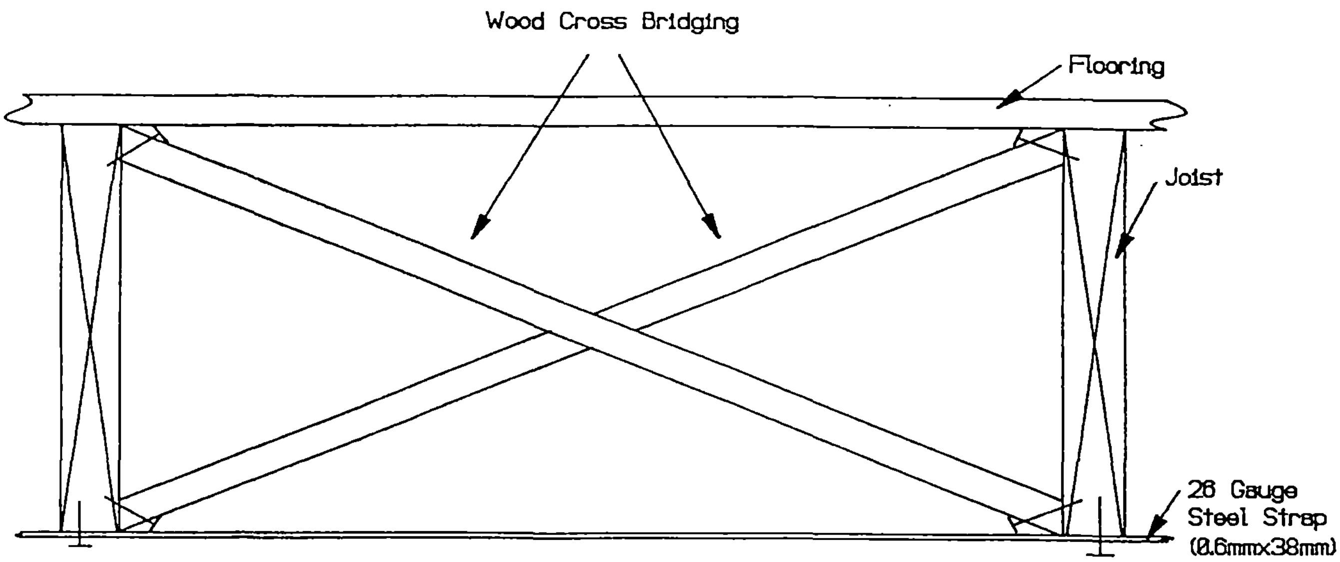

Figure 5 - Wood Cross Bridging With
Light Gauge Steel Strap

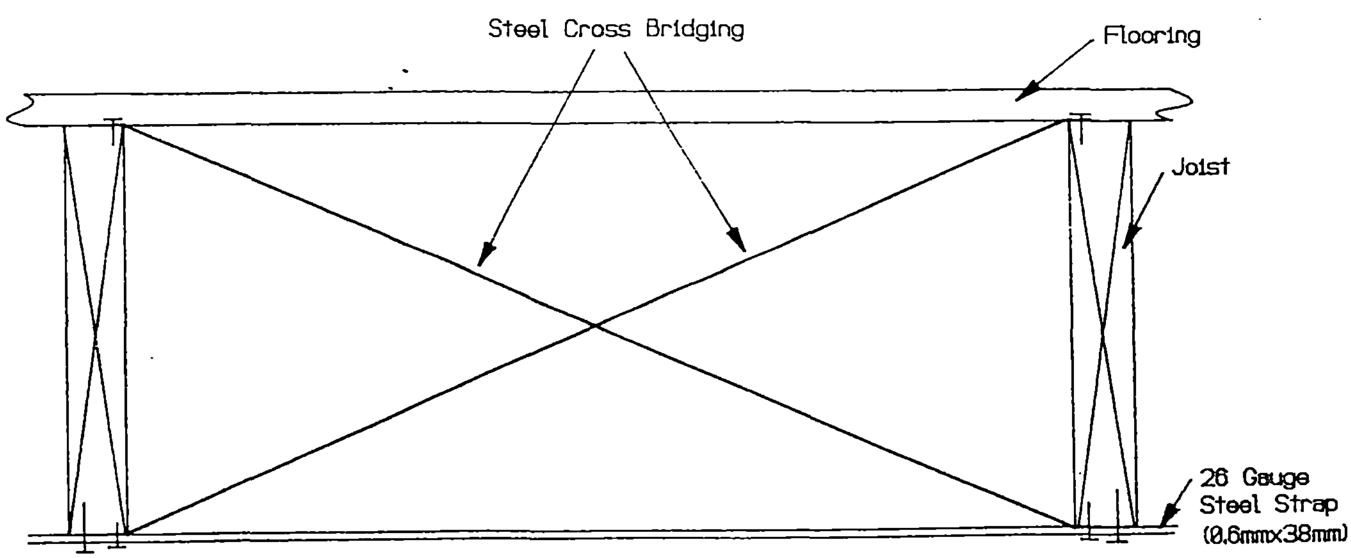

Figure 6 - Steel Cross Bridging
With Light Gauge Steel Strap

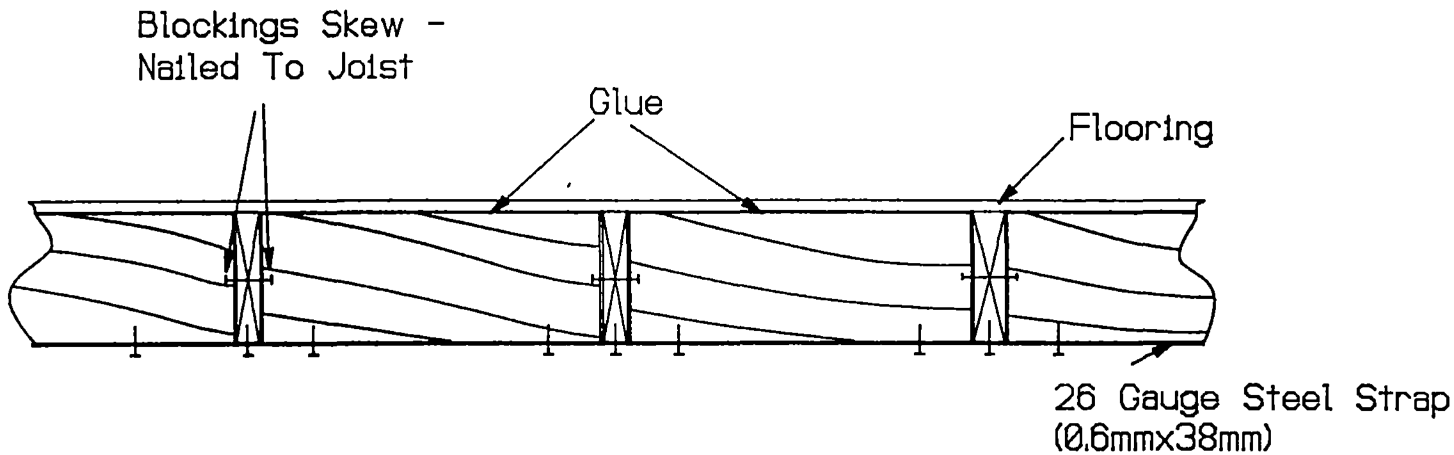

Figure 7 - Bridging With Solid
Blockings And Light Gauge
Steel Strap

4. Solid blockings with a light gauge steel bottom strap

The blockings were off-cuts from the joists. A bead of construction glue was applied to the upper surface of each blocking which was then bonded to the bottom side of the flooring. The blockings were skew-nailed into place using nominal nailing with one 65mm nail at each side. A continuous 26 gauge mild steel strap (0.6mm x 38mm) was attached to the bottom surfaces of the blockings and the joists as illustrated in Figure 7. Nails were driven through the steel strap into the joist and blocking pieces. The steel strap connected all blockings and joists, to form an effective continuous secondary beam running across the span. The glued connection at the top and the nailed steel strap ensure that some degree of composite action occurred.

The results for the screening tests are presented in Table 5 as first natural frequency and the frequency ratios. A higher frequency ratio implies a more effective bridging. The results demonstrate the benefit of having a continuous bottom strap. It also highlights the superiority of the bridging with solid blockings and a bottom steel strap over the other options. This form of bridging was then adopted in modified system 4 to quantify its effectiveness in a full size floor system.

Table 5 - Results of bridging screening tests.

Bridging details	f_1 (Hz)	f_2/f_1	f_3/f_1
Wood cross bridging	27.97	1.136	1.657
Wood cross bridging with bottom strap	28.00	1.135	2.000
Steel cross bridging with bottom strap	28.25	1.110	1.340
Solid blockings with bottom strap	27.37	1.123	2.157

Notes : f_1 = first natural frequency
f_2 = second natural frequency
f_3 = third natural frequency

Comparing the results from systems 1 and 4 in Table 3 confirms that this form of bridging is more effective than traditional cross bridging. An added advantage of the recommended bridging detail over wood cross bridging with bottom steel strap which has a marginally inferior performance (Table 5) is that it is not sensitive to shrinkage movement in wood as it relies on the glued connection at the top and the continuous bottom strap to transfer loads. A wood bottom strap could be used instead of a light gauge steel strap, but may not be as suitable if a ceiling is required below the floor. This form of bridging is not expected to be significantly more expensive to install than traditional bridging systems.

4.3 Edge joist support

The effect of supporting all edges instead of just ends of joists was studied by toe-nailing edge joists to a bottom bearing plate which was in turn anchored to the ground via steel I-beams. Nails were 63mm common nails spaced at 150mm centres. The addition of edge joist support stiffened the floor in the across joists direction compared with those in the "new" reference floor for stage 1, as indicated by the increases in natural frequencies other than the fundamental in system 5. Lowering of the fundamental natural frequency by a significant amount is thought to be a function of the increase in the degree of isotropy of a floor system. Similar results were found by Chui and Hu (1990) on wood-I floor systems. The damping of the first mode was found to be significantly higher with the addition of edge support. This high damping means that the first mode of vibration may have little contribution to the overall motion in a floor with edges supported.

For the frequency-weighted rms acceleration, significant reductions in A_r values were observed at some locations due to increase in floor stiffness. There is evidence that the A_r values in other locations along the impacted joist are relatively insensitive to edge joist support conditions.

It appears from these results that edge support is an in-expensive means of improving floor performance and should be included whenever possible in practice. This practice is often adopted by builders. Different details of attaching edge joists to foundations and stud walls are given in "Canadian Wood-Frame House Construction" (CMHC 1984). When difficulty is encountered in achieving any of those details, it is suggested that a double-joist be used at an edge, which should replicate reasonably well a supported edge. In such a case the cost in carrying out this practice consists of mainly the material cost for the extra two joists.

4.4 Artificial damping material

Artificial damping materials are extensively used in controlling vibrations in machinery and building foundations. There does not appear to have been any prior research on the use of "dampers" in controlling vibrations in wooden floor systems. Whilst it was recognised that a comprehensive study on this topic was not possible within the scope of this project, some exploratory testing was included.

After consultation with a supplier, a neuprene material[2] was acquired for use as the damping material. It came in the form of a 6mm thick by 50mm wide strip. Two floors were tested for this purpose: one with neuprene placed between joist and flooring, and the other with the neuprene placed between underside of joists and their supporting bearing plates. In the first floor (system 6) 50mm x 50mm pieces were cut from the strip and placed between flooring and joists at 300mm intervals along each joist. In the second floor (system 7) 50mm x 50mm pieces were placed between joists and their supports. The same nailing schedule as in the reference floor was used. No attempt was made to select nailing points and some nails were driven through pieces of neuprene.

Inserting an elastic material between flooring and joists or between joists and supports in the manner described above could lead to a reduction in the composite action between the two components and thus the floor stiffness. This concern is supported by reduction in the natural frequencies measured from the test floors relative to those for the reference floor. Whilst the first natural frequencies for systems 6 and 7 were only lowered slightly compared with the new reference floor, there were significant decreases in the higher natural frequencies. This reduction in composite action is thought to explain the observed increase in A_r values for both systems 6 and 7.

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[2] *Neuprene 060 supplied by Ontario Rubber*

The expected function of the damping material was to enhance the damping capacity of the floors, which would help to increase the rate of decay of vibration amplitudes, and thus lead to lower A_r values. As expected the average damping ratio for the first five modes of vibration was found to be increased by the damping material. However, the amount of increase in damping was not large enough to offset the increase in A_r values brought about by the reductions in natural frequencies caused by loss of composite action.

4.5 Flexural rigidity of flooring

Currently the common materials used for flooring purposes in residential construction are OSB and plywood. Because of the characteristics of the material, a floor built with plywood flooring generally has higher flexural rigidity in the across-joist direction and lower self mass compared with one built with an alternative OSB flooring. Both these factors increase natural frequencies of a system. This explains the higher natural frequencies of system 8 compared with those in the new reference floor. The plywood was 18.5mm Douglas fir plywood. The increase in floor stiffness also led to an overall reduction in A_r, but in some locations a significant increase in A_r was observed. This is because, due to reduced inertia effects, a lighter system produces higher amplitude vibrations when excited dynamically than a heavier system, if all other parameters are equal.

Limited tests were performed on samples taken from sheets of OSB and plywood used to construct test floors to determine their moduli of elasticity and densities. The results are presented in Table 6. Each modulus of elasticity (E) value in Table 6 represents the mean of results from twenty specimens. Each density value is the mean of all E specimens. The specimens were 18.5mm x 50mm x 600mm and cut from 2 panels. They were tested by the vibration approach described in Appendix II. E_x is the modulus of elasticity in the longer dimension of a panel. The panels were laid with their longer dimension perpendicular to joists. Thus E_y refers to the modulus of elasticity in the direction of joists.

Table 6 - Properties of flooring materials at test conditions.

Material	Thickness (mm)	E_x (MPa)	E_y (MPa)	Density (kg/m^3)
OSB	18.5	5712	2177	634
Plywood	18.5	6802	2936	480

Notes : E_x = modulus of elasticity in the longer board dimension
E_y = modulus of elasticity in the shorter board dimension

It can be noticed that the plywood was only about 19% stiffer than OSB in the across-joists direction (E_x) but 32% lighter. Thus the mass factor was more dominant in this case. This highlights the need to consider the mass as well as the flexural rigidity of a flooring when attempting to improve floor performance through the use of a suitable flooring material.

4.6 Glued flooring-to-joist connections

Elastomeric glue is sometimes used in floor construction to avoid squeaking. The use of glue to attach flooring to joists has also been known to increase the degree of composite action between the two components which can result in an increase in floor stiffness.

To investigate the effect of the use of a typical construction glue on the response characteristics of the test floor, system 9 was constructed with an elastomeric glue[3]. Clamping pressure was applied by nailing the OSB to the joists and the glue was allowed to set for 48 hours prior to testing.

The results shown in Table 3 indicate that there was very little change in floor performance (expressed in terms of the natural frequencies and A_r) when nails were replaced by a combination of glue and nails. Thus, the use of construction glue for improving mechanical vibration performance does not appear to be justified.

4.7 Verification systems - stage 2

Stage 2 was performed to assess whether the benefit of a few selected practices can be extrapolated to a floor with different joist size and plan dimensions. General details were as discussed in Section 2.

From the results in stage 1, it was apparent that the two most cost-effective methods of enhancing vibrational performance are: edge joist support and an improved form of bridging using solid blockings and a bottom steel strap. These two details were therefore the variables selected for investigation in stage 2.

Table 4 presents the results for stage 2. It can be seen that when each variable was introduced into the floor alone the results generally show a similar trend to that obtained in the bigger floor (stage 1). When edge joist supports were added, the first natural frequency was lowered substantially and the associated damping ratio increased. The higher natural frequencies were also raised, but by a relatively small amount. The

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[3]*LePage Ultragrip 9000*

A_r values at all monitoring locations were reduced. This finding differed slightly from that for the bigger floor in which the acceleration responses at locations either side of the impacted joists were higher when between-joists bridging was used. Unpublished work by Wood Science and Technology Centre has shown that the effectiveness of between-joists bridging is related to the aspect ratio (width/span) of a floor. The floor in stage 1 had an aspect ratio of 1.034 whereas the floor in stage 2 had a corresponding value of 1.132. This confirms that floors with high aspect ratios benefit more from the use of between-joists bridging than those with low aspect ratios.

In system 12 the effect of combining the two variables i.e. edge joist supports and bridging was evaluated. As expected the improvements in response parameters used to quantify performance were greater than using either edge joist support or bridging alone.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The following conclusions, with respect to vibrational performance, can be drawn from tests on floors in this study:

1. It is beneficial to increase number of lines of bridging. However, the amount of improvement decreases drastically after one line of bridging for floors with span 4.06m, width 4.2m and a joist spacing of 600mm.
2. The use of neuprene pads as dampers between flooring and joists or between joists and bearing plates is not effective. In some instances, an increase in response amplitudes can result due to loss of composite action.
3. The use of "stiffer" flooring such as plywood instead of OSB does not lead to an improvement in performance due to the lower unit mass of the plywood compared with OSB.
4. There is no advantage in using an elastomeric glue to attach flooring to joists. This can lead to a slight increase in floor stiffness, but the improvement is small. The primary advantage of using such a glue is in reducing squeaking in vibrating floor systems.

It is recommended that the following features should be incorporated into domestic floor constructions in order to optimize vibrational performance:

1. Support of the edge joists.
2. Install between-joists bridging having a continuous bottom strap and a capacity to interact with the flooring under motion. One line of bridging gives good performance for floors with spans less than or equal to 4 m. For

floors with a span greater than 4 m, more than one line of bridging may be required. An effective form of bridging detail is illustrated in Figure 7.

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APPENDIX I

Report on visits to Institute for Research in Construction, NRC and Forintek Canada Corporation, Ottawa.

Institute for Research in Construction IRC, NRC (April 30, 1990).

IRC has been conducting research on floor vibration for over ten years. Their main emphasis has been on vibration performance of concrete slab-steel beam type construction.

I was received at IRC by Dr. J.H. Rainer, Head of their structures section. Technical discussion with Dr. G. Pernica followed the general introduction by Dr. Rainer on the activities of IRC. Dr. Pernica has conducted a lot of the recent IRC work on floor vibration. He has collected data on the characteristics of dymanic loading created by various human activities such as walking, running, jumping and dancing.

Their recent interest is in improvement of vibration performance of existing floor systems (remedial work). Specifically Dr. Pernica has been investigating various means of increasing damping capacity of floors. Previously he has worked on friction dampers which he found to be not very effective and impractical to install, especially during remedial work. His recent pursuit in this subject area has produced a new form of damper; tuned mass damper. This is basically a system consisting of a spring or rubber base and a heavy mass on top of it. The mass is adjusted or "tuned" such that the natural frequency of the damper coincides with a natural frequency of the floor system. Dr. Pernica also explained how the mass of damper and its position affect the effectiveness of the damper. Samples of the rubber material used in his study for making dampers were brought back to the WSTC. These will be tried to select the most suitable damping materials to be used in the CMHC project.

The objective of the CMHC project is to produce improved construction detailing for better vibration performance. It was agreed that future work in other areas such as derivations of design criteria and methods is also required.

Literature relating to IRC's previous work in this area, design of damper and manufacturers' brochures on damping materials were obtained from IRC during the visit.

Forintek Canada Corporation (May 1, 1990).

The purpose of this visit is to gain an insight into the work done by Dr. D.M. Onysko on floor vibration during the seventies. Dr. Onysko has conducted both laboratory and field testing on full size wooden floors.

His laboratory tests investigated primarily the effectiveness of various forms of between-joist bridging in stiffening floor systems. In addition he conducted vibration testing using different impact devices. These included dropping objects from a height and heel-impacting. In his tests characteristics of heel-drop impacts produced by a number of people were measured by a load cell. A copy of the unpublished report containing the tests was obtained during the visit. This will provide valuable information for making the impact device in the new CMHC project.

In his field work, around 100 floors were tested across Canada. He measured static deflection at floor centres under a concentrated load of 100 kg and frequency and damping of the vibration, caused by an impact. He correlated owner assessments of floors with these parameters, and found that a reasonable correlation exists between human acceptability and static deflection. Based on this work he recommended some static deflection criteria for controlling vibration in wooded floors. These criteria provided the basis for the derivation of the new allowable spans given in the 1990 edition of the National Building Code of Canada.

Dr. Onysko went over his test procedure and data, and discussed the problems he encountered during his tests. He also demonstrated a computer program developed by him to predict static and dynamic responses of wood floors systems. He promised to send a copy of the program to WSTC together with some of his publications in the floor vibration area.

<u>Summary</u>

1. The visit to IRC resulted in the attainment of technical information regarding methods for enhancing damping capacity of floor systems and vibration tests conducted on floors built with heavier material.

2. Dr. Onysko of Forintek has given some useful advice on collecting heel impact data, fabrication of an impact device and testing procedures.

APPENDIX II

Beam vibration test to determine modulus of elasticity of floor components.

The modulus of elasticity of (E) of a beam can be determined from vibration tests. This is based on the fact that for a beam, E is related to its fundamental natural frequency, density and physical dimensions. For a free-free support beam with rectangular cross section, the relationship can be expressed as follows (Warburton 1984):

$$E = 0.946 \frac{f_1^2 L^4 \rho}{d^2} \qquad [1]$$

where f_1 is the fundamental natural frequency

L is the span

ρ is the density

d is the depth

In this study a test beam (a joist or a flooring strip) was suspended by two soft springs and was excited into motion by an instrumented hammer. The vibration was measured by an accelerometer. Both the impact force and vibration signals were analyzed by a spectrum analyzer. From the resulting spectrum the fundamental natural frequency was identified. The soft springs ensured that the beam vibrated in a free-free support mode. The density was determined by direct weighing and measurement of physical dimensions.

Tables 7 and 8 show the properties of joists in stages 1 and 2 respectively.

Table 7 - Properties of joists in stage 1 at test conditions.

Joist	E (MPa)	Density (kg/m^3)
1	11241	416
2	10009	383
3	11020	499
4	10580	520
5	10712	497
6	10211	486
7	11235	474
8	9974	477

Table 8 - Properties of joists in stage 2 at test conditions.

Joist	E (MPa)	Density (kg/m^3)
1	11189	429
2	14023	590
3	12433	562
4	11069	522
5	11930	414
6	10641	446
7	12417	461

APPENDIX III

Concept of frequency-weighted root-mean-square acceleration.

Human response to building vibrations has been found to be related to the frequency components, levels of vibration and rate of decay of peak amplitudes. International standard ISO 2631 (1978) and British standard BS 6472 (1984) provide general guidance on evaluation of human response to building vibrations. These documents propose that frequency-weighted root-mean-square (rms) acceleration of a vibration signal should be evaluated when assessing the human response to that vibration. This parameter is chosen because it accounts for all primary factors that govern human response to vibrations. Root-mean-square or rms acceleration takes into account the rate of decay and level of vibration factors. Frequency-weighting recognises the fact that humans are most sensitive to frequencies in the range 4 Hz to 8 Hz. The levels of sensitivity decreases moving away from this range. A suitable frequency-weighting procedure is outlined in ISO 2631 (ISO 1978). Mathematically the rms acceleration of a signal is expressed as:

$$A_r = \sqrt{\int_0^T a(t)^2 dt / T} \qquad [2]$$

where A_r = rms acceleration

$a(t)$ = acceleration at time t

T = duration of vibration

It can be observed from Equation 2 that a fast rate of decay leads to a low Ar value. Human thresholds used to evaluate given response levels are contained in the relevant standards such as ISO 2631 (1978) and BS 6472 (1984).

In this study A_r values were calculated based on a one second duration suggested by Chui(1986b).