Influence of between-joists bridging elements on static and dynamic response of wood joisted floors

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Abstract

Excessive vertical vibration of lightweight floors caused by walking or similar activities can be annoying to building occupants. Previous studies have shown that the vibrational performance of floors having wood joists is enhanced by installing one or more lines of bridging elements that form transverse spines in the across-span direction. This paper presents an experimental study that defined relationships between the effective flexural rigidity of such spines and response characteristics of wood joisted floors. Behaviors of spines having both normal and special types of bridging elements were investigated, with the special types of elements able to create a broad range of spine flexural rigidities. It was found that all types of transverse bridging spines have a small influence on fundamental natural frequency but can increase higher order modal frequencies considerably. Relatively stiff types of transverse bridging spines reduced static deflections caused by concentrated gravity forces considerably. An experimental method is presented for quantifying effective flexural rigidities of transverse bridging spines. Suggestions are made concerning application of the research findings in vibration serviceability design of lightweight wood joisted floors.

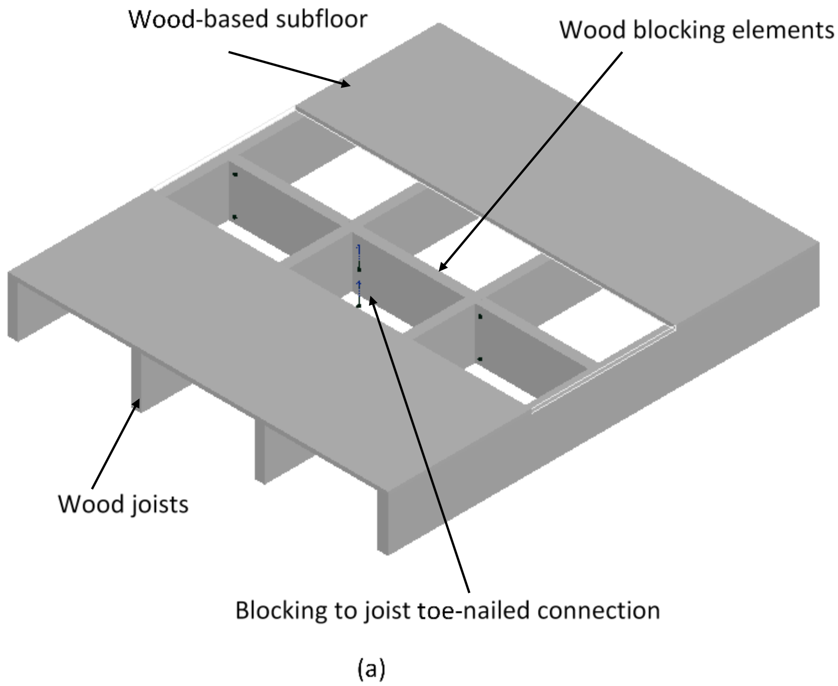
Key words

Bridging; dynamic response; experiments; natural frequencies; serviceability; static deflection; transverse stiffness; wood floors.

1. Introduction

Vertical vibrations of floors caused by normal human activities like walking can be annoying or even disturbing to building occupants. It is a problem that applies most often to lightweight floors because, when excited, they tend to produce higher than normal levels of acceleration than heavy floors of a similar span. Vibration serviceability problems can occur in floors constructed with wood-based products simply because of the low mass to stiffness ratios they possess [1–3]. Although mass to stiffness ratios are important, it is equally important to pay close attention to construction detailing because that also controls how floors vibrate under different types of impacts and other sources of excitation [4]. Most modern lightweight wood floors are constructed using closely spaced joists made from sawn lumber or engineered wood products, such as Laminated-Veneer-Lumber (LVL) or wood I-joists, overlain with structural wood panels and flooring. Investigation of reported vibration serviceability problems with such floors suggests that solutions lie in properly addressing size and spacing of the joists and use of construction details that engage multiple joists in resisting applied concentrated loads [5,6]. It follows from the above that paying attention to selection of construction details has the purpose of ensuring that floors will not flex in the across-span direction in a manner that can potentially cause adjacent vibration mode interaction, leading to high level of vibration amplitudes [7,8].

As is well known from field experience, the performance of floors with wood joists and wood panel sheathing and flooring is improved by installing bridging elements to create one or more stiffening spines in the across-span (transverse) direction [1,3,9]. Transverse bridging spines are most often solid blocking or cross-bridging inserted between joists, Fig. 1. However, despite their widespread application the mechanisms by which spines of such transverse bridging elements function has not been fully elucidated. Hence, their performances have not been optimized.



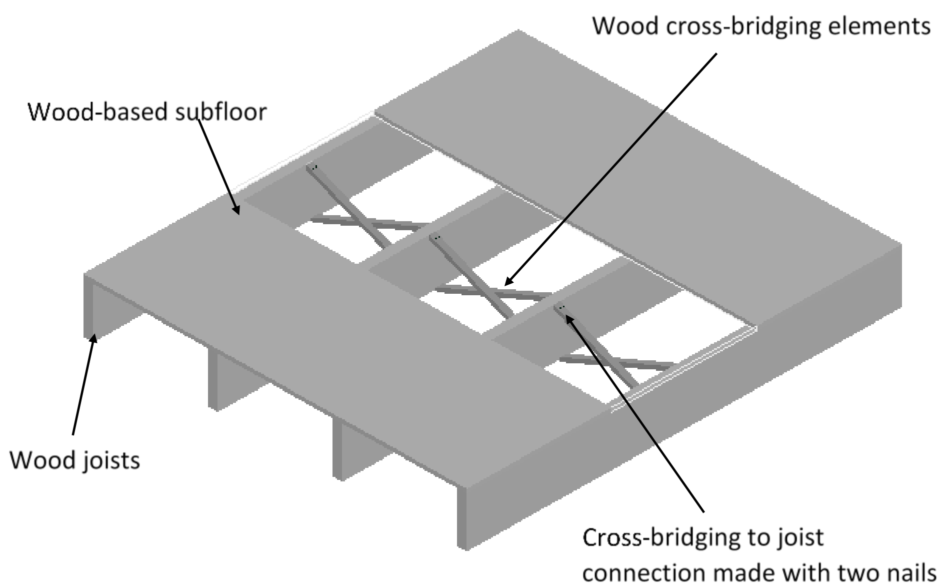


Fig. 1. Conventional bridging spines (a) solid blocking (b) cross-bridging

Providing transverse spines of bridging elements is not the only way to stiffen floors in the across-span direction. Chui [10] suggested installation of an additional layer of floor sheathing over the joists, while Hu and Tardif [11] suggested suppressing the floor response by coupling it to structurally competent partition walls. Ohlsson [3] advocated reducing the spacing of floor joists. However, various investigators have reported that using transverse bridging spine is the most cost-effective strategy in enhancing vibration performance of wood floor systems [12–15]. Work by Onysko [16] and Hu and Tardif [17] has suggested that a bridging spine at mid-span is the most effective and that for the bridging spines to be effective for long-span floor systems, the spacing between adjacent spines should be no more than 2m.

Field investigations and surveys have been carried out in several countries to correlate occupant satisfaction with performances of floors in residential and mercantile buildings with parameters that engineers can estimate using simple formulas [18]. Amongst the parameters that can be calculated with reasonable reliability are fundamental natural frequency (f_1) and static deflection caused by a concentrated gravity force of 1 kN placed at the centre of a floor (d_1) [1,8,9,19,20]. Employing f_1 and d_1 as design parameters is based on the premise that natural frequencies of floors should lie above a certain threshold level to avoid resonance of human bodies [2,3] and floors should be sufficiently stiff to prevent excessive flexural deformation in the across-span direction. The latter is required to minimize adjacent mode interaction, which may lead to higher vibration amplitudes. Providing transverse bridging spines is an effective means to stiffen the floor in the across-span direction. Other approaches such as the use of a thicker sheathing and presence of a ceiling can also achieve similar stiffness enhancement effect. This study focuses on an approach to measure effective flexural rigidities of transverse bridging spines and how these rigidities influence floor stiffness in the across-span direction. The significance of characterizing the effective flexural rigidity of transverse bridging spines is that it can be incorporated into a system model to predict floor system response to static and dynamic loads [21]. The model [21] is based on ribbed-plate theory [22] and considers a timber floor as a system consisting of a thin plate reinforced by ribs running in either one or two orthogonal directions. The static deflection under a point load at the centre of floor and the fundamental natural frequency can be calculated as in Equation (1) and Equation (2), respectively, considering floor construction details and incorporating the flexural rigidity of a row of bridging elements.

$$d_1 = \frac{4P}{ab\pi^4} \times \sum_{m=1,3,5..} \sum_{n=1,3,5..} \frac{1}{\left(\frac{m}{a}\right)^4 D_x + 2\left(\frac{mn}{ab}\right)^2 D_{xy} + \left(\frac{n}{b}\right)^4 D_y} \tag{1}$$

$$f_1 = \frac{\pi}{2\sqrt{\rho}} \sqrt{D_x \left(\frac{1}{a}\right)^4 + 2D_{xy}\left(\frac{1}{ab}\right)^2 + D_y \left(\frac{1}{b}\right)^4} \tag{2}$$

where a = span of floor, b = width of floor, P = point load at the centre of floor and ρ = density of subflooring material. D_x takes account of the composite flexural rigidity of the joists and the spacing. D_{xy} considers the shear rigidity of plate and torsional rigidity of the joists and D_y depends on the effective flexural rigidity of transverse bridging spines and the subfloor stiffness in that direction. Further details are given in [21]. In order to calculate D_y, the bridging spine rigidity must be known. There is currently no reliable method of measuring that spine rigidity. With the characterization of the bridging spine rigidity, it is then possible to quantitatively evaluate the influence of bridging spine rigidity on static deflection and first natural frequency of timber floor systems. This is also discussed in this paper.

2. Test Program

A test program was devised to focus on how characteristics of a single transverse bridging spine, created using bridging elements, influenced f_1 and d_1 of floors. To achieve this goal the test program consisted of two components. The first component was the determination of the effective flexural rigidity of the transverse bridging spines that were used in the subsequent full size floor tests. The second component was the testing of full size floors to determine the static and dynamic floor characteristics. LVL joists were used rather than sawn softwood lumber because LVL has lower variability in dimensions and elastic stiffness between nominally identical pieces. Low variability in joist characteristics was desired because that would avoid possible masking effects other variables had on floor response parameters [2,5]. The primary focus of the study was to understand the influence of stiffness of bridging spines on floor performance parameters.

Rectangular plan geometry and simple support conditions along all edges were adopted to maximize effects of changing bridging element stiffness on floor response characteristics. Transverse bridging spines employed were solid blocking pieces, lumber cross-bridging with and without bottom strapping, and special bridging elements of variable stiffness. The baseline condition of no bridging elements installed was also investigated. A subsidiary study was conducted to characterize the effective flexural rigidity of each type of bridging element.

2.1. Full-size floor tests

Floor span and width were 4.20 m and 3.66 m, respectively, Fig. 2. Joists were 240 mm deep by 44 mm thick LVL and spaced 610 mm apart. Mean LVL joist properties were: modulus of elasticity in bending = 11,700 MPa, and shear modulus as a joist = 1,270 MPa. These properties were measured using modal testing technique developed by Chui [23]. The subfloor was 19 mm construction sheathing grade Oriented-Strand-Board (OSB) with tongue-and-grooved edges. Mean OSB properties were: modulus of elasticity in bending parallel to stiff axis = 9,640 MPa; modulus of elasticity in bending perpendicular to stiff axis = 4,860 MPa; and density = 658 kg/m^3 [9]. Panels of subfloor were oriented with their stiff in-plane axis in the across-span direction, with a staggered jointing pattern, and fastened to joists using 63 mm long gauge 10 (4.83 mm diameter) wood screws spaced as indicated in Fig. 2. Floors were supported on shallow light-frame walls as shown in Fig. 3, making it easy to measure static deflection of joists from the underside using dial gauges having an accuracy of 0.01 mm. Dial gauge readings were read by a technician at regular load intervals to allow a continuous load-deflection response to be constructed after the deflection test.

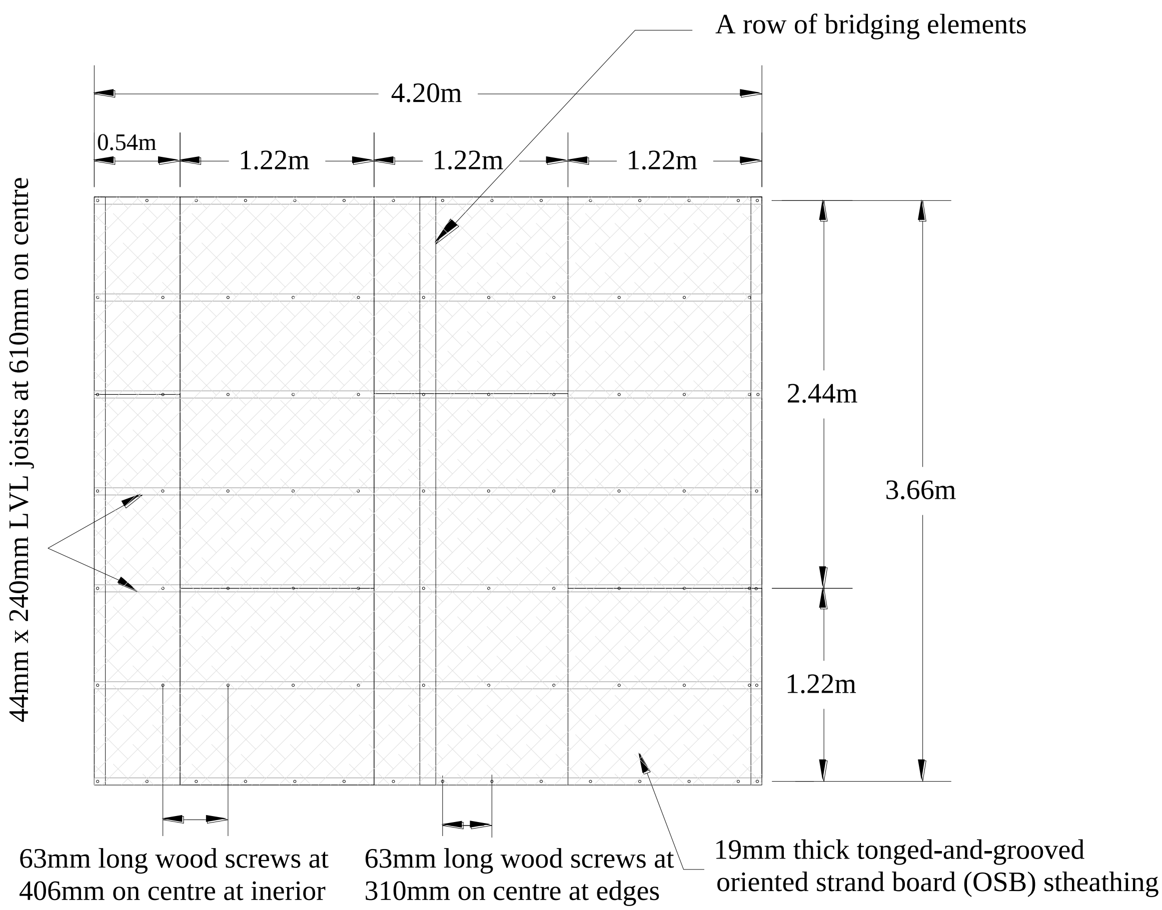


Fig. 2. Plan view of floor layout with a row of bridging elements

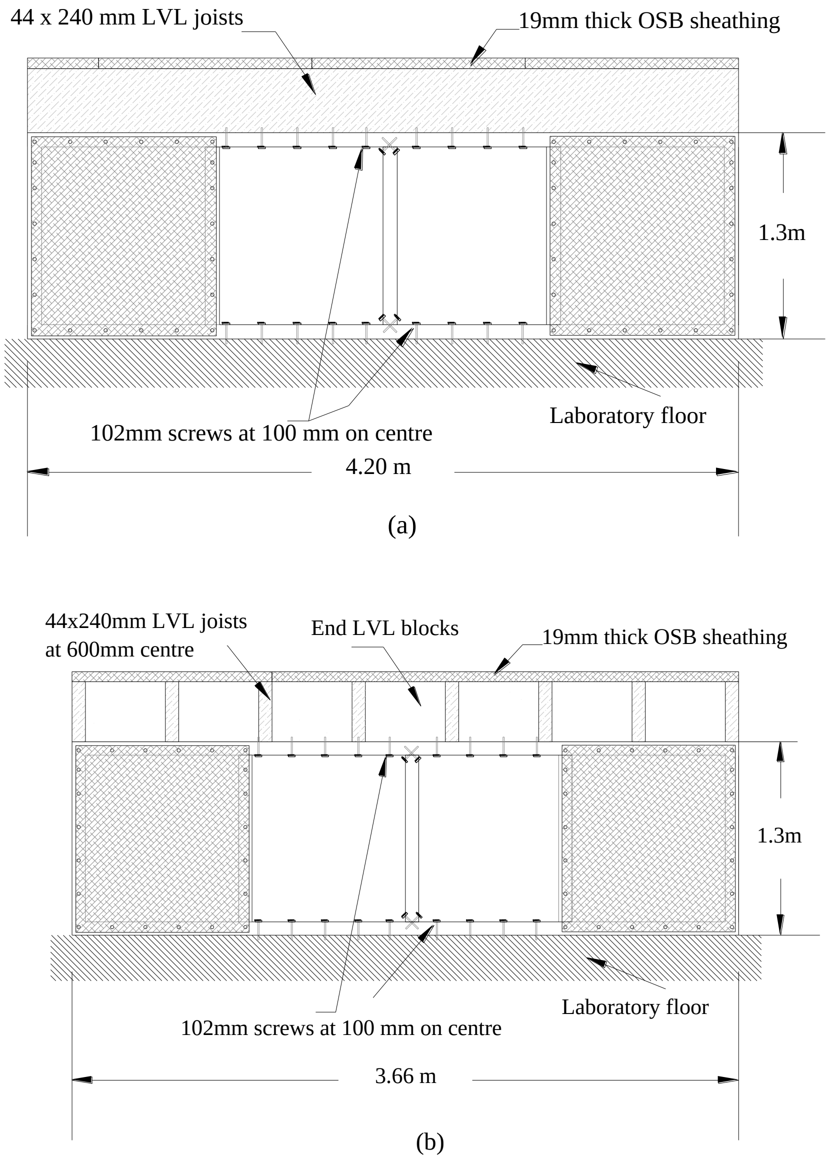


Fig. 3. Test floor layout (a) along-span elevation (b) across-span elevation

Table 1 shows the various floor arrangements investigated. Where installed, solid blocking elements were single pieces of 38 mm by 240 mm sawn spruce lumber toe-nailed to LVL joists using two 63 mm long gauge 8 (4.19 mm diameter) common nails. Each blocking to joist connection had two nails with one driven from each side at top and bottom. Cross-bridging comprised two pieces of 38 mm by 51 mm sawn spruce lumber, each fastened to joists using two 63 mm long gauge 8 (4.19 mm diameter) common nails, Fig. 4. Where installed, strapping was 19 mm by 89 mm spruce board that was attached to the underside of cross-bridging and attached to each joist by two 63 mm long gauge 10 (4.83 mm diameter) wood screws, Fig. 4.

Table 1. Static deflection response of floors with and without a bridging element spine

Type of bridging elements	Equivalent beam flexural rigidity, EI_b (kNm^2)	Static deflection under 1 kN load, d_1 (mm)	Reduction in deflection relative to baseline (%)
Baseline [a]	0	1.3	0
Cross-bridging	45	1.18	10
Solid blocking	57	1.10	14
Cross-bridging with strapping	91	0.98	25
Special - 1 screw [b]	40	1.17	9
Special - 3 screws	61	1.11	15
Special - 5 screws	78	1.04	20
Special - 8 screws	92	0.96	26
Special - 13 screws	98	0.93	29
Special - 13 screws + adhesive	110	0.90	31

[a] Floor tested without addition of any bridging elements.

[b] Number of screws located at each end of a special bridging element

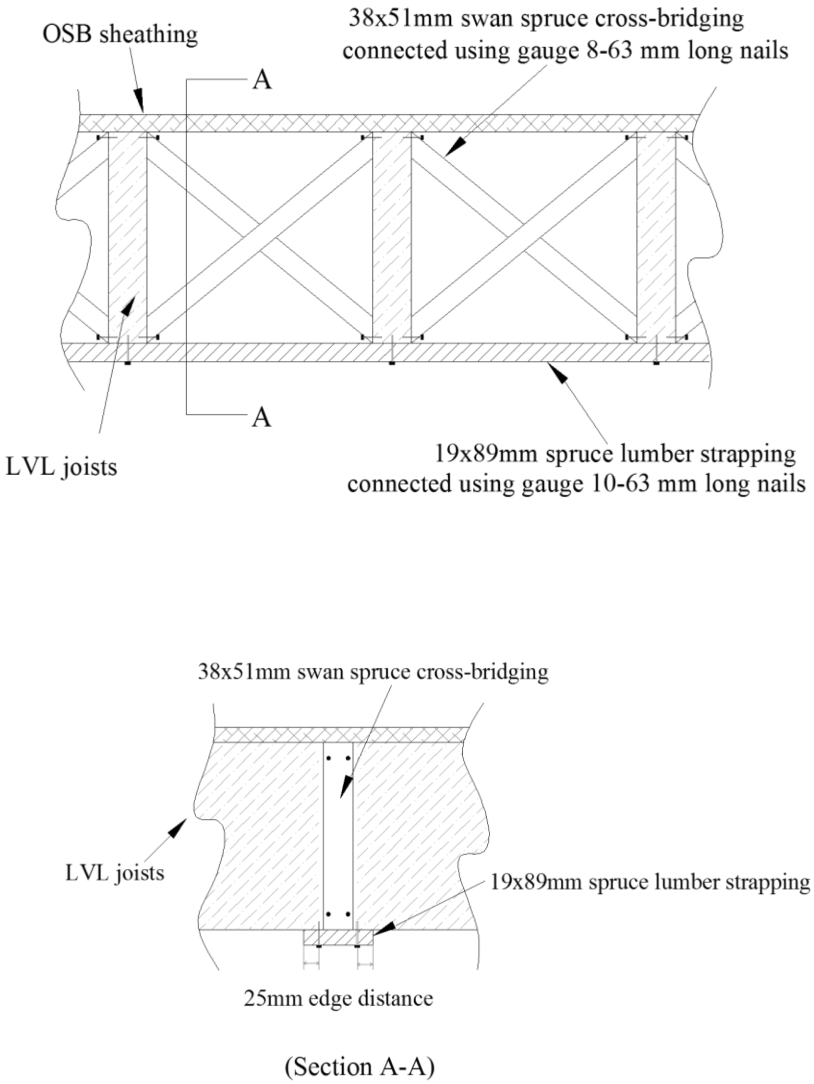


Fig. 4. Cross-bridging plus strapping

Special bridging elements were created in a manner that allowed the stiffness of the joints between LVL blocking elements and joists to be changed by altering the number of screws attaching blocking elements to aluminum brackets. A total of eight aluminum brackets were employed for each blocking element, with four located on either face as shown in Fig. 5. The number of screws per bracket ranged from 1 to 13 (i.e. 1, 3, 5, 8 or 13). Additional tests were performed using both 13 screws and epoxy resin to attach blocking pieces to brackets resulting in approximately rigid blocking to joist connections.

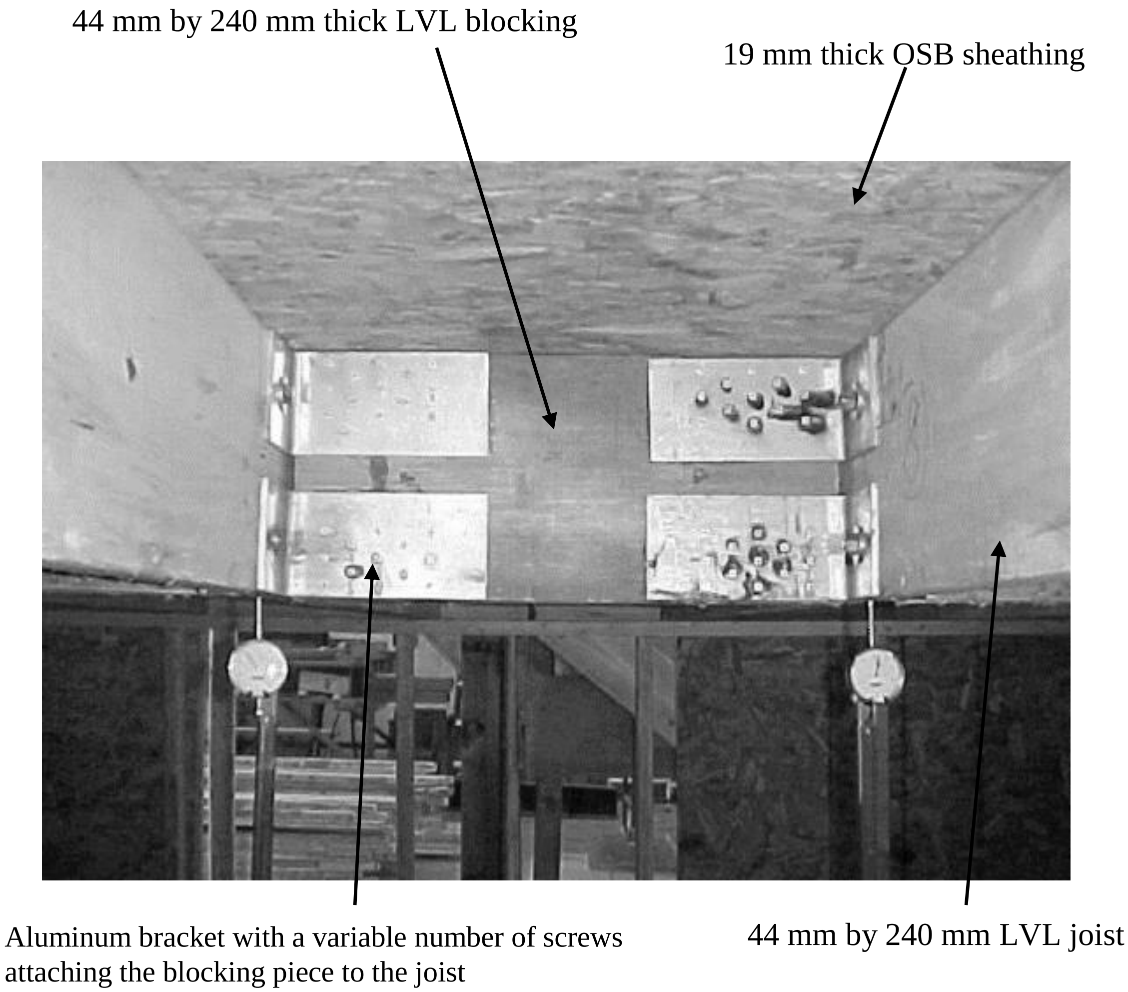


Fig. 5. Example of a special bridging element

For the floor arrangements shown in Table 1, the joists and subfloor were the same. The only difference was in the bridging details stated. For each floor d_1 was measured by applying a 1 kN concentrated load to the floor surface above the central joist at its mid-span, following the procedure by Onysko [1]. Hammer impact modal testing was performed on each floor arrangement to determine its vibration natural frequencies without any additional mass. Following the test procedure by Smith and Chui [5], each floor was excited by an instrumented hammer at a location that would excite the first five vibration modes. The vibration responses were measured by an accelerometer at mid-span and quarter points of each floor joist to allow the mode shapes to be constructed to confirm the mode number. The impact force and acceleration signals were analysed by a spectrum analsyer to determine the natural frequencies and mode shape displacements. Damping ratios were also calculated but the results showed no sensitivity to bridging details, hence they are not discussed in the paper.

2.2. Testing to measure flexural rigidity of transverse bridging spines

Tests were conducted to quantify the flexural rigidity of transverse bridging spines that used in the floor. Under the test procedure, assemblies consisting of two bridging elements and three LVL joist segments were loaded in three-point bending, Figs. 6 and 7. For special bridging spines, two 44mm by 240mm LVL block elements of 610 length were used. Solid blocking elements were 38 mm by 240 mm and cross-bridging were comprised of two pieces of 38 mm by 51 mm sawn spruce lumber with and without 19 mm by 89 mm spruce board strapping. The bridging elements were connected to LVL joist segments by adopting the same connection configuration that was used in the floor tests. In the test method, the load was increased gradually using a cross-head displacement speed of 1.5 mm/min, with the maximum value of P being between 1 and 4 kN depending on the flexibility of the test specimen. That test permitted measurement of the effective flexural rigidity, EI_b, of an equivalent spine comprising a number of bridging elements. Equation (3) was used to calculate EI_b as a function of rotational stiffness, k_r, and joist spacing, J_{sp}, with the former estimated from test data using Equation (4).

$$EI_b = k_r\, J_{sp} \tag{3}$$

$$k_r = \Delta P\, \left(\frac{\Delta\delta}{\Delta\theta}\right) \tag{4}$$

where $\Delta\delta/\Delta\theta$ is the slope of the plot of the vertical displacement at mid-span (δ) versus average rotation at the supports (θ), and ΔP is the increment in applied load corresponding to the slope calculation. The complete derivation of Equations (3) and (4) is given in Khokhar and Chui [24]. Taking account of both δ and θ in Equation (3) permits the inclusion of effects of all deformation components, including bending, shear and axial displacements in bridging elements and slip in bridging element connections in the effective flexural rigidity, EI_b.

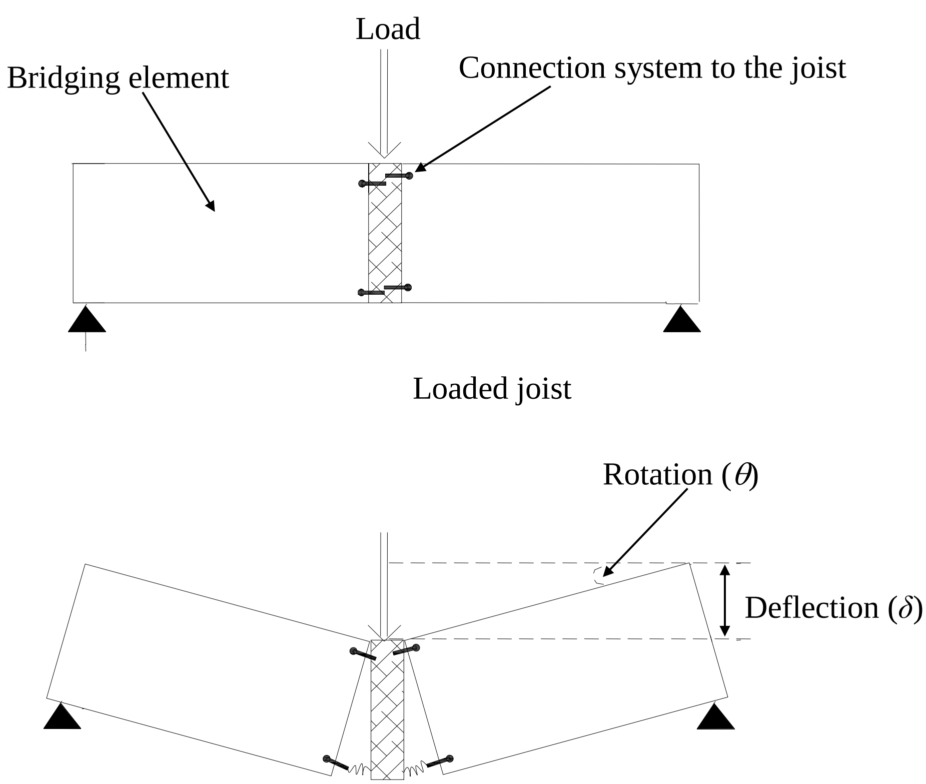
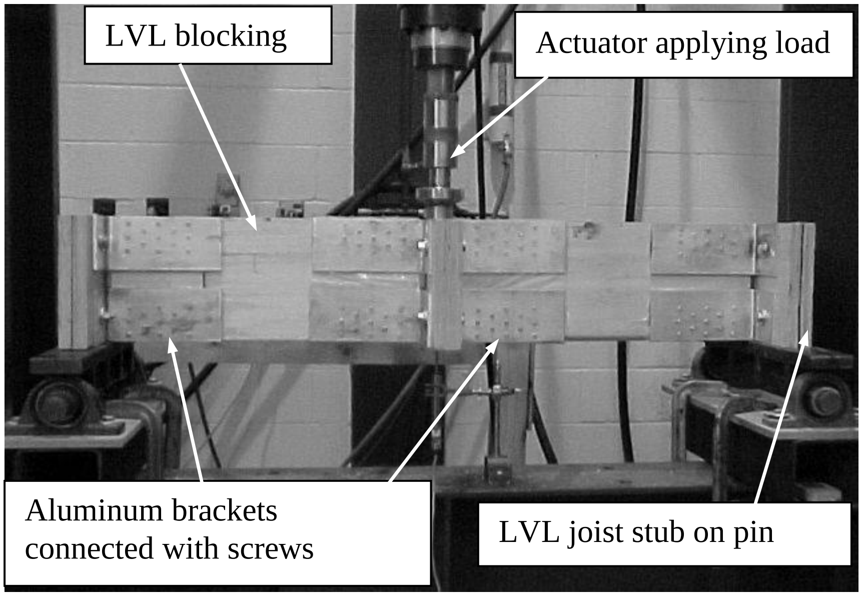
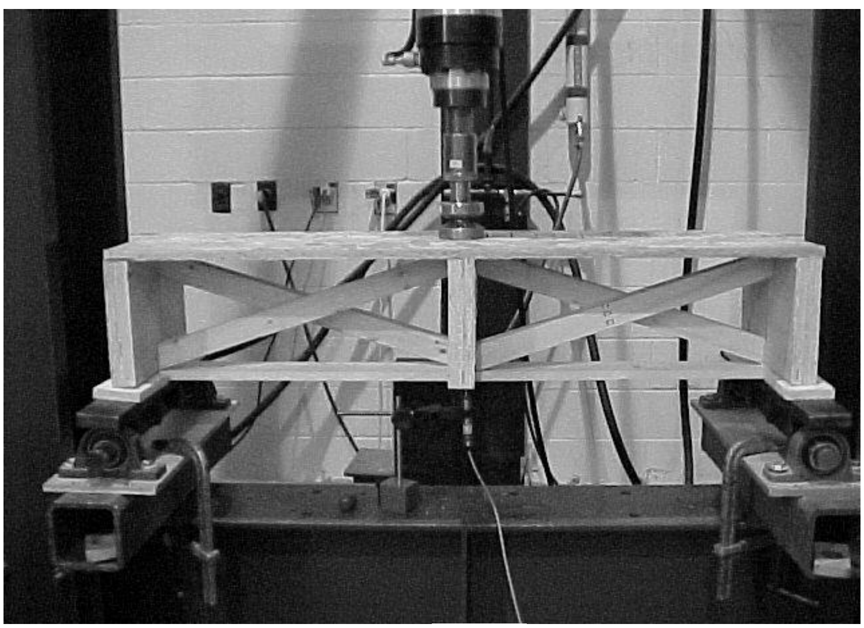


Fig. 6. Scheme of an isolated bridging element test arrangement



(a)



(b)

Fig. 7. Test set up (a) special bridging element (b) cross-bridging with strapping

3. Results and Discussion

Table 1 summarizes the measured d_1 for EI_b values ranging from 0 to 110 kNm^2, with the limiting EI_b values corresponding to the null situation of no bridging spines and the extreme of bridging elements rigidly connected to joists. The common situations of cross-bridging or blocking elements attached to joists using screws or nails, respectively, corresponded to effective flexural rigidities in the order of half the upper limit value (i.e. 45 and 57 kNm^2 respectively). Cross-bridging with strapping resulted in an EI_b of 91 kNm^2, demonstrating the practicality of constructing stiff bridging element spines. It is reasonable to speculate other construction details that result in provision of a tension resistance on undersides of joists in the across-span direction (e.g. addition of plasterboard ceiling) similarly improves effectiveness of bridging elements.

As expected, Table 1 shows that d_1 values decrease when EI_b is increased. For the particular floor layout the relationship between d_1 and EI_b is very close to linear as shown in Fig. 8.

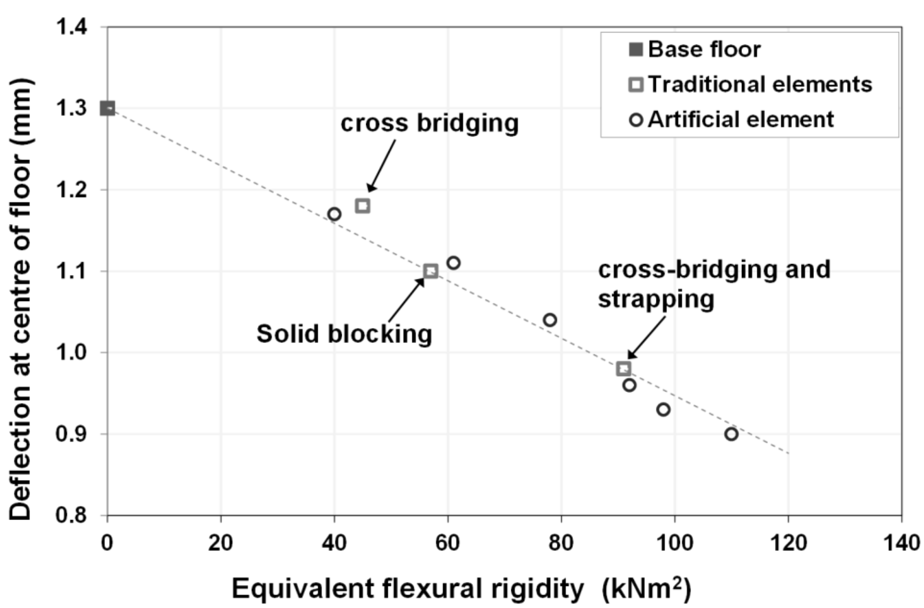


Fig. 8. Static deflection under 1 kN load at center of floor versus effective flexural rigidity of bridging

This means that when a concentrated load is placed at the centre of a floor, stiffness contributions of joists acting compositely with semi-rigidly attached OSB sheathing and a bridging element spine located at mid-span were sensibly linearly additive. From a structural mechanics perspective, this means that the stiffness of the subfloor was relatively negligible. However, departures from that will most likely be associated with situations where a thick subfloor is used.

Table 2 summarizes the first five vertical vibration natural frequencies (f_i, i = 1,.., 5) of each floor arrangement. The mode shape was also extracted from modal testing data to confirm the mode numbers [9]. As the raw results show, there was no consistent positive influence of bridging elements on f_1, except for the floor system having cross-bridging and strapping. This was because in all, except the cross-bridging/strapping case, the decrease in frequency caused by mass of bridging elements roughly cancel out the increase due to increased floor stiffness. Similar results have been reported previously [2]. Fig. 9 shows the relationship between EI_b and the ratios of f_1 values for other floor arrangements to f_1 for the baseline condition of no bridging elements. Cases where the ratio is less than 1.0 are ones where modal mass effect is stronger than the modal stiffness effect, and the opposite is true when the ratio is greater than 1.

Past studies have suggested that simplified design analysis methods, like using effective stiffness and mass for an isolated joist, result in estimates of f_1 that are within 10 percent of test values [5,18]. It can therefore be considered reasonable to use such simplified estimates during application of contemporary vibration serviceability design criteria. Results here suggest that in many instances simply using the baseline condition of no bridging elements installed would often lead to an acceptable estimate of f_1 irrespective of what type of bridging element spines floors have. Although suggesting appropriate design practices for vibration serviceability of lightweight wood joisted floors is not the primary purpose of this paper, it is clear from the test results that for floors similar to those investigated design criteria employing only d_1 and f_1 can be applied with reasonable precision without need for complex supporting structural analysis.

Table 2. Free vertical vibration frequencies of floors with and without a bridging element spine

Type of bridging elements	Equivalent beam flexural rigidity, EI_b (kNm^2)	Natural frequency (Hz)				
		f1	f2	f3	f4	f5
Baseline floor [a]	0	20.8	25.8	32.4	37.8	45.8
Solid blocking	47	20.5	30.9	44.5	55.6	66.5
Cross-bridging	55	20.5	29.0	40.8	53.3	64.5
Cross-bridging with strapping	91	21.8	32.7	43.5	58.0	70.0
Modified Baseline floor [b]	0	18.8	23.1	28.4	33.4	39.6
Special - 1 screw [c]	40	19.3	27.4	40.0	53.2	66.0
Special - 3 screws	61	19.4	28.6	41.4	54.2	67.7
Special - 5 screws	78	19.5	29.2	42.0	54.8	67.3
Special - 8 screws	92	19.6	29.3	42.4	55.2	68.0
Special - 13 screws	98	19.9	30.2	42.7	56.0	69.2
Special - 13 screws + Adhesive	110	20.5	30.2	43.0	56.0	70.0

[a] Floor tested without addition of any bridging elements.
[b] Floor tested without addition of any bridging spines, but with addition of aluminum brackets to which special bridging elements were fixed.
[c] Number of screws located either side at each end of special bridging elements.

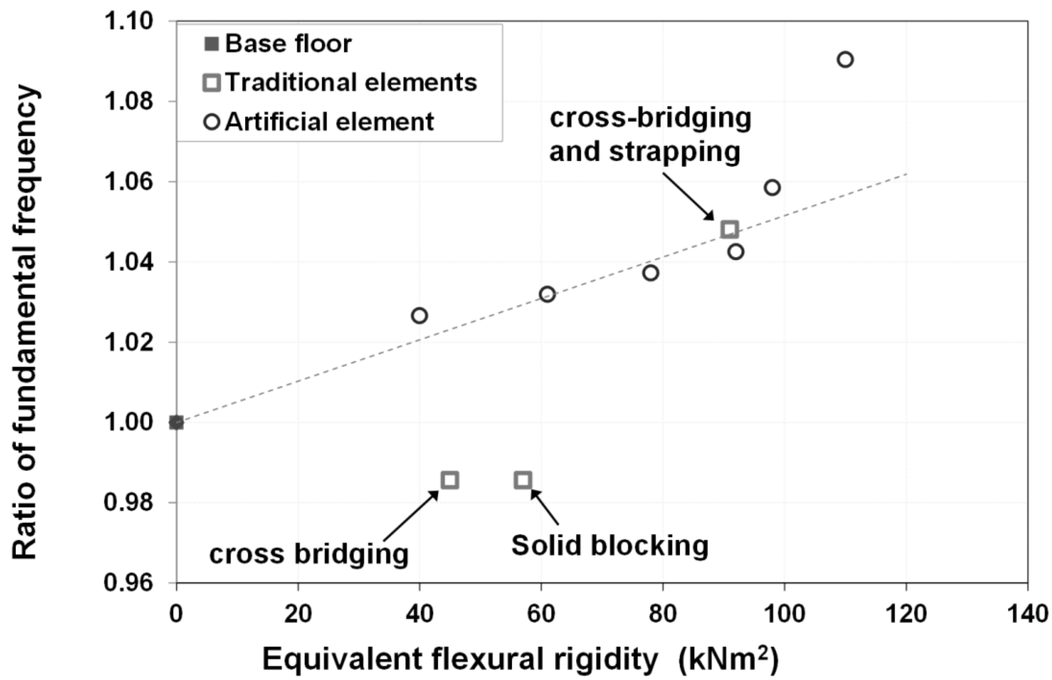


Fig. 9.

Effect of effective flexural rigidity of bridging spine on fundamental natural frequencies of floors (normalized to that of floor system without bridging spine)

Addition of bridging element spines positively impacted natural frequencies other than f_1 in the sense that it increased values f_2 to f_5 including increasing separations between adjacent modal frequencies, as seen in Table 2. As already discussed, it is well known that this is desirable in terms of how it effects building occupant ratings of performances of wood joisted floors [1,3,7]. However, as has also been extensively reported, accurate prediction of natural frequencies other than f_1 can be difficult and impractical to obtain for normal engineering design [2,19]. Consequently, it is generally more reliable, in terms of calculation efficiency, to use f_1 and d_1 as vibrational serviceability design for lightweight wood joisted floors [25]. It should be noted that f_1 is largely controlled by along-joist floor system stiffness and mass, whereas d_1 is influenced by floor system stiffnesses in the major and minor directions. Therefore d_1 would be reduced and modal separation increased by any increase in stiffness properties of bridging elements. The results in Tables 1 and 2 clearly show that d_1 can be used to effectively control modal separation as a design parameter.

4. Conclusions

The overarching finding of the reported study is that it is advantageous to incorporate between-joist bridging elements as a method of improving dynamic performance of lightweight wood joisted floors, with the main reason being that it increases mode spacing which has the benefits of reducing modal interaction and number of dominant vibration modes that can be excited.

In summary, new findings are:

- Irrespective of the type of bridging elements used, incorporating a spine(s) of bridging elements in wood joisted floors improves their vibration performance.
- The fundamental vertical natural frequencies of floors similar to those tested are weakly related the flexural rigidity of bridging element spines.
- Effective flexural rigidity of transverse bridging spines can be a practical basis for estimating the static displacement of floor systems containing such spines. It follows that vibration serviceability design criteria based on estimation of static displacements can be implemented in relatively simple ways for lightweight wood joisted floors.
- It is feasible for design guidelines to classify relative effectiveness of alternative types of bridging elements in simple ways. For example, using cross-bridging or solid blocking could be classified as satisfactory methods for most situations, and using cross-bridging and strapping attached to undersides of joists could be classified as effective in all situations.

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