

INFLUENCE OF STIFFNESS OF BETWEEN-JOISTS BRACING ON VIBRATIONAL SERVICEABILITY OF WOOD FLOORS

Aamir Khokhar¹, Ying Chui², Ian Smith³

ABSTRACT: Installing joist bracing consisting of components like solid blocking or cross-bridging elements can be an economical and effective means of mitigating vibration levels associated with unserviceable lightweight joisted wood floors. Effectiveness of different joist bracing methods depends on the location, geometric arrangement and stiffness of installed bracing elements. This paper presents an experimental investigation of how the equivalent flexural rigidities of joist bracings methods correlate with engineering parameters used in serviceability design of lightweight floors. Engineering parameters addressed are vertical deflection due to a central concentration static load, and low order natural vertical natural frequencies. Results show that the equivalent flexural rigidity of joist bracing correlates with static deflection of floors and natural frequencies. However, despite stiffening floors in the across-joists direction the extra mass of joist bracing elements can cause reduction in their fundamental natural frequencies. A method of determining the equivalent flexural rigidities of alternative joist bracing methods is demonstrated.

KEYWORDS: Bracing elements, Floors, Natural frequencies, Static deflection, Vibration serviceability, Wood

1 INTRODUCTION

Traditional wood floor systems are composed of a series of parallel joist members which support a mechanically semi-rigidly attached structural subfloor, and often other flooring layers, Figure 1. This produces quite lightweight rib stiffened plate arrangements that commonly have discontinuities in the plate layer(s) associated with the choice of subflooring and flooring layers. In relatively recent times (circa post 1960's) the norm in North America has been to use wood-based sheathing materials as subfloor layers, in combination with joists of various types. Today wood joist materials include sawn lumber, engineered wood composite materials, I-joists, and open-web joists. Strength of joists tends not to be the dominant issue in applications that encompass residential and some commercial building occupancy situations. The issues of concern more commonly are static deflection behaviour of floors under gravity loads, and the vertical serviceability vibration responses of floors [1].

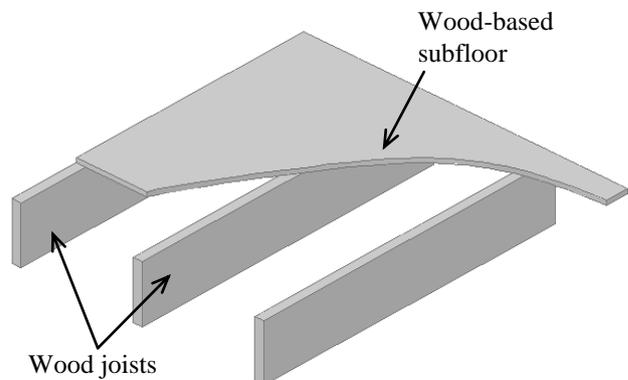


Figure 1 Joisted wood floor without joist bracing elements

Parallel arranged joists have a one way rib stiffening effect on floors, orthotropic characteristics and discontinuities in subfloor and flooring materials, methods of attaching subflooring to joists, and choice of flooring support methods and locations, usually combine to make static and dynamic responses of joisted wood floors very complex. It is therefore difficult to control the behaviours of floors using prescriptive construction practices or simple engineering design methods. Opinion surveys have been conducted to identify vibration response parameters that correlate with acceptability of floor vibration responses to building occupants. Such surveys have suggested that static deflection under a concentrated load applied at the centres of floors

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correlates building occupant perceptions of acceptability of various floors [2-4]. Similarly, various opinion surveys have suggested that building occupant satisfaction correlates quite well with fundamental natural frequencies of floors [2-4]. Sometime studies have also investigated correlation of satisfaction ratings with separation intervals between natural frequencies of low order vertical vibration modes of floors [3,5,6].

Building occupant opinion surveys reflect subjective everyday experiences of respondents of how well floors in buildings they occupied performed. In other cases opinions were pseudo occupant opinions based on short-term assessment of serviceability of specially built floors under controlled or uncontrolled laboratory conditions. In all cases researchers made measurements to determine floor characteristics like vertical deflection under a concentrated gravity load and the vertical fundamental natural frequency. Post-survey analyses of occupant opinions have suggested that the parameters vertical deflection under a concentrated gravity load and the vertical fundamental natural frequency are quantitative measurements that can be used to discriminate between floors that have acceptable serviceability performance, and floors that are unacceptable in that respect. By extrapolation it has been suggested that engineers can use static deflections and fundamental natural frequency predictions to screen out floor design solutions that would potentially result in unacceptable vibration performance. Consequently, a number of design criteria and methods have been proposed based on separate or combined application of static deflection and natural frequency responses of floors [4,6,7]. However, acceptance of such criteria and methods is controversial, because of the subjective nature of correlations on which those methods are based and the empirical nature of parameter values suggested as defining the boundary between satisfactory and unsatisfactory floor performance. The upshot is that unresolved debate recognises that control of certain floor response characteristics is desirable and engineering design methods have a role to play in that, but exactly how engineers should apply the knowledge is unresolved.

The philosophical approach that underpinned the research described here was to assume that at some point protagonists will resolve the issue of how to make generalised vibration serviceability calculations that are robust across at least wide classes of floor types and specific building occupancy classifications. It was further assumed that when that stage of agreement is reached, irrespective of the specifics of the agreed practices, there will be need for mechanics based engineering calculation methods that determine how construction variable influence key floor response parameters.

The remainder of this paper addresses an experimental investigation that determined if there exist unambiguous relationships between vertical static deflection responses and fundamental vertical natural frequencies of lightweight joisted wood floors and the equivalent

flexural rigidities of between-joist bracing systems. This reflects that various past studies have concluded that such relationships exist [2,3,5,8-14]. However, those studies did not quantify the reliability of relationships or define how engineers can determine equivalent flexural rigidities of various joist bracing methods.

2 JOIST BRACING METHODS

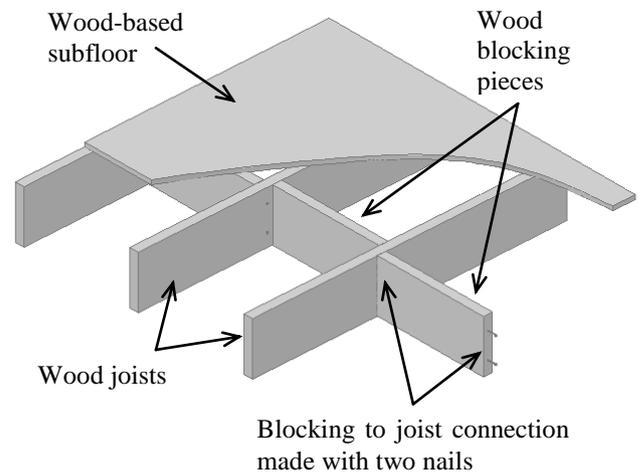


Figure 2: Between-joists solid blocking method

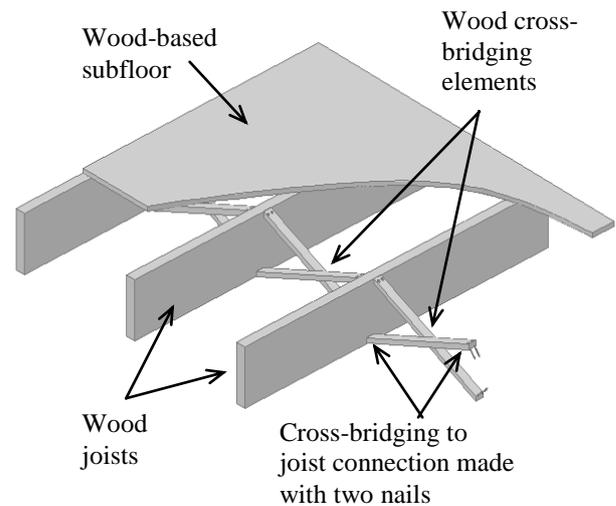


Figure 3: Between-joists cross bridging method

There are various methods of bracing joists in wood floors. In all cases the primary objectives of incorporating joist bracing elements are: to keep joists in place and laterally separated so that they properly perform as rib stiffeners to floor plates; to prevent lateral instability of joists; and in some cases to prevent warping of joist cross-sections. Relative to vibration serviceability the most important of those objectives is ensuring that joists act properly as rib stiffeners. The other two objectives are related to maximising floor capacities and avoiding undesirable modes of failure at overload. The minimum requirement for bracing floor joists is that there be bracing provided at the ends of joists, at locations of intermediate joist support when joists are continuous across adjacent span, and at

locations of concentrated vertical load transfers to floors (e.g. at locations where floors support columns). Normally adherence to these minimum requirements is a mandated prescriptive requirement of design codes. When floor joist span to depth ratios are relatively large and/or if joists are of types prone to instability or warping (e.g. rectangular cross-sections with large depth to width ratios, wood I-joists) additional joist bracing is incorporated, and can be a mandated requirement of timber design codes [e.g. 15]. Figures 2 to 4 show examples of joist bracing methods commonly employed for making across-joists bracing at locations other than ends of joists. The focus here is on that particular class of bracing elements because those are the ones over which designers have discretion that directly relate to vibrational serviceability of floors. The between-joists solid blocking and some other methods are suitable used to brace joists at their ends, or other locations where joists are supported.

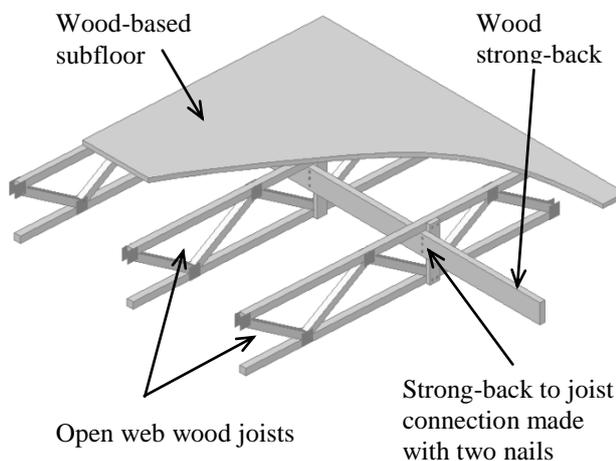


Figure 4: Strong-back method

3 TEST PROGRAMME

An experimental test programme was designed to:

- Clearly articulate presence of absence of a relationship between the engineering characteristics of joist bracing methods and elements, and engineering parameters related vibration serviceability of wood floors.
- Create data than can be directly used to verify and provide input data for numerical models for predicting static vertical deflection and natural vertical vibration responses of wood floors.

A number of numerical static deflection and modal frequency prediction models have been reported in the literature [e.g. 10,16-18], or could be built using commercial software packages that employ the finite element approximation or other well-known structural engineering methods. In existing and prospective models arrangements of joist bracing elements are/could be characterised as equivalent beam bending elements having flexural rigidities, EI_b , values representative of particular joist bracing methods.

Scope of the test programme was tests on full-size floor systems with rectangular cross-section wood joists, and tests on isolated arrangements of bracing elements.

3.1 TESTS ON FLOOR SYSTEMS

The approach taken was to construct a full-size floor with only bracing at ends of joists under laboratory conditions, and sequentially alter that floor to incorporate various mid-span joist bracing methods. Static displacement and modal responses of the unaltered floor (i.e. without any mid-span joist bracing) were the reference/base conditions for quantifying effects of added bracing. The approach was taken to eliminate the possibility of extraneous influences on observed effects of alterations. Sequencing of alterations was done so that modifications did not damaged the floor at any intermediate stage, and loading levels were always well below those required to cause damage. Thus, all observations were in the elastic response range. Also to minimize extraneous influences on observations, the selected joist material was Laminated Veneer Lumber (LVL) which is a wood-based product that is more dimensionally stable and less variable in its physical and mechanical properties than sawn lumber.

The base floor arrangement was as shown in Figure 5. LVL blocking pieces inserted between ends of joists brace the joist at their ends, Figure 6. The joists had the cross-section dimension 45 mm × 241 mm. Subflooring was 19 mm thick tongue-and-grooved Oriented Strand-Board (OSB) sheathing panels oriented with their stiff axes in the across-joists direction. The jointing pattern between sheathing panels and spacing of fasteners that attached them to joists was typical of North American practice.

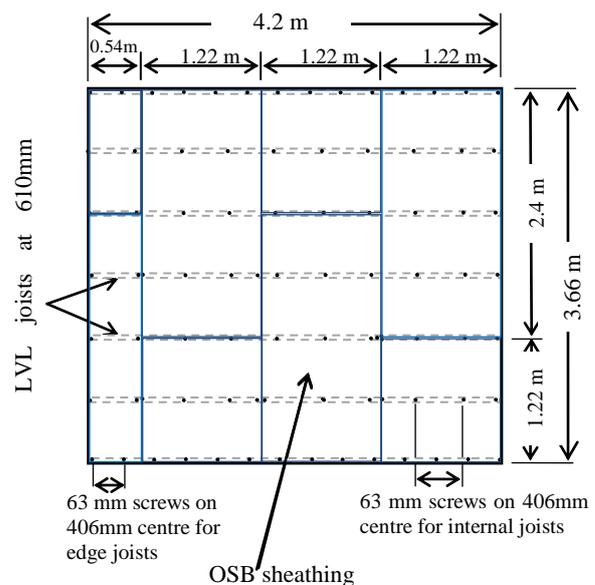


Figure 5: Plan view of floor layout without joist bracing

All four floor edges were supported throughout their length by a short light-frame wall, as shown in Figure 7 and 7. Perforations in the walls allowed access to the underside of the floor for making alteration to joist

bracing, and for measurement of static deflection responses. The overall test arrangement was representative of what is commonly referred to as light-frame platform construction, which is the dominant method for low-rise buildings in North America. Also to note is that supporting floor systems on all four edges maximized the influence of mid-span joist bracing on the floor response characteristics of primary interest. This minimized the possibility of arriving at ambiguous cause and effect results.

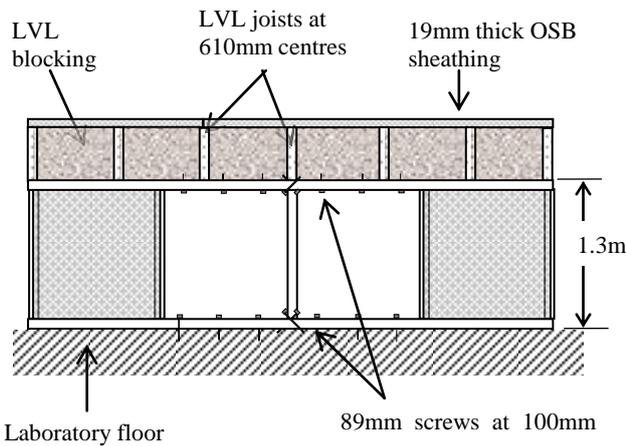


Figure 6: End (across-joists) end elevation of test floors

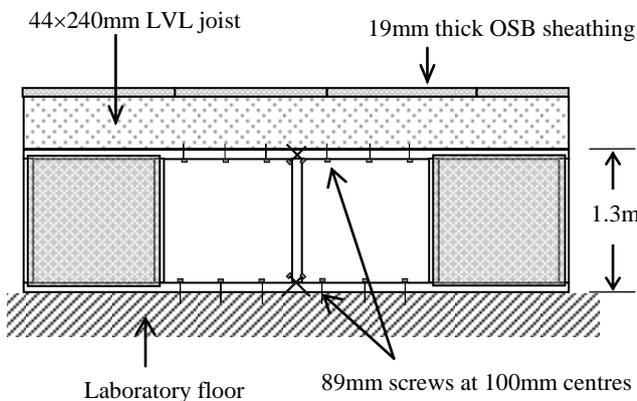


Figure 7: Side (along-joists) elevation of test floors

The floor was first tested without mid-span bracing elements installed (base floor system). Alterations that followed utilized traditional joist bracing methods, and a special bracing method (subsequently referred to here as ‘artificial’ bracing). The traditional methods investigated were cross-bridging (Figure 3), solid blocking (Figure 2), and cross-bridging plus a bottom wood strapping (see Section 3.2, Figure 12). The artificial bracing method is shown in Figure 8.

Using the artificial joist bracing method it was possible to vary the equivalent flexural rigidity of a line of between-joists bracing elements by changing the number of screws attaching the aluminium brackets in blocking piece-to-joist connections. The number of screws attaching blocking pieces was varied from 1 to 13 per

aluminium bracket. Note: there were brackets ‘front and back’ of blocking piece. After conclusion of other alterations, the stiffness of the artificial bracing method with 13 screws per bracket was supplemented by bonding blocking pieces to the underside of the subflooring. That final alteration resulted in a joist bracing method nominally equitable to the maximum achievable equivalent EI_b .

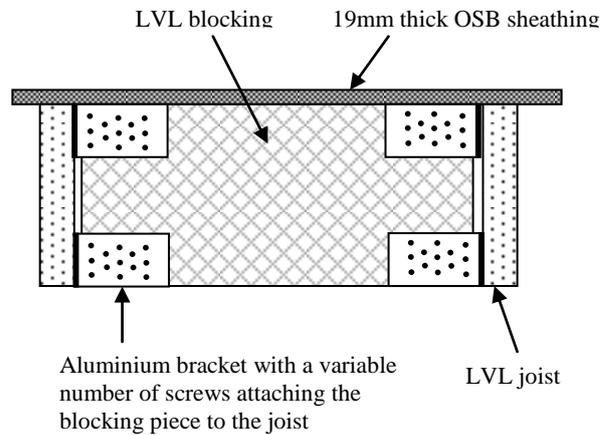


Figure 8: Artificial joist bracing method

Static vertical deflection responses of systems were determined by placing a 1 kN concentrated load at the floor centre (Figure 9) and measure the deflection at mid-span of each joist (Figure 10). Modal vibration tests were conducted to determine the several lowest vertical natural frequencies of each floor system, based on the free their vibration responses caused by hammer impacts.

3.2 TESTS ON ISOLATED ARRANGEMENTS OF BRACING ELEMENTS

As shown by Khokhar [10], EI_b of any particular joist bracing method can be defined as the product of an effective rotational spring stiffness term K_r and joist spacing J_{sp} , equation (1). The K_r is measure using test setups like those in Figures 11 and 12. The effective spring stiffness term reflects the rigidity of the bridging element(s), the arrangement of bracing element(s), and rigidity of any connections between bracing elements, and rigidity of connection between bracing elements and joists.

$$EI_b = K_r \times J_{sp} \quad (1)$$

The types of joist bracing methods investigated by testing isolated arrangements of bracing elements corresponded to the types incorporated into full-size floor systems (Section 3.1). Such tests were replicated five times for each bracing method so that average load versus deformation responses, from which estimates of K_r were determined, would reflect the averaging effect of responses of individual between-joists bracing elements that occurs in a floor.



Figure 9: 1 kN load at centre of floor



Figure 10: Dial gauges for measuring mid-span deflections of joists

4 RESULT AND DISCUSSION

Table 1 summarises static deflection test results for full-size floor arrangements, and the equivalent EI_b values derived from isolated arrangements of bracing elements tests and equation (1). As those values show, there is a clear inverse relationship between the equivalent flexural rigidity of joist bracing methods and the static deflection at the centre of any floor, irrespective of the specifics of the employed bracing method. That relationship is presented graphically in Figure 13

It is to be noted that for the types of floor arrangements investigated, cross-bridging alone was the least effective

and cross-bridging with strapping the most effective amongst the three types of traditional joist bracing methods studied. Comparison of the static deflection behaviour of floors with traditional and artificial joist bracing methods suggests that cross-bridging with strapping approaches is the only traditional method that is close to being able to optimize the across-joists stiffness performance of joisted wood floors.

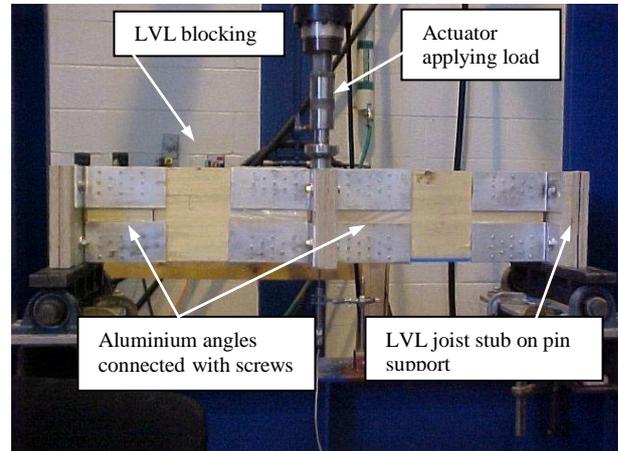


Figure 6: Setup for testing artificial bracing elements

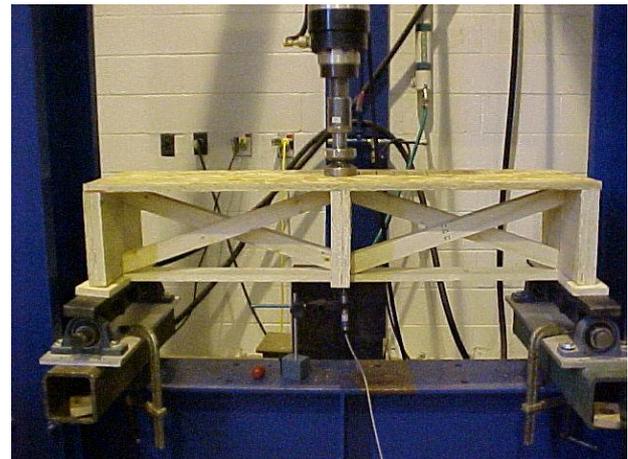


Figure 7: Setup for testing cross-bridging with strapping

The linearity of the relationship between EI_b and static deflection in Figure 13 reflects that the load and deflection measurements were located at the centres of floor systems, and that joists were braced at mid-span. Were load or the displacement response to it to be at other locations, and if the joists were braced differently, the relationship would not be linear. This is mentioned to make it clear that use of an engineering parameter like vertical static deflections at the centre of a floor due to a concentrated force of 1 kN is only indicative of the general effect of joist bracing on floor responses, and has no explicit value beyond utilization in a particular floor performance assessment criteria.

Tight clustering of experimental points around the straight line relationship in Figure 13 indicates that (for floors with construction characteristics similar to those

of the tested arrangements), floors aggregates all features of the joist bracing methods in a manner consistent with using beam element representations of bracing methods in static deflection behaviours models of joisted floors.

Table 1: Vertical static deflections at centres of floors due to a concentrated force of 1 kN

Joist bracing method	Flexural rigidity of bracing, EI_b (kNm^2)	Static deflect'n under 1 kN (mm)	Reduction in deflection, relative to base floor system (%)
Base floor*	0	1.3	0
Cross-bridging	45	1.18	9
Solid blocking	57	1.10	15
Cross-bridging and strapping	91	0.98	25
Artificial – 1 screw**	40	1.17	10
Artificial - 3 screws	61	1.11	15
Artificial - 5 screws	78	1.04	20
Artificial - 8 screws	92	0.96	26
Artificial - 13 screws	98	0.93	28
Artificial - 13 screws + adhesive	110	0.90	31

* Floor without joist bracing.

** Floor without joist bracing elements but with addition of aluminium brackets for artificial lateral elements.

*** Number of screws located at each end of an artificial element.

Table 2 presents the first five vertical natural/modal frequencies (f_i , $i = 1.5$) of the floor systems. Other modal response information like mode shapes and viscous damping ratios extracted from measured floor responses to hammer impacts is reported by Khokhar [10]. As the tabulated results show, there is no consistent positive influence of joist bracing on the fundamental frequency (f_1). With the exception of the case the floor system had cross-bridging and strapping, f_1 values were sensibly unaltered or reduced with the addition of joist bracing. The reason for this was that in all but the one case, addition of bracing elements increased the modal mass more than the modal stiffness. Similar results have been reported previously [6]. Figure 14 shows the relationship between EI_b and the ratio of the f_1 for altered systems to the f_1 of base systems. To note in this respect is that the initial base floor system response is used to assess the proportional effects of traditional bracing methods on f_1 ; but the modified base floor (i.e. no joist bracing elements but with aluminium brackets added) is the reference point for assessing the proportional effects

of artificial bracing methods. This is done so that the figure more clearly indicates that altering the vibration responses of joisted wood floors depends on counteracting influences of addition of elements on mass and stiffness. The influence of bridging construction detailing choices on f_1 is also clear from the different effects of installing cross-bridging alone versus cross-bridging and strapping.

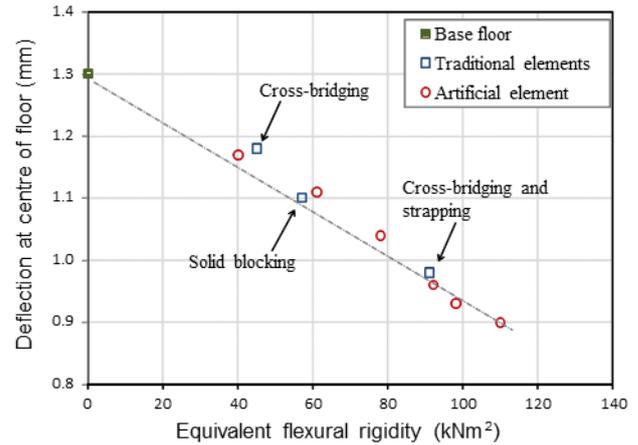


Figure 8: Static deflection at centre of floor versus bracing element flexural rigidity

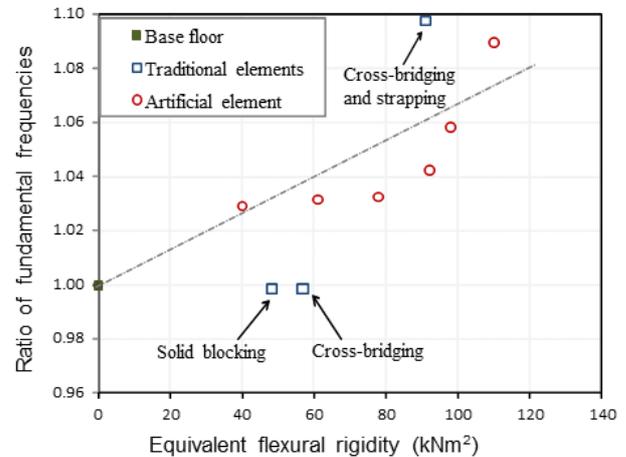


Figure 9: Effect of bracing element flexural rigidity on fundamental free vertical vibration frequencies of floors (based on scaling frequencies to those of floor systems without joist bracing)

As is also demonstrated by results in Table 2, the primary positive impacts on natural frequencies from addition of joist bracing to floors (like those investigated) is that modal frequencies other than fundamental natural frequencies are increased. In the particular cases studied the joist bracing resulted in significantly greater separations of modal frequencies (i.e. differences in magnitudes) which is cited in the literature as a primary positive influence on building occupant perceptions of the serviceability of lightweight wood floors [1-3,7,16]. However, it is to be noted that natural frequencies other than f_1 can only be estimated

reliably by sophisticated numerical models outside the scope of currently normal engineering design practice [16]. This creates a conundrum for designers in the sense that they must use f_1 as an artefact for implying positive influence of joist bracing of frequencies like f_2 to f_5 , knowing that complexities of vibration performance of joisted wood floors make such inferences unreliable. This at least in part explains why there is much noise in opinion survey based deductions in the literature about relationships between floor serviceability performance and possible engineering design criteria (Section 1).

The parenthetic broad finding of the study discussed in this paper is that it is advantageous to incorporate joist bracing as a method of controlling the dynamic responses of lightweight joisted wood floors, because such practice reduce the likelihood of modal clustering which can lead to amplifications of motions experienced by building occupants. However, design advice to designers cannot be prosaically simple, as some investigators have suggested, because the likelihood of modal clustering also depends on other factors including, for example, the plan aspect ratios and shapes of floors.

Table 2: Fundamental and higher vertical natural frequencies of floors with and without a bracing elements

Joist bracing method	EI_b (kN m ²)	Natural frequencies (Hz)				
		f_1	f_2	f_3	f_4	f_5
Base*	0	20.8	25.8	32.4	37.8	45.8
Solid blocking	47	20.8	30.9	44.5	55.6	66.5
Cross bridging	55	20.5	29.0	40.8	53.3	64.5
Cross-bridging and strapping	91	21.8	32.7	43.5	58.0	70.0
Modified base floor**	0	18.8	23.1	28.4	33.4	39.6
Artificial – 1 screw***	40	19.3	27.4	40.0	53.2	66.0
Artificial - 3 screws	61	19.4	28.6	41.4	54.2	67.7
Artificial - 5 screws	78	19.5	29.2	42.0	54.8	67.3
Artificial - 8 screws	92	19.6	29.3	42.4	55.2	68.0
Artificial - 13 screws	98	19.9	30.2	42.7	56.0	69.2
Artificial - 13 screws + adhesive	110	20.5	30.2	43.0	56.0	70.0

* Floor without joist bracing.

** Floor without joist bracing elements but with addition of aluminium brackets for artificial lateral elements.

*** Number of screws located at each end of an artificial element.

It is clear that ideas related to combined consideration of the static deflection and fundamental natural frequency as parameters controlling vibration serviceability are

likely militate towards construction of better wood floors. Yet this does not translate to the expectation that particular design criteria related to those parameters can have any universal validity, because those parameters are not the only ones that will be important in many instances. It is for this reason that this paper has the simple purposes of adding a degree of clarification on mechanical effects joist bracing methods have for a particular type of floor system, and demonstrating equivalent flexural rigidity is a viable way of quantifying the characteristic mechanical behaviours of between-joists bracing methods.

5 CONCLUSIONS

The following conclusions derive from the experimental study reported here:

1. Equivalent flexural rigidity of between-joists bracing methods is a reliable indicator of effects that different methods have on static deflections of lightweight joisted wood floors.
2. The method reported here for characterising the equivalent flexural rigidities of joist bracing methods for lightweight joisted wood floors is reliable.
3. It should not be assumed that all traditional or novel joist bracing methods will have positive effects on (i.e. increase) vertical fundamental natural frequencies of lightweight joisted wood floors. However, adoption of traditional, and potentially other, joist bracing methods can increase higher modal frequencies of such floors.
4. For the type of lightweight wood floor systems investigated traditional cross-bridging combined with strapping to the undersides of joists is the most effective practical methods of bracing joists.

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REFERENCES

- [1] I. Smith: Vibration of timber floors - serviceability aspects. *In: Timber Engineering*, John Wiley and Sons, Chichester, England, 241-266, 2003.
- [2] Onysko, D. M.: Serviceability criteria for residential floors based on a field study of consumer response”, *Project Report 03-50-10-008*, Forintek Canada Corp, Ottawa, ON, Canada, 1985.
- [3] Ohlsson, S. V.: Springiness and human induced floor vibration: A design guide. *Document No. D 12-1988*, Sweden Council for Building Research, Stockholm, Sweden, 1988.
- [4] Hu L. J.: Serviceability design criteria for commercial and multi-family floors. *Canadian*

Forest Service Report No. 4, Forintek Canada Corp, Sainte-Foy, Q.C., Canada, 2000.

of World Conference on Timber Engineering, Shah Alam, Malaysia, 2002 (On CD-Rom).

- [5] Chui, Y. H.: Evaluation of vibrational performance of light-weight wooden floors: Determination of effects of changes in construction variables on vibrational characteristics. *Research Report No. 2/86*, Timber Research and Development Association (TRADA), High Wycombe, UK, 1986..
- [6] Chui, Y. H.: Vibrational performance of wooden floors in domestic dwellings. *PhD Thesis*, Brighton Polytechnic, Brighton, UK, 1987.
- [7] Dolan, J. D., Murray, T. M., Johnson J. R., Runte, D. and Shue, B.C. Preventing annoying wood floor vibration. *J. of Structural Eng.*, ASCE, 125(1):19-24, 1999.
- [8] Hu, L. J., Chui, Y. H. and Onysko, D. M.: Vibration serviceability of timber floors in residential constructions. *Progress in Structural Engineering and Materials*, 3(3):228-237, 2000.
- [9] Smith, I. and Chui, Y. H. Construction methods for minimizing vibration levels in floor with lumber joists. *Canadian J. of Civil Eng.*, (19): 833-841,1992.
- [10] Khokhar, A. M.: Influence of bracing stiffness on performance of wooden floors. *MScFE Thesis*, University of New Brunswick, Fredericton, NB, Canada, 2004.
- [11] Colville, J., Angleton, H. D., Snodgrass, D., King, J. M.: Bridging in residential floor construction. *Report No. LR-6*, National Association of Home Builders Research Institute Laboratory, Rockville, Maryland, USA,1961.
- [12] Onysko, D. M. and Jessome, A. P.: Effectiveness of various bridging methods. *Information Report OP-X-51*, Eastern Forest Products Laboratory, Ottawa, ON, Canada,1973.
- [13] Chui, Y. H.: Use of conventional cross-bridging in wood I-joist floors. *Final Report to Canada Mortgage and Housing Corporation*, University of New Brunswick, Fredericton, Canada,1999.
- [14] Stark, J. W.: The effect of lateral bracing on dynamic response of wood floor system. *MSc Thesis*, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA,1993.
- [15] Canadian Standards Association: Engineering design in wood. *Standard 086-09*, CSA, Toronto, Canada, 2009.
- [16] Smith, I. and Hu, L.J.: Prediction of vibration serviceability of ribbed plates by modal synthesis, International Colloquium on Structural Serviceability of Buildings, Göteborg, Sweden, June 8-11, International Association for Bridge and Structural Engineering, *Report 69*: 243-250, IABSE, Bern, Switzerland, 1993.
- [17] Chui, Y. H. Application of ribbed-plate theory to predict vibrational serviceability of timber floor systems. *Proceedings of World Conference on Timber Engineering*. Shah Alam, Malaysia, 2002.
- [18] Hu, L. J., Chui, Y. H. and Jiang, L. Verification of a finite element model for wood-based floor structures with lateral reinforcements. *Proceedings*