WORLD CONFERENCE ON TIMBER ENGINEERING 2025
BRISBANE, AUSTRALIA
Advancing Timber for the Future Built Environment

AN INVESTIGATION INTO THE INFLUENCE OF TRANSVERSE BRIDGING SPINES ON THE VIBRATIONAL PERFORMANCE OF TIMBER FLOORS

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ABSTRACT: Adding bridging elements between joists that form transverse bridging spines is an effective method for minimising excessive vibration levels in wood floors, which are associated with human discomfort. The effectiveness of a bridging spine depends on its flexural rigidity, which accounts for both the bridging element rigidity and its connection mechanism to the joist. This paper presents an experimental study conducted to quantify a broad range of flexural rigidities of bridging spines. A ribbed-plate model, which requires the spine flexural rigidity as an input, was used to predict static deflection and the fundamental natural frequency of a timber floor. The results indicate that increasing the bridging flexural rigidity can reduce static deflection by up to 40%. However, it was found that all types of transverse bridging spines have a minimal influence on the fundamental natural frequency.

KEYWORDS: Wood I-joist, Bridging elements, Rotational Stiffness, Static Deflection, Fundamental Natural Frequency.

1 – INTRODUCTION

Traditional wood floor systems are composed of a series of parallel timber joists overlaid by wood-based sub-flooring, which is mechanically semi-rigidly connected to the joists in a perpendicular direction, as shown in *Figure 2*. Wood-based sheathings, such as particleboard, oriented strand boards (OSB) or plywood, most often act as the flooring. While, wooden joist members, including solid-sawn wood, open-web joists or engineered wood I-joists, which are commonly used for residential timber frame construction. Due to structural composition, wood floors behave as a light-weight rib-stiffened plate system that has discontinuities in the sub-flooring, which produces an orthotropic system with a stiffness along-joists that is much higher than across-joists direction.

Wood floor structures have been proven to be strong and stiff enough to meet ultimate and serviceability requirements. However, due to their lightweight nature and orthotropic behaviour, they have a tendency to produce amplified vibration motions when subjected to human footfalls or similar impacts on floor surfaces. Such amplified motion results from closely spaced or clustered natural frequencies and is strongly influenced by the across-joist construction details and the ratio of floor width to joist span. When such amplifications occur, they can cause a serviceability problem, leading to human discomfort.

Several research studies have been conducted to identify vibration response parameters that correlate with human acceptability to floor vibration. Static deflection under a point load at the floor centre has been found to be a reliable indicator for vibrational serviceability for certain types of wood-based floors [1,2,3]. The natural frequencies of a structure are also recognised as a good predictor of human response to vibration of that structure caused by impact type excitation. Increasing the first natural frequency [4,5] and raising the higher natural frequencies [5,2] leads to improved vibrational serviceability of wooden floors.

Controlling static deflection under a concentrated load, together with preventing the fundamental modal frequency from falling low enough to enter the range causing human discomfort, are actions that are quite easily implemented based on standard engineering

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https://doi.org/10.52202/080513-0402

mechanics methods [6-8]. Controlling the higher natural frequencies of vertical vibration is also desirable because that counteracts modal clustering and amplification of motions, and also can eliminate another undesirable phenomenon known as beating [9]. However, in design, it is impractical to implement such control because even quite complex numerical predictions are insufficiently accurate in the prediction of other than the first 2 or 3 lowest natural frequencies [6]. Proper selection of the static deflection limit used in conjunction with deflection under a concentrated load, although indirect, can be effective in ensuring adequate separation of modal frequencies [3,9].

Various construction methods have been proposed for improving floor serviceability. In the UK, joist floor designers are typically responsible for the joist specification and placement of joists in residential floors. They often recommend closely spaced joists to reduce the load on each joist and thereby decrease its deflection. Certainly, increasing the number of joists in the floor enhances stiffness along the span, reducing static deflection and increasing the fundamental natural frequency. However, researchers [3,6] have warned that this method exacerbates differences in stiffness between across and parallel to the joist span, thereby narrowing the spacing between the higher natural frequency modes. Consequently, decreasing the spacing between joists increases the interaction between modes, which is associated with higher vibration amplitudes. The addition of partition walls parallel or perpendicular to the joist direction also improved vibrational performance of wood floors in terms of static deflection, frequencies, and increased damping [10]. However, this approach was found to be less economical, and such partitions also caused permanent deformation on floor joists, leading to discomfort when the occupant walks by. Adding extra flooring layers was also employed, as the addition of floorings was associated with decreased static deflection and an increase in separation at higher modal frequencies. However, researchers warned that such floorings decrease the fundamental natural frequency and affect the damping ratios [6,11].

The most economical and effective means appears to be adding a row of bridging elements between joists (transverse bridging spines) at the centre of floors [12-15]. The addition of such a bridging spine contributes to the improvement in performance by distributing the static load between the joists and increasing floor system stiffness in the across-joists direction, resulting in primarily a reduction in static deflection. Transverse bridging spines currently used by the construction industry can be classified into two categories: discrete (e.g. solid blocking or cross bridging), as shown in *Figure 1* and *Figure 4*, and continuous (e.g. strong-backs or strapping), as shown in *Figure 4*. From earlier research on floors built with solid-sawn timber joists, Onysko and Jessome [12] concluded that solid blocking and cross-bridging spines reduced static deflection under a concentrated load, and Chui [5] showed that both types are very effective in raising higher natural frequencies. The effectiveness of these discrete bridgings can be further enhanced when they are used in conjunction with a bottom strapping [14]. For floors built with open-web trusses, the common type of continuous bracing used is strong-back. Research on this type of floor system also found the strong-back to be an effective element in reducing static deflection and raising higher natural frequencies [15,16].

Khokhar et al [15] demonstrated that the effectiveness of a row of transverse bridging spines primarily depends on its equivalent flexural rigidity (EI_b), which incorporates the bridging element material and dimensional properties, as well as its connection mechanism to the joists. They proposed a test method to determine the EI_b By measuring the rotational stiffness of a single bridging element and joist spacing. Their findings showed that an increase in EI_b leads to a significant reduction in static deflection and separation of higher modal frequencies in a typical timber floor. However, the study found that the fundamental natural frequency was not significantly affected by an increase in the EI_b.

The significance of characterising 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 [17]. The model is based on ribbed-plate theory [18] 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 the floor and the fundamental natural frequency can be calculated as in Eqs. (1) and (2), respectively, considering floor construction details and incorporating the flexural rigidity of a row of bridging elements.

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

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

where a = span of floor, b = width of floor, P = point load at the centre of floor and ρ = density of subflooring. D_x

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takes account of the composite flexural rigidity of joists and spacing. D_{xy} considers the shear rigidity of the plate and torsional rigidity of 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 [17]. In order to calculate $D_{y,}$ bridging spine rigidity must be known.

The revised draft of Eurocode 5 [19] provides a design calculation method to control vibrations in timber floors, which requires the inclusion of the stiffness of a row of bridging elements located at the mid-span of the floor. Currently, the only available guidance in the UK on bridging is provided by builder insurers such as the NHBC [20], which mandates the insertion of cross-bridging or timber blocking in wood joisted floors at their mid-span. Khokhar et al [15] demonstrated such traditional bridging spines produce very low EI_b and have limited impact on floor performance compared to modified bridging spines, which provided much higher EI_b. Building on the work of Khokhar et al [15], the work described in this paper is intended to further on characterization of the bridging spine rigidity and aim to achieve a wide range of EI_b. It is then possible to quantitatively evaluate the influence of bridging spine rigidity on static deflection and the first natural frequency of a typical timber floor system. This is also discussed in this paper.

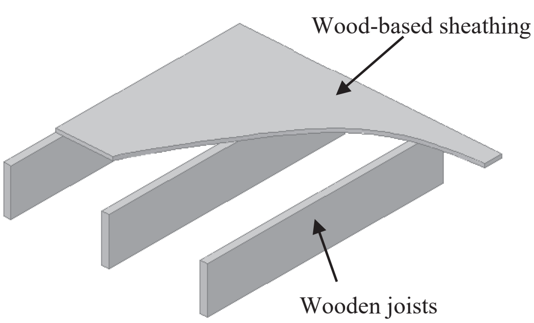


Figure 2: A typical wood floor system

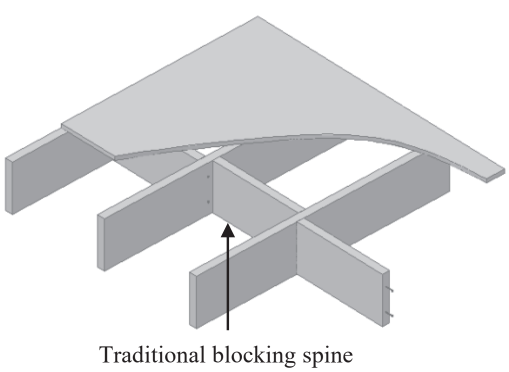


Figure 1: A wood floor with a row of traditional blocking elements connected by two nails with wood joists.

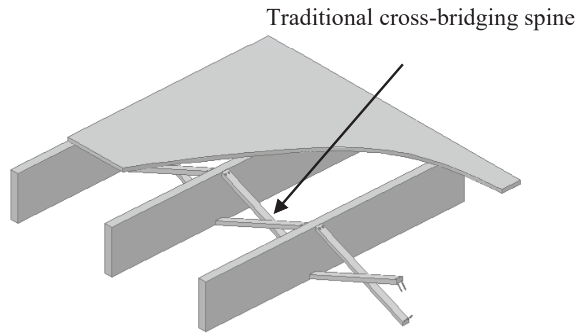


Figure 4:A wood floor with a row of traditional cross-bridging elements, connected by two nails with wood joists.

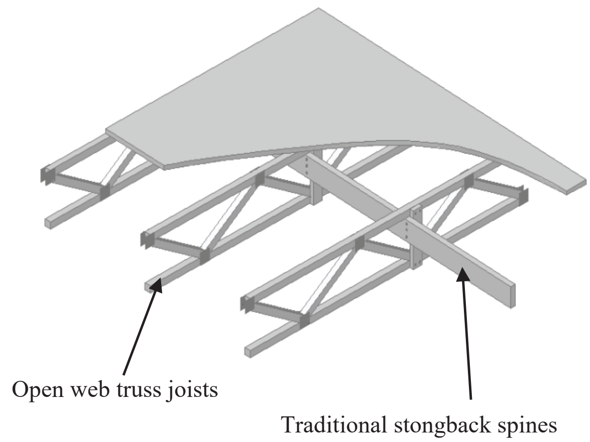


Figure 4: A wood floor with traditional strongbacks in open web truss joists.

2 – TEST PROGRAMME

2.1 TEST METHOD

The bridging element test method, proposed by Khokhar [21] and Khokhar et al [15] was used to evaluate the rotational stiffness of bridging element systems, which then can allow the calculation of the flexural rigidity of transverse bridging spines. In this test method, two bridging elements of 650mm length were connected to a central I-joist stub. The samples were tested under a three-point bending test with 1200mm as the distance between supports. The central joist was 245mm in height with flanges 47mm wide and 45mm deep (JJI-245A). An Instron universal testing machine of 100 kN capacity was used. Vertical displacements were measured at the middle of the specimens at the central joist stub. In addition, vertical deflections were also recorded at 75mm and 525mm from each support, as illustrated in *Figure 5*. Horizontal displacements were measured at the top at bottom of the sample to estimate the relative movement of bridge elements in relation to the central joist during

https://doi.org/10.52202/080513-0402

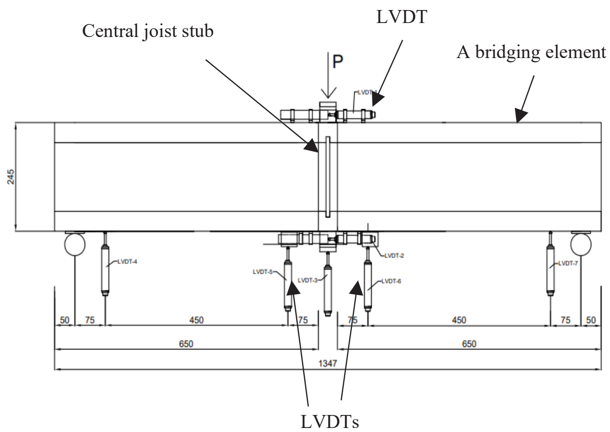
the test. LVDTs with a 10mm maximum range were used to measure horizontal displacements, whereas 25mm maximum range gauges were selected for vertical displacements. An 8-channel StrainSmart data acquisition system was used to record the data from all 7 gauges and the load cell. Twenty-one bridge element systems were tested. For each system, five replicates were tested at a rate of 1mm/min, as recommended by Khokhar [21]. Details of bridging element systems are described in the following section.

2.2 BRIDGING SPINE SYSTEMS

The proposed twenty-one bridging spine systems were categorised in four different groups. In the first variant, 12 systems were built using four blocking elements (45×245 mm) and three types of connection systems. Bridging elements were sourced from Glulam, laminated veneer lumber (LVL), timber I-joists with 45×47 mm flanges (JJI-245A) and with 45×97 mm flanges (JJI-245D), as detailed in *Figure 6*. These blocking elements were connected to the central stub using nails, screws and combination of screws and adhesives. 65 mm long Ringshank nails were 3.5 mm in diameter and screws were 4.5mm in diameter and had fully threaded 70mm length. The use of screws was intended as a replacement of traditional nails as this fastener type has a greater lateral and withdrawal capacity than nails. The adhesive used was the same as the glue applied in the manufacturing of timber I-Joists (i.e. polyurethane).

Another variant was proposed by replacing the metal hangers with C24 timber blocks (45×47× 245mm). The timber blocks were glued and screwed to the flanges of joists forming the connection between the bridging elements and the central joist (*Figure 7*). The proposed systems within this group increased the glued contact area between the joists in the connection and the timber blocks by filling the web gaps with OSB fillersthat glued and screwed to the web. A third system added M12 bolts to the previous system to provide additional tension stiffness.

The fourth group was hybrid system and consisted of screwed I-blockings and commercially available cross-bracing and thin steel straps, as demonstrated in *Figure 8*. This hybrid system allows the blocking to resist shear forces, whereas the metal straps and cross-bracing provide additional tensile strength. Straps were 5mm thick and 600mm long. In another type, two restraining straps were also used to connect both bridging elements by creating a small hole in the central joist. For this system, OSB fillers were used to enhance the connection. The restraint straps are already sold with holes at regular distances. Again, screws with additional resistance to slippage were used to attach these steel straps to the sample. Finally, the third system used shallow joists (195 mm deep) as bridging elements to allow the restraining strap to be positioned at the bottom flange. It should be noted that the ceiling is usually directly applied to the joist's bottom flanges in UK residential construction. Therefore, the use of these straps with full-depth joists is problematic and hence the use of shallow joists.



(a)

(b)

Figure 5: (a) A schematic diagram and (b) a typical single bridging element test setup

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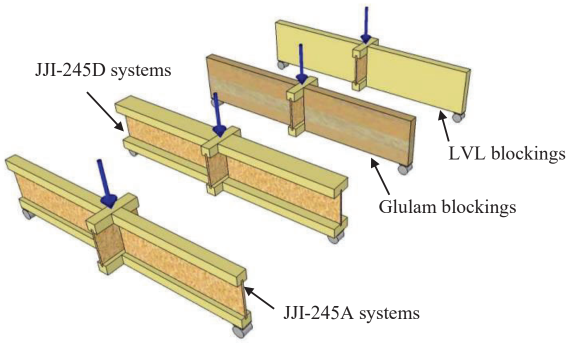

Figure 6: Typical blocking systems tested for bridging rotational stiffness

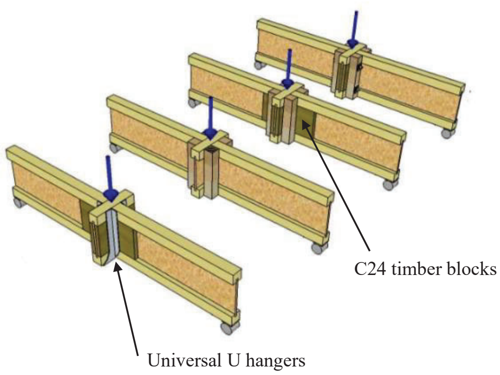

Figure 7: Typical blocking systems reinforced with steel hangers and timber wood blocks

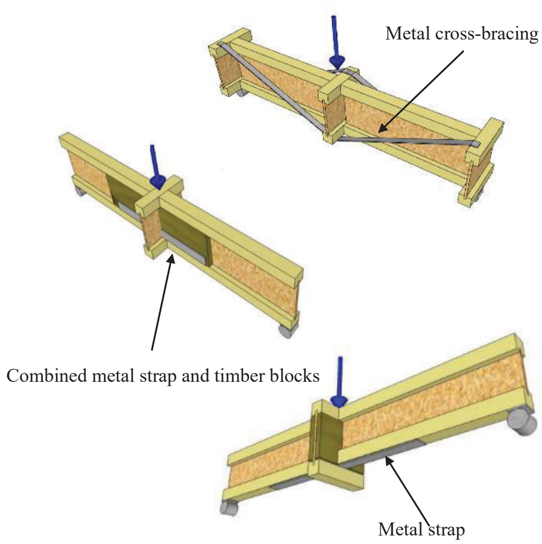

Figure 8: Typical hybrid bridging systems tested for the rotational stiffness

Khokhar [21] proposed an equation to estimate the bridging spines EI_b using the rotational stiffness of bridging elements (K_r) and joist spacing (J_{sp}) within the floor structure.

$$EI_b = K_r \times J_{sp} \tag{3}$$

The rotational stiffness was determined as the slope of the load vs central deflection curve measured from the tested bridging element specimens, as shown in *Figure 9*.

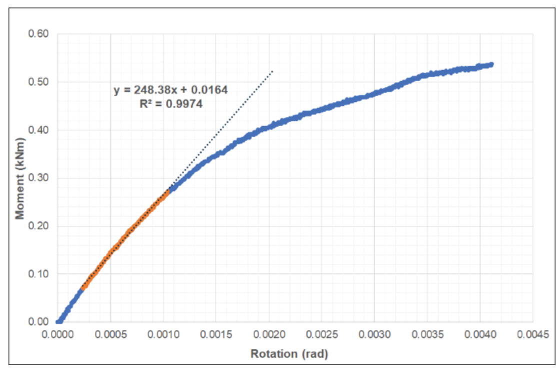

Figure 9: A typical moment and central rotation of bridging elements

The value of the moment and rotation were calculated using the values of vertical deflection and load measured. The slope was calculated using the guidelines given in BS EN 408 [22] to calculate the slope of the load vs deflection curve between 10% to 40% of the failure load. The selected section within this range was such that it included the largest portion of this interval, giving a correlation larger than 0.99. This section should contain an interval between 20% to 30% as a minimum requirement, otherwise, the test would be disregarded. Fortunately, the correlation for all test pieces was very high, and all tests managed to get a value meeting the stated requirements. The value of this rotational stiffness was halved to give the K_r.

3 – RESULTS AND DISCUSSION

3.1 BRIDGING ELEMENT ROTATIONAL STIFFNESS

Table 1 Table 1 presents the average rotational stiffness for each system, which is compared to the traditional nailed system currently used on construction sites when bridging spines are employed. Across all tested systems, the coefficient of variation (CoV) ranged from 10% to 15%, depending on the system type. The results indicate that the rotational stiffness of bridging elements can be increased by up to 3.5 times compared to the current level by adopting the blocking system with 245D glued and screwed connections.

Table 1: Average bridging stiffness of tested bridging elements

System No	System Code	System Description	Bridging Stiffness K_r
1	JJAN	245A+ Nailed	0
2	JJACB	245A+ with metal cross-bracing	13%
3	JJATS	245A+ screwed from top only	14%
4	GLN	Glulam Nailed	15%
5	HA	245A+ on hangers	29%
6	JJASC	245A+ screwed from sides only	38%
7	LVLN	LVL Nailed	50%
8	UMEST	195A+ blocking with metal strap underside	56%
9	JJAS	245A+ Screwed (top and bottom)	67%
10	JJDN	245D Nailed	90%
11	GLS	Glulam Screwed	91%
12	MEST	245A+ with horizontal metal strap	103%
13	LVLS	LVL Screwed	107%
14	JJDS	245D Screwed	116%
15	TB	245A+ with timber blocks	176%
16	JJAGS	245A+ glued and screwed	211%
17	TBW	245A+ with timber blocks and web stiffeners	272%
18	TBR	245A+ with timber blocks and steel rods	276%
19	LVLGS	LVL Glued and Screwed	327%
20	GLGS	Glulam Glued and Screwed	332%
21	JJDGS	245D Glued and Screwed	349%

The results indicate that screwed connections outperform traditional nailed ones in terms of rotational stiffness. This stiffness is further enhanced when the blocking ends are also glued to the joists. For the same type of connection and fixings (i.e., nails or screws), the test results suggest that rotational stiffness increases with the bending stiffness of the blocking. Among the systems tested, hybrid configurations incorporating metal straps exhibited the highest ultimate failure loads. However, their rotational stiffness was lower than that of systems using LVL or 245D blocking screwed to the central joist.

Hybrid systems with metal straps were the strongest ones, achieving larger ultimate failure values than any other system. However, their rotational stiffness value was lower than other systems such as those with LVL or 245D blocking screwed to the central. Inspection of hybrid test pieces revealed that slippage in the metal strap in hybrid systems is an important factor when stiffness is the key variable rather than strength. The fact that customised fixings were used to decrease this issue shows that it is difficult to integrate this stiffer steel metalwork into timber-based bridging elements using fasteners. The addition of adhesive seems to overcome this problem for timber based sytems. Thus, the use of epoxy type adhesives, which could bind the steel to the timber, may be more successful. Although such customised steps would probably be difficult to implement in building sites, given the complexity of the application. It should be noted that timber glue adhesives are already commonly used on sites to join the decking to the joists.

This lack in performance in metalwork-based systems can also be seen in bridging systems with hangers. Furthermore, the addition of M12 bolts to timber block systems only increased the performance by 4%, which is disappointing considering the additional amount of work required to insert these bolts in each test piece. The validity of *equation 3* relies on the assumption that the test angle of slope (α) could be calculated using the central deflection and the blocking length. It also estimates that the opening angle between the central joist and blocking elements (θ) is the same as the angle of slope.

The placement of gauges in this test programme allowed for testing these two assumptions. Considering the arrangement of gauges in test pieces, the test slope angle was measured directly underneath the blocking element (450mm in length) at 75 mm from the centre and from support, and was compared with the central deflection. *Figure 10* shows that there is a correlation which closely matches the blocking length. Furthermore, it can also be concluded that the value of the opening angle can be reasonably approximated to the slope angle. The measurement of compressive and tension displacements was also correlated with the central deflection (*Figure* and *Figure 12*). Results show that there is a good correlation between the central joist compression stiffness perpendicular to the grain and central deflections, as well as the resistance to fastener withdrawal at the bottom side, with the test central deflection. This correlation is further improved when metalwork type systems are excluded. This fact can be seen in the figures below, where those points further to the trendline correspond to strap or other metalwork based systems.

It is also interesting to note that increasing the contact area in the compressive side between bridging elements and central joist significantly increases the rotational stiffness system performance such as the case of the 245D where the contact area was doubled compared to a 245A+ or 45x245 glulam and LVL. This increase in area reduces the compressive deformation at the top which reduces the central deflection. Such improvement can be enhanced if adequate fixing methods are used to decrease the displacements at the bottom side.

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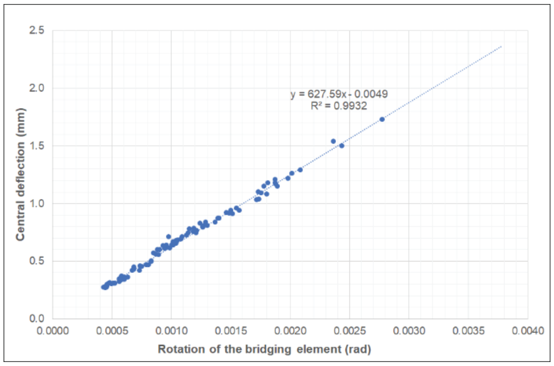

Figure 10: A comparison of the central deflection tested specimens and the rotation of the bridigng elements at 75mm from the centre

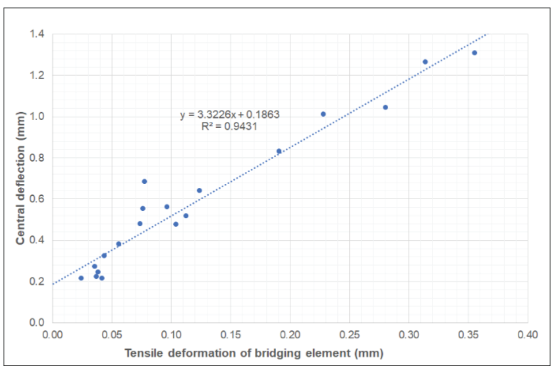

Figure 11: A correlation between the central deflection and compressive deformation of a bridging element

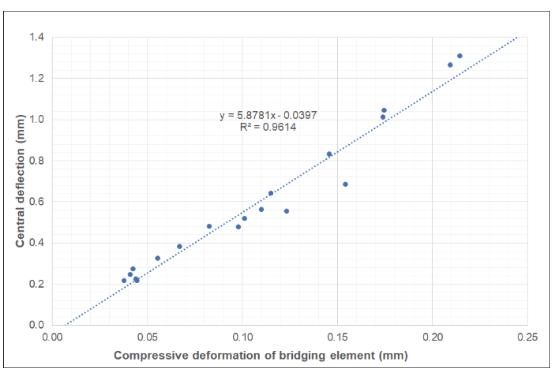

Figure 12: A correlation between the central deflection and tensile deformation of a bridging element

3.2 FLEXURAL RIGIDITIES OF TESTED BRIDGING SPINES AND RIBBED PLATE MODEL PREDICTION

The flexural rigidity (EI_b) of tested bridging systems were calculated using *equation (3)* and joist spacing of 600mm. The ribbed plate model [17] was used to determine the static deflection and fundamental natural frequency (*equations 1 and 2*) of a timber floor tested by Khokhar [], incorporating the calculated EI_b. *Figure 1* provides the correlation between $EI_{bs}$and the predicted static deflections. The lowest EI_{bs} of 80 k*Nm*^{2} was obtained when timber I-joists bridging elements (45×47mm flange section) with nailed connections. The use of I-joists with wider flanges (45×97mm) combined with glued and screwed connections produced with 275% higher flexural rigidity than bridging spine with the lowest EI_{bs} . The ribbed-plate model predicts that bridging spines with EI_{bs} ranging from 79 to 296 kNm^2 would reduce static deflection from 25% to 41%. The relationship between EI_{bs} and static deflection is almost linear initially, similar to what Khokhar et al [2] found, then it provides polynomial behaviour.

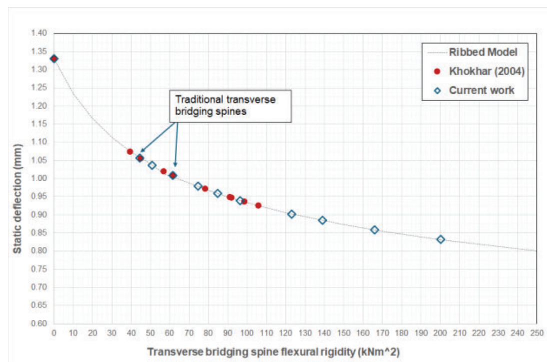

Figure 113: Influence of evaluated flexural rigidity of bridging spines on static deflection of a timber floor tested by Khokhar [].

It can be seen that traditional bridging systems tested proved to be relatively flexible compared with other types and in terms of deflection reduction (10%). Hence, the effectiveness of traditional bridging spines in service seems to be limited compared to the predicted results from the ribbed-plate model for the systems proposed in this research. In this work, an increase in EI_b raises the first natural frequency slightly, with the maximum increase in the first natural frequency being about 5%. This was also reported by Khokhar et al [15].

4 – CONCLUSIONS

This study quantified a broad range of flexural rigidity of bridging spines by modifying bridging element stiffness and geometry, and its connection system to the joist. Ribbed-plate model predictions show that an increase in bridging spine rigidities has a strong influence on the static deflection of a floor under a concentrated load as up to 40% reduction in static deflection was obtained. An increase in bridging rigidities leads to a small to moderate increase in the first natural frequency. At the current stage, full-scale floor tests are in progress and the influence of tested bridging spines on static deflection, natural frequency values and higher order modal natural frequency separation and will be published.

5 – ACKNOWLEDGEMENT

The financial support of James Jones and Sons for supporting the research program is gratefully acknowledged. The first author acknowledges the financial support of Edinburgh Napier University for attending the conference.

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