Effects of Local Stiffening on the Dynamic Performance of Timber Floors

Jan WECKENDORF
Research Student
CTE, SEBE, Napier University
Edinburgh, Scotland, UK

Binsheng ZHANG
Lecturer in Structural Engineering
SEBE, Napier University
Edinburgh, Scotland, UK

Abdy KERMANI
Professor of Timber Engineering
CTE, SEBE, Napier University
Edinburgh, Scotland, UK

David REID
Senior Lecturer in Structural Engineering
SEBE, Napier University
Edinburgh, Scotland, UK

Summary

Due to current design and construction practices light-weight timber flooring systems invariably suffer vibration problems. This paper examines the concept of local stiffening to enhance the natural frequency of typical UK-built timber flooring systems and to locally reduce the point load deflections and the vibration amplitudes at sensitive locations. A series of full-scale laboratory tests carried out at Napier University has confirmed the efficiency of the proposed concept.

1. Introduction

Excessive vibrations of structural timber flooring systems cause undue inconveniences to occupants. Serviceability design requirements to overcome this problem are to raise natural frequencies and reduce static point load deflections and vibration amplitudes of the floors. A satisfactory level cannot always be achieved if current construction practices and design rules are used to control timber floor vibrations. Hence, much research is needed to further investigate this.

The vibrational behaviour of typical rectangular two-side supported flooring structures was experimentally and analytically examined in detail. A simple concept of locally stiffening flooring structures was further adopted to attain lower modal amplitudes and static deflections at identified sensitive locations in addition to raised natural frequencies.

2. Background and Concept

From subjective site observations and consequential numerical studies (on four-side supported floors), Smith and Chui [1] found that a very flexible joist in floor centre could affect the vibration performance of light-weight floors in a highly negative way, in particular for the first vibration mode. Ohlsson [2] reported many complaints about floor vibration associated with large movements for floor areas close to unrestrained edges. Studying the typical mode shapes in transverse direction for two side-supported timber flooring structures can thus help to identify highly sensitive locations with large modal displacements (see Fig. 1).

It could be beneficial to lower the modal amplitudes and the static deflections at these locations and generally to raise the natural frequencies. To achieve this, the identified sensitive locations need to be stiffened.

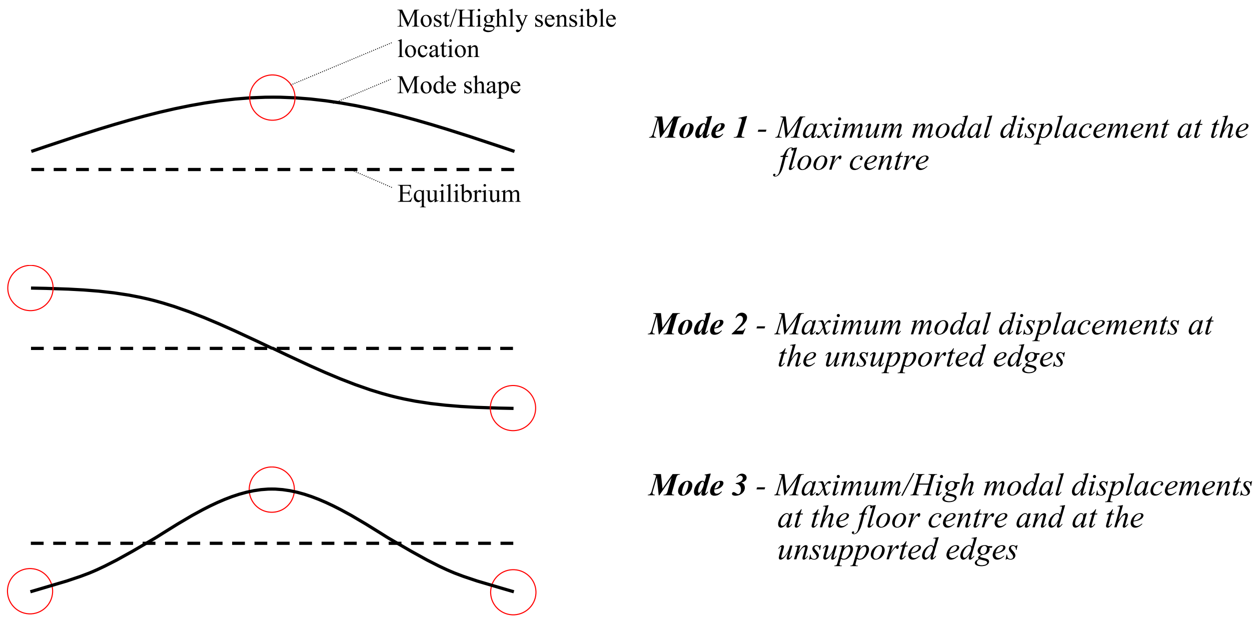


Fig. 1 First three major vibration mode shapes in transverse direction for one-way spanned two-side supported rectangular floors with corresponding modal amplitudes

The concept of increasing the stiffness at dynamically sensitive locations is very simple and hence easy to apply. Instead of using single I-joists evenly distributed over the whole structure, double I-joists are placed at the floor areas where high modal displacements may occur. Positioning double joists along the central line is expected to benefit the first and third modes of vibration, and placing double joists at the edges could particularly enhance the second and also the third mode. Constructing the floor with double joists along the central line and edges could thus benefit the first three major modes simultaneously by increasing natural frequencies, lowering the modal amplitudes and additionally reducing static point load deflections at the location of the double joists and neighbouring joists. Furthermore, I-joists with increased flange width could be used to amplify the described effects.

3. Experimental Approach

The reference floor had a size of 3.5 m × 2.44 m and was constructed with five I-joists of 220 mm depth and 45 mm flange width, at a spacing of 600 mm. The floor was decked with 19 mm particleboard. Double joists were introduced as follows:

Floor 1 Double joists along the central line only

Floor 1a Double joists with wider flanges (97 mm wide) along the central line

Floor 2 Double joists along the edges only

Floor 3 Double joists along the edges and the central line.

The ends of the I-joists were fixed onto the supports by screws as shown in Fig. 2.

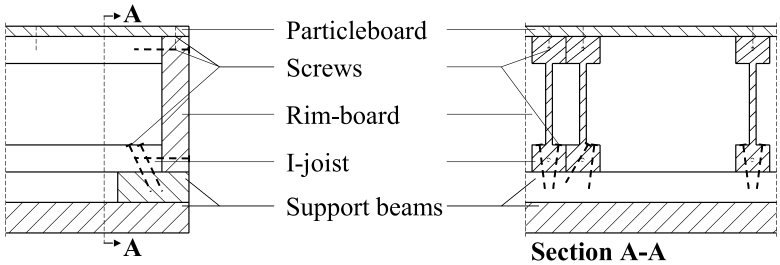


Fig. 2 Detailed end support conditions of the I-joists

The static deflection was measured at the centre of the floor and at mid-span of one of the adjacent joists under a load of 1 kN over a small area at these locations. For two-side supported floors, the mid-span deflection under point load at the unsupported edges is expected to be higher than that at the floor centre under point load if single joists are equally spaced, due to a reduced load-sharing effect for the former. Therefore, higher deflection may occur for the joists adjacent to the central joist for the narrow reference floor tested.

The vibration tests were carried out using a random excitation method. A total of 27 measurement points on the top floor surface were selected, including 25 points equally distributed and two reference points. This allowed identifying all natural frequencies and mode shapes of interest. In the ARTeMIS software package, two methods, the Enhanced Frequency Domain Decomposition (EFDD) and the Stochastic Subspace Identification (SSI), were used to obtain the modal parameters [3][4].

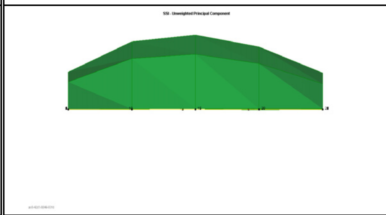
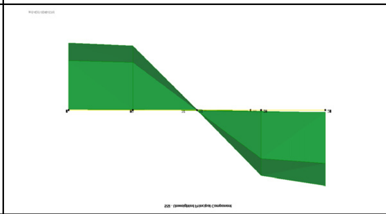
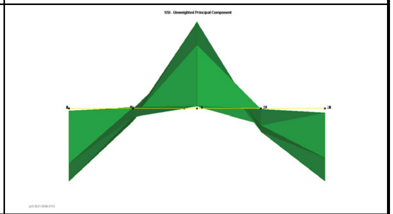
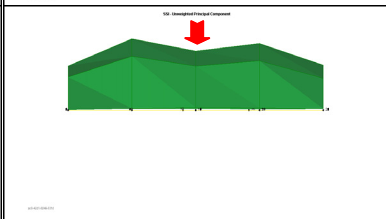
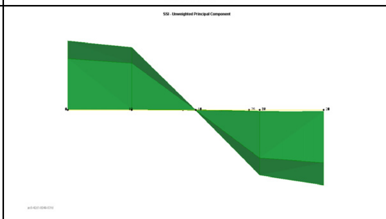
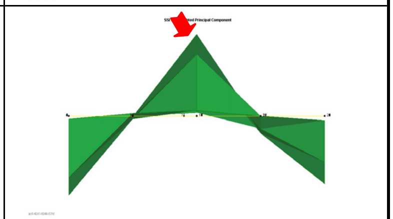
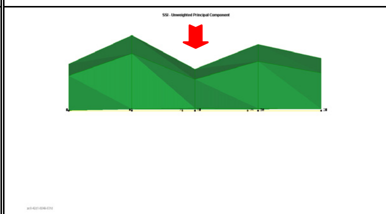
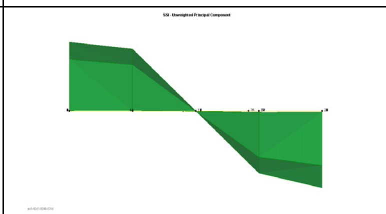
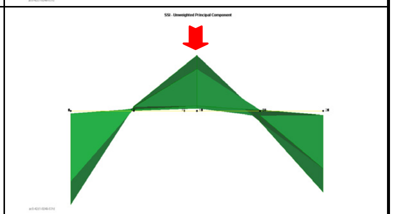
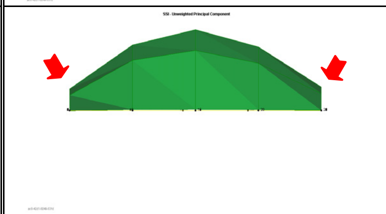
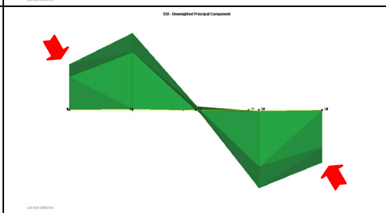
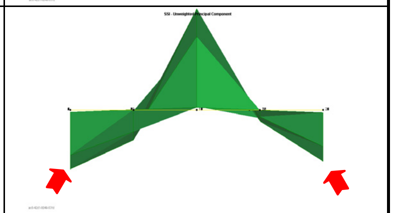
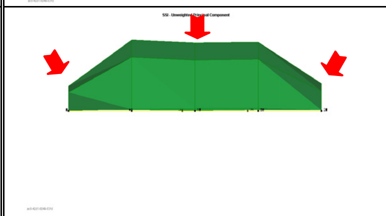
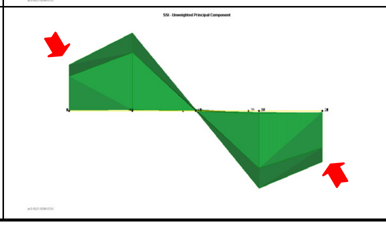
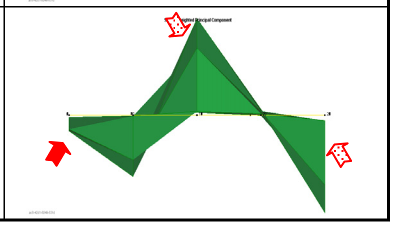
4. Results

The effects of double joists on the first three major vibration modes, the corresponding natural frequencies and the static mid-span deflections of the central and neighbouring joists are discussed.

4.1 Mode shapes

The variations in the modal shapes of the first three major modes in transverse direction due to the proposed structural modification are illustrated in Table 1.

Table 1 - Variation in the first three major mode shapes in transverse direction (unscaled)

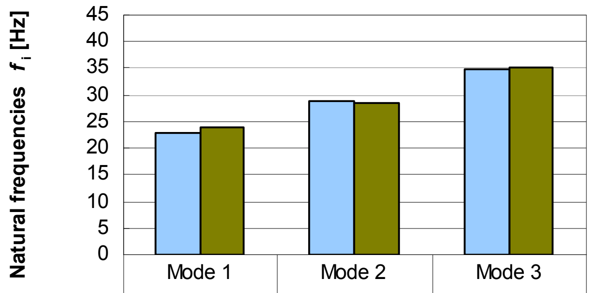
Floor	Mode 1	Mode 2	Mode 3
Ref.			
1			
1a			
2			
3			

For the comparison of the mode shapes, it should be noted that no absolute values for the amplitudes were measured and the movement is relative. Because the additional joists increased both floor mass and stiffness, initial vibration amplitudes of the modified floors may not increase in comparison to those of the reference floor.

The test results show that the double joists along the central line lowered the modal displacements at this location largely for Mode 1 and notably for Mode 3. This effect can especially be seen for Floor 1a where the lowest displacement was observed at the centre of the whole cross section for Mode 1 and a lower displacement in the centre than at the edges for Mode 3. The double joists at the unsupported edges clearly lowered the displacements at these locations and the mode shapes approached those for four-side supported floors for the first two modes. Only mode shape 3 of Floor 3 was rather inconclusive.

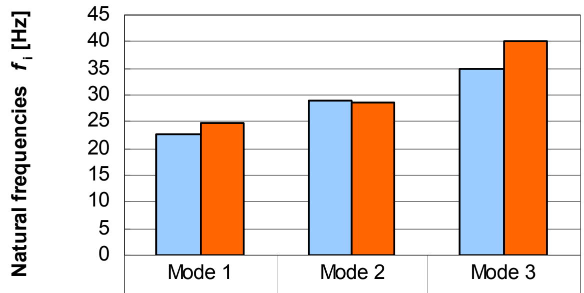
4.2 Natural frequencies

Increasing the number of floor joists is expected to raise the natural frequencies due to the increase in stiffness. However, the efficiency is dependent on the location of the joist. From Fig. 1, increasing the stiffness at floor centre in the span direction may benefit the frequencies of the first and third major modes. Raising the stiffness at the unsupported edges may particularly enhance the frequencies of the second and third major modes. The results from this experimental investigation are shown in Fig. 3.



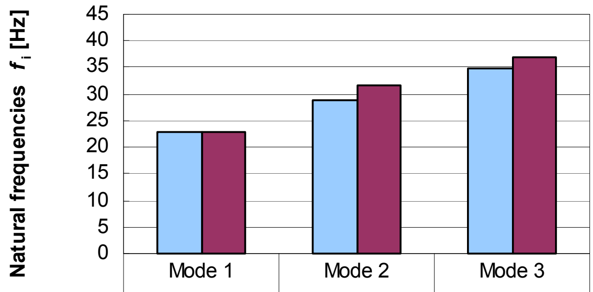
	Mode 1	Mode 2	Mode 3
Floor Ref.	22.70	28.80	34.82
Floor 1	23.87	28.58	35.32

a) Reference Floor vs. Floor 1



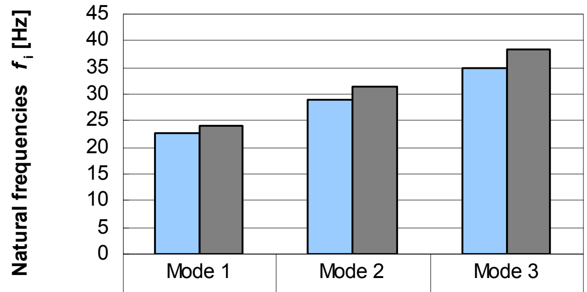
	Mode 1	Mode 2	Mode 3
Floor Ref.	22.70	28.80	34.82
Floor 1a	24.93	28.56	40.17

b) Reference Floor vs. Floor 1a



	Mode 1	Mode 2	Mode 3
Floor Ref.	22.70	28.80	34.82
Floor 2	22.95	31.49	36.96

c) Reference Floor vs. Floor 2



	Mode 1	Mode 2	Mode 3
Floor Ref.	22.70	28.80	34.82
Floor 3	24.16	31.45	38.32

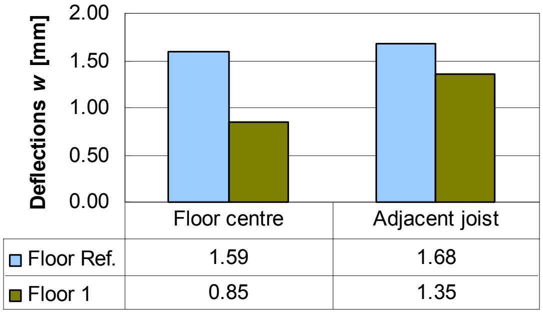
d) Reference Floor vs. Floor 3

Fig. 3 Natural frequencies of the first three major vibration modes

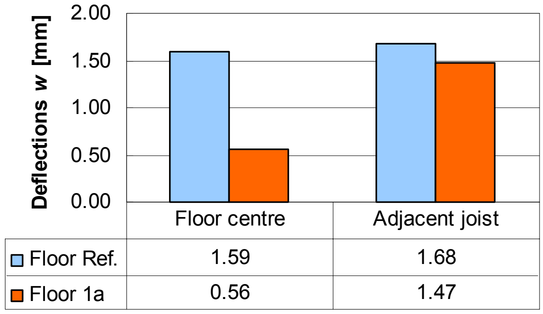
As it can be seen, double joists increased the natural frequencies if they were placed at the location of high modal displacements and had little effect if the location was a node. Increasing the stiffness of the double joists amplified this positive effect (Fig. 3b)).

4.3 Static point load deflections

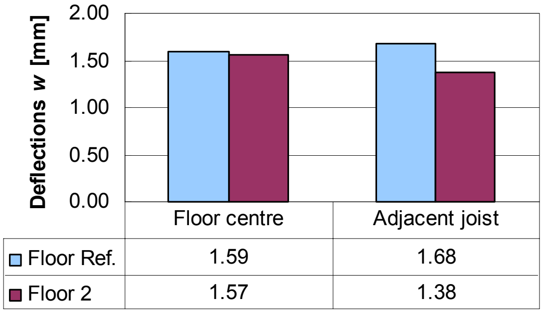
The deflection of the floors was measured at floor centre and at mid-span of one of the adjacent joists, to study how the deflection would be affected locally in floor centre and to which degree neighbouring joists would benefit from using double joists. The test results are presented in Fig. 4. Deflection at the edges was not measured, but a similar trend of reduced deflections to that for the floor centre due to double joists could be expected.



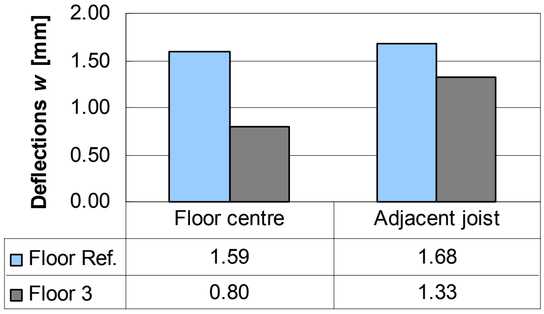
a) Reference Floor vs. Floor 1



b) Reference Floor vs. Floor 1a



c) Reference Floor vs. Floor 2



d) Reference Floor vs. Floor 3

Fig. 4 Deflections at floor centre and at mid-span of adjacent joist

Fig. 4 shows that double joists reduced the deflections significantly where they were placed and that they also had a positive effect on the deflection of adjacent joists since load was less distributed. The deflection at floor centre sustained a largest reduction due to the configuration for Floor 1a (Fig. 4b)) and a lowest reduction for Floor 2 (Fig. 4c)). This can be expected as the double I-joists with wider flanges were placed along the centre of Floor 1a but only double I-joists with regular flanges were placed along the edges for Floor 2.

4.4 Summary of test results

Using double joists at the sensitive locations helped to lower modal amplitudes and to reduce the static deflection at the locations for double joists and adjacent joists. Furthermore, natural frequencies could be increased for individual vibration modes, depending on the location of the double joists. Significant effects were especially observed where double joists with wider flanges were placed in floor centre. This led to an increase of 10% in the frequency of the first vibration mode. Additionally, the floor centre exhibited lowest modal displacement of the whole cross section for the same mode. The frequency of the third major mode increased by 15% and the corresponding modal displacement in floor centre, which had the maximum displacement for the reference floor, was lower than the modal displacements at the unsupported edges. The static deflection in the centre of this floor could be reduced by 65%.

The comparison of the mode shapes of Floor 2 with the reference floor (Table 1) indicates that the double joists at the edges had a very positive impact on the mode shapes. In particular the shapes of the first two modes approach those for four-side supported floors.

5. Discussion and Conclusions

The application of double joists to achieve the above mentioned goals worked well for the light-weight floors tested. Even though an increase in natural frequencies and a decrease in modal amplitudes and static deflections may also be achieved by lowering the joist spacing, double joists could more effectively stiffen sensitive locations. As described in Section 2, the stiffness of the central joist and the movement at unrestrained edges considerably contribute to unsatisfactory vibration performance.

If the same height is maintained for I-joists, an increase in stiffness can be obtained by increasing flange width or web width. Even though floor structures with equally spaced single joists of the same type may fulfil the requirements for stability, it could be useful from the serviceability aspect to select stiffer joists for floor centre and edges. Double joists could be especially effective for this. For existing light-weight flooring structures with unsatisfactory vibrational performance, it can be a very simple option to lower the modal amplitude and local static deflection at the identified disturbing location by just adding another joist.

Future research needs to focus on the efficiency of double joists on large-scale light-weight floors. For very wide floors, it could be useful to further investigate whether narrower joist spacing at the edges and in floor centre can be more efficient while the spacing of the other joists is remained unchanged. This can be done in combination with double joists.

To sum up, it is recommended that the edges of two-side supported light-weight flooring systems be stiffened with double joists to lower their modal amplitude, producing modal shapes which approach those of four-side supported floors, at least for the first two major modes. The use of double joists in floor centre can considerably affect the first vibration mode of light-weight flooring systems in a positive way. Undertaking any or all of these measures may increase the comfort level.

6. Acknowledgements

James Jones & Sons Ltd. provided material for experimental work on the timber floors used for the study in this paper. The Royal Academy of Engineering, UK, financially supported the visit to this conference. Both their support is gratefully acknowledged.

7. References

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