Edinburgh, Scotland
EURONOISE 2009
October 26-28

The influence of resilient bars on plate vibration

Shenzhi Su [a]
Sean Smith [b]
Building Performance Centre
Edinburgh Napier University
42 Colinton Road, Edinburgh
EH10 5BT

Charles A. Fairfield [c]
School of Engineering and the Built Environment
Edinburgh Napier University
10 Colinton Road
Edinburgh
EH10 5DT

ABSTRACT

Resilient bars can provide low-cost, effective improvement to sound insulation performance. They are increasingly popular in timber framed floor/ceiling assemblies in the UK following the upgrading of The Building Regulations' requirements. Resilient bars are often modelled as springs isolated from the two connected plates, forming a mass-spring-mass system. However as a furring system of plates, resilient bars may modify the vibration energy distribution across a connected plate by acting as stiffeners. The authors investigate this issue by measuring acceleration levels at different locations relative to the fixing positions and thereby derive vibration waveforms for the connected plate in a small-scale structural simulation of a floor-ceiling system. The results were compared with timber joist-ribbed, and timber brander-ribbed, structures. The vibration modes of a suspended plate were also measured for comparative purposes. The results indicate that resilient bars did not perform as stiffeners whereas joists and timber branders *did* effectively stiffen their connected plates. Resilient bars neither forced orthotropic plate behaviour at low frequencies, nor separated the plate into sub-plates at higher frequencies. Compared with a stiffened plate, the radiation efficiency below the plate's critical frequency may not be increased by resilient bars as occurred with more conventional stiffeners. Resilient bar-ribbed plates may also differ from independent plates. The modal behaviour of resilient-bar ribbed plates is more complex and their effect on modal density and radiation efficiency are worthy of further research.

---

[a] E-mail address: s.su@napier.ac.uk
[b] E-mail address: se.smith@napier.ac.uk
[c] E-mail address: c.fairfield@napier.ac.uk

1. INTRODUCTION

Bradley and Birta[1] modelled their resilient bar structure as a mass-spring-mass system, in which resilient bars were treated as springs, and the connected plates as rigid masses. Brunskog and Hammer's[2] test rig for obtaining the dynamic stiffness of resilient bars comprised two rigid masses and small samples of resilient bars in between. However floor and ceiling plates are not rigid. Resilient bars as a furring system may affect the vibration modes of the plates. Nightingale *et al.*[3] undertook statistical energy analysis (SEA) modelling for resilient bar structures and assumed that resilient bars entirely decoupled the joists from the ceiling board and thus applied the modal density and radiation efficiency of independent plates for resilient bar-ribbed plates. This assumption will be analysed in this work.

It has been found that when a plate is ribbed by stiffeners, such as beams, through fixings, line connections between the plate and beams are observed at low frequencies, and point connections at higher frequencies[4,5]. When the plate is solid line-connected with beams, the structure will behave as a large orthotropic plate at lower frequencies and be subdivided into smaller plates by stiffeners at higher frequencies[6]. This paper will investigate whether such phenomena will also be present in a resilient bar ribbed plate; the way in which resilient bars affect the vibration waveforms of the connected plate will also be examined. Firstly, the bending stiffness of resilient bars is derived and compared with that of timber branders and an equivalent width of 11 mm thick oriented strand board (OSB) strip. Then, the energy transmitted to an 11 mm thick OSB ribbed by resilient bars, timber branders and timber joists respectively will be measured over three zones: on fixing points, between fixing points, and between ribs. This comparison will investigate whether or not resilient bars act as conventional stiffeners. Lastly it will illustrate the measured waveforms present in a suspended OSB, and a joist-ribbed OSB, timber branders, and resilient bars. It will further demonstrate whether or not resilient bars perform as stiffeners.

2. BENDING STIFFNESS OF RESILIENT BARS AND TIMBER BRANDERS

The bending stiffness of resilient bars, timber branders (35 mm wide × 60 mm deep) and an 11 mm thick OSB strip was obtained by measuring Young's modulus and calculating the moment of inertia of the cross-sectional profile. The results are shown in Table 1: the resilient bar type used here was one order of magnitude less stiff than those timber branders used but one order stiffer than the equivalent width of OSB strip. It is thus possible that resilient bars perform as stiffeners although any mode's wavelength relative to their spacing should also be considered influential. Resilient bars are normally fixed to plasterboard; OSB was chosen here because the board can be reused in subsequent tests to avoid variation caused by re-build uncertainties in the models. The bending stiffness of 11 mm thick OSB is about 1.4 times that of 12.5 mm thick plasterboard with a density of 800 $kg\,m^{-3}$. As resilient bars are much stiffer than an equivalent width of 11 mm thick OSB, they are also expected to be much stiffer than an equivalent width of 12.5 mm thick plasterboard.

Table 1: Bending stiffness of resilient bars and timber branders.

	Resilient bar	Timber brander 35 mm wide 60 mm deep	OSB strip
Bending stiffness EI (Nm^2)	230	7690	17 (35 mm wide) 22 (45 mm wide)

3. PLATE ENERGY DISTRIBUTION: THE EFFECT OF RIBBING CONDITIONS

Accelerations were measured at fixing points (on-screw), between fixing points (inter-screw), and between frames (inter-joist) on a 2.4 m × 1.2 m × 11 mm thick OSB plate which was, in turn, timber joist-, timber brander-, and resilient bar-ribbed. Excitation was by instrumented hammer. Measurement points are shown in Figures 1 and 2: data in Figures 3 to 5.

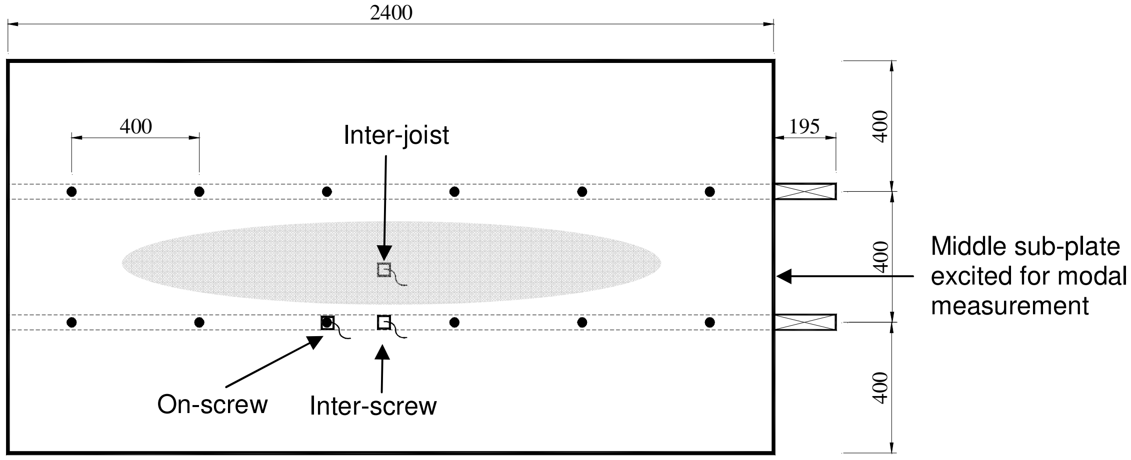


Figure 1: Measurement points on the receiving joist-ribbed OSB (RHS shows x-section; all dims mm).

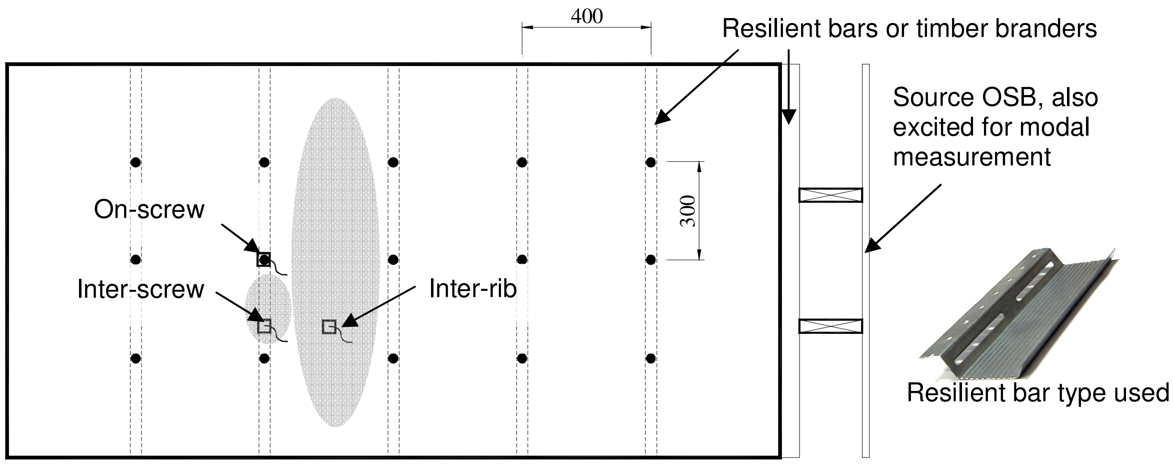


Figure 2: Measurement points on the receiving resilient bar-, or timber brander-ribbed OSB (RHS shows x-section; all dims mm).

When the plate was joist-ribbed, at frequency $f < 50$ Hz, acceleration levels were independent of the location of the measurement point. Within the range 63 Hz $\leq f \leq$ 315 Hz the measured inter-screw acceleration levels departed from the on-screw measurements and approached those found between the joists. At $f > 315$ Hz, the inter-screw acceleration levels were close to those between the joists; they differed from on-screw measurements by about 10 dB. When the plate was ribbed by timber branders, similar tendencies were observed albeit with different transition frequencies and amplitudes. For $f < 100$ Hz, acceleration levels barely differed: for 125 Hz $\le f \le$ 800 Hz, acceleration levels between screws were similar to the on-screw measurements; they were much lower than those measured between timber branders. Above 1 kHz, inter-screw acceleration levels approached those between timber branders.

At low frequencies, the stiffened plate behaved as if orthotropic. The energy distribution had no correlation with screw location but was determined by its modes. At higher frequencies, the stiffeners, and their fixing points or lines, broke the continuity of bending modes. Similar phenomena related to fixings were also observed by Craik and Smith[4]. They proposed that if the bending wavelength (corresponding to wave velocity c_B) was larger than the fixing spacing, the plate was connected to the frame along the fixing line. If the bending wavelength was less than the fixing spacing, *s*, then the plate was connected at fixing points. The approximate transition frequency f_p is derived thus:

$$f_p = \frac{c_B}{2s} \tag{1}$$

Accordingly below f_p, on-screw acceleration levels were similar to those between screws but different from those between stiffeners. Fixing lines sub-divided the plate into multiple sub-plates. Above f_p multiple sub-plates were able to revert to a single large plate, so acceleration levels between screws became close to those between stiffeners once more. In contrast to timber joist- and timber brander-ribbed plates, when the plate was ribbed by resilient bars, no significant acceleration level differences were observed across all measurement points throughout the frequency range of interest. It indicated that resilient bars did not sub-divide the ribbed plate as stiffeners.

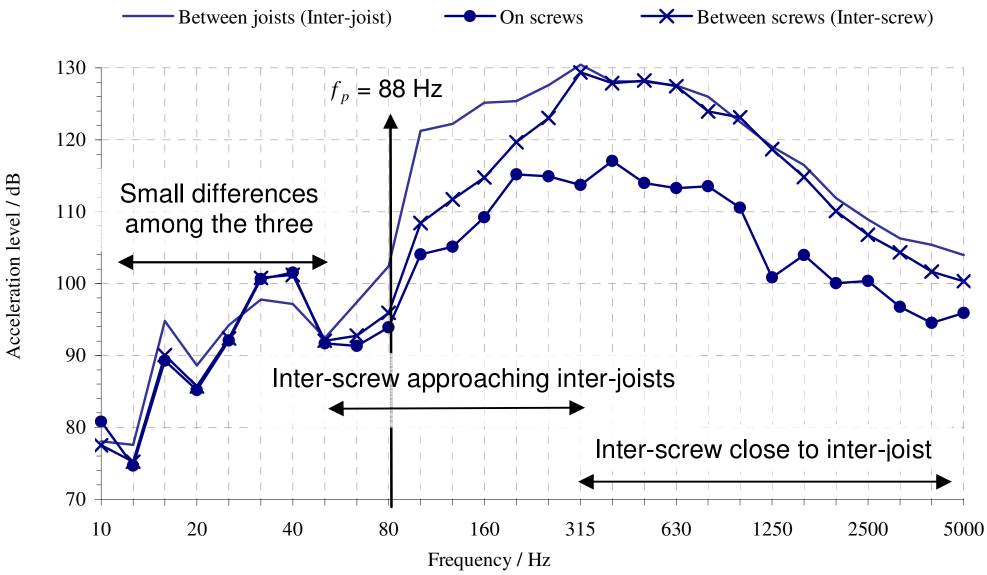


Figure 3: Measured acceleration levels: on-screw, inter-screw, and inter-joist.

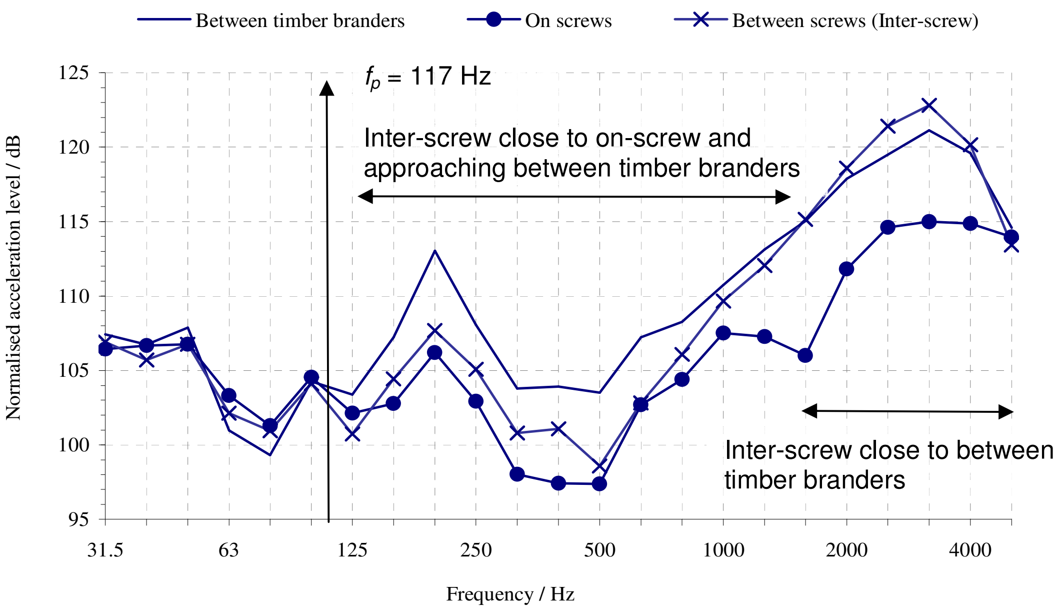


Figure 4: Measured acceleration levels: on-screw, inter-screw, and between timber branders.

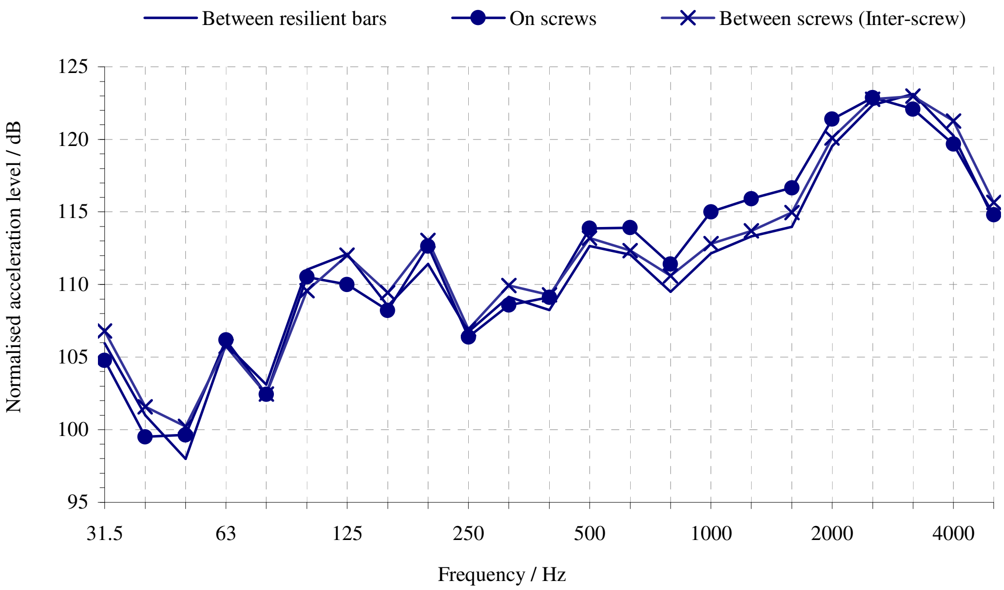
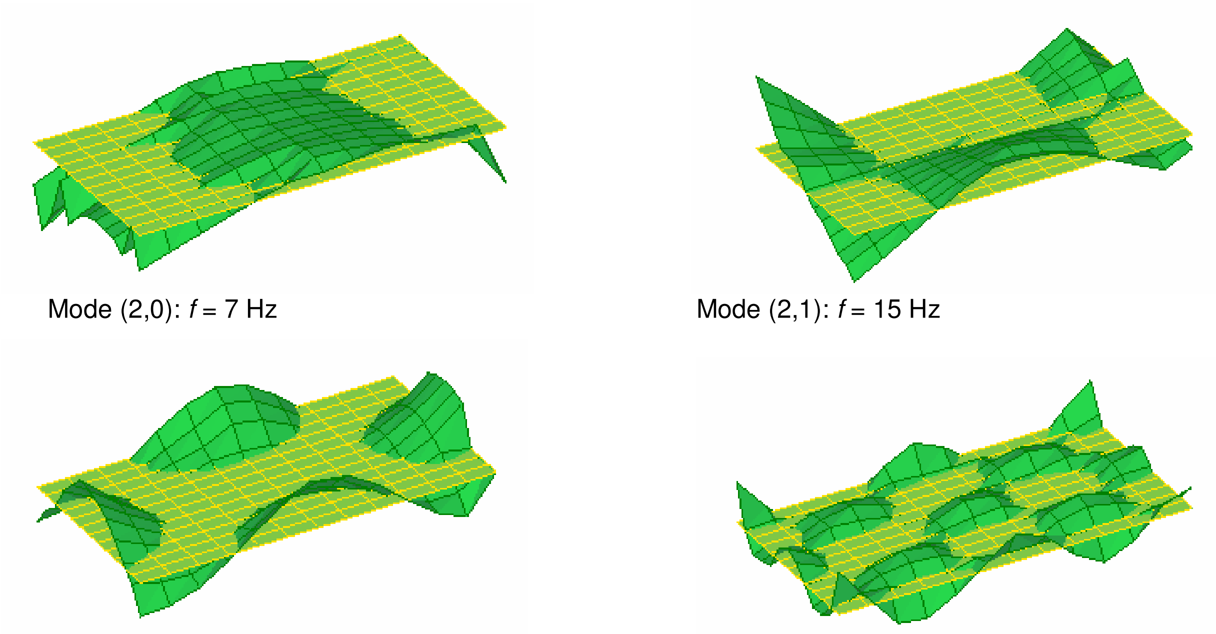


Figure 5: Measured acceleration levels: on-screw, inter-screw, and between resilient bars.

4. PLATE VIBRATION MODES

Modal measurements were carried out on the same OSB boards under four conditions: suspended, fixed to two joists (see Figure 1), as a receiving plate in a timber brander structure (see Figure 2), and as a receiving plate in a resilient bar structure (again, see Figure 2). The measurement procedure was to mount accelerometers at two random points as references; and then attach a group of accelerometers over the nodes of an imaginary grid on the board. At all points, the amplitude and phase differences between positioned and reference accelerometers were measured during excitation. Modal shapes were derived using ARTeMIS, experimental modal analysis software[7]. The output mode shapes were unscaled as the aim was to investigate the effect of different rib systems on the plate's mode shapes.

This section illustrates a few, key, waveforms at the frequency response peaks for each structure. Distinct modes were observed in the suspended plate as shown in Figure 6. For the joist-ribbed plate, at low frequencies it performed as if orthotropic (see Figure 7). At f > 45 Hz, the plate was effectively divided into three sub-plates, each with its own modal frequencies. At high frequencies, such sub-division by joists was not observed. This was consistent with the project's broader findings[8]. The modes of the timber brander-ribbed plate were less distinct than those of the joist-ribbed plate, as shown in Figure 8: nevertheless, similar behavioural trends were observed in these joist-ribbed plates. Sample waveforms at frequency peaks for resilient bar-ribbed plates are shown in Figure 9. The waveforms differed from both the suspended, joist-, and timber brander-ribbed plate modes in that no clear modes were observed. It explains why in such a structure, no vibration response differences were observed at different measurement points, as shown in Figure 5.



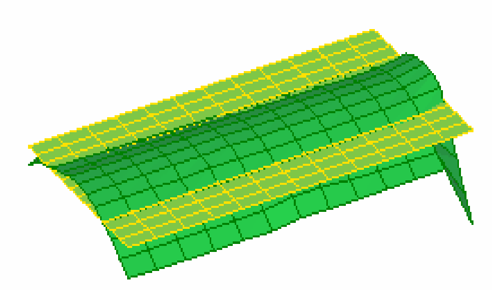
Mode (2,0): f = 7 Hz

Mode (2,1): f = 15 Hz

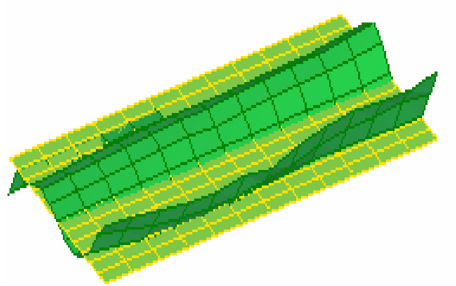
Mode (2,2): f = 34 Hz

Mode (4,4): f = 150 Hz

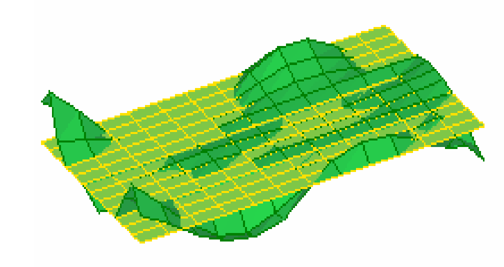
Figure 6: Mode shapes/waveforms: suspended plate.



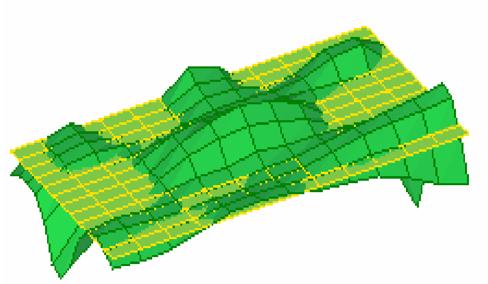
Mode (0,2): f = 18 Hz. As the joists increased stiffness in the longitudinal direction, the first mode deformed along the short axis.



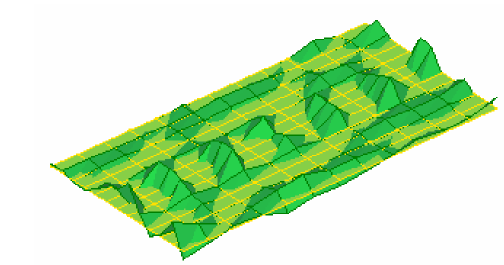
Mode (0,3): f = 36 Hz. The second mode also deformed along the short axis.



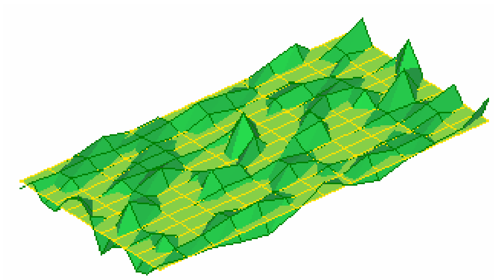
The waveform at f = 45 Hz. The plate was separated into three sub-plates by the joists. Modes formed in the two side sub-plates.



The waveform at f = 97 Hz. The plate was again separated into three sub-plates. The most energetic mode formed in the centre sub-plate.

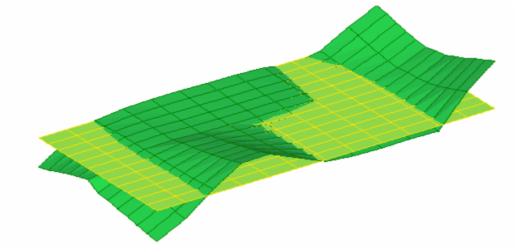


The waveform at f = 441 Hz. The plate was still separated into three sub-plates by joists. Modes formed in the middle sub-plate.

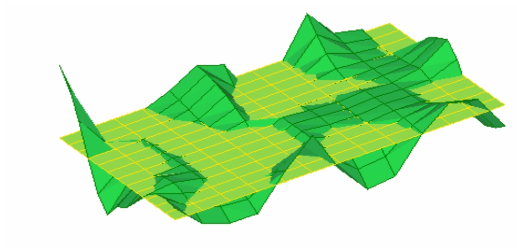


At $f > 450$ Hz, no separation was seen between waveforms.

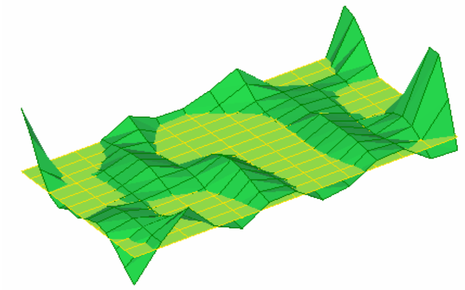
Figure 7: Mode shapes/waveforms: joist-ribbed plate.



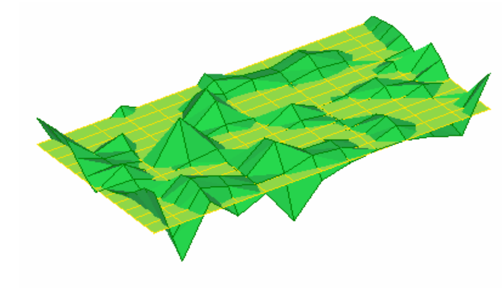
The first mode detected at f = 24 Hz. Timber branders stiffened the plate along its short axis, thereby influencing subsequent bending.



Waveform at f = 96 Hz.

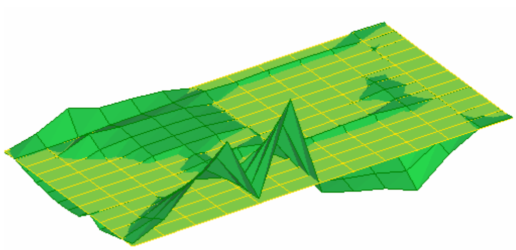


Waveform at f = 128 Hz. The mode was not clear, but did show a tendency to bend about the long axis.

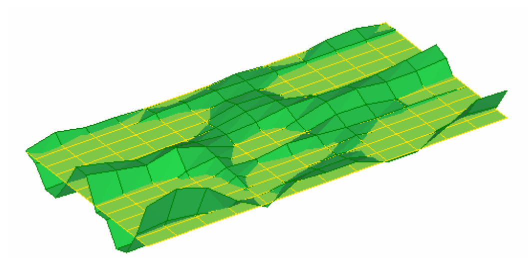


Waveform at f = 248 Hz: no clear modes were recognised.

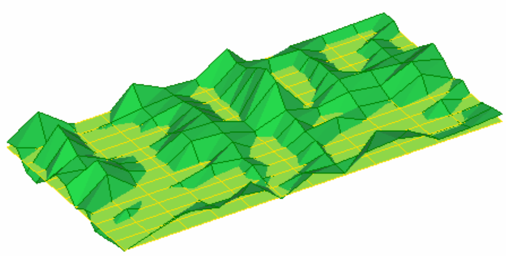
Figure 8: Mode shapes/waveforms: timber brander-ribbed plate.



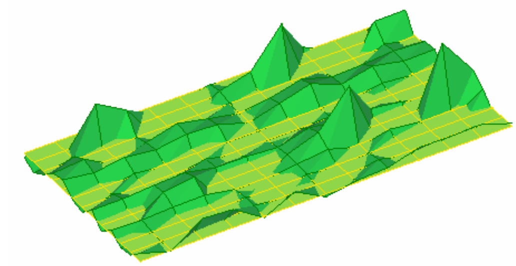
Waveform at f = 24 Hz



Waveform at f = 120 Hz



Waveform at f = 224 Hz



Waveform at f = 352 Hz

Figure 9: Mode shapes/waveforms: resilient bar-ribbed plate.

5. DISCUSSION

The constructive interference of travelling and reflecting waves cause response peaks in the frequency response spectrum. The modal measurements in Section 4 indicate that resilient bars could disturb mode formation; thus one could expect resilient bars to have damped the plate's vibrations compared with an independent, suspended plate. For independently acting plates, the radiation efficiency below their critical frequency is low due to cancellation of the motions of air particles in the near-field caused by the waveforms themselves. Consequently, the disturbance of modes by resilient bars may affect this cancellation and increase radiation efficiency.

Nightingale *et al.*[3] assumed resilient bars removed any coupling between joists and ceiling plates, and thus the modal density and radiation efficiency of independent plates were applied for resilient bar-ribbed plates in their SEA model. The findings of this current work suggest that the modal density and radiation efficiency could be similar to an independent plate. However, the modal behaviour may be more complex and their influence on modal density and radiation efficiency is worthy of further research.

This research also indicated that resilient bars did not perform as stiffeners whereas joists and timber branders *did*. The models for joist- and timber brander-ribbed plates were unsuitable for resilient bar-stiffened structures. Many studies on line connected, stiffened, plates show that the addition of stiffeners creates sub-plates thus increasing the radiation efficiency below the critical frequency[4,9,10]. As resilient bars did *not* cause plate sub-division in this work, such a phenomenon may *not* appear. Simple mass-spring-mass models can not address the influence of resilient bars on the waveforms of plates as discussed elsewhere[8].

6. CONCLUSIONS

The derived bending stiffnesses showed that resilient bars are one order of magnitude stiffer than the equivalent width of 11 mm thick OSB strip. This indicated the possibility of resilient bars performing as stiffeners if the OSB is ribbed by resilient bars. The acceleration levels at different points relative to the fixings were measured on joist-, timber brander-, and resilient bar-ribbed structures. Modal tests were also carried out on these types of structures together with tests on a suspended plate. Both types of tests indicated that resilient bars did not perform as stiffeners in the manner of joists and timber branders. They neither modified the behaviour to orthotropic at low frequencies nor sub-divided the plate into sub-plates at higher frequencies. The models for the plates ribbed by stiffeners, such as joists and timber branders, were not applicable to resilient bar-ribbed/stiffened structures. Resilient bar-ribbed plates also performed differently from independent plates. The modal behaviour of resilient-bar ribbed plates is more complex and their influence on modal density and radiation efficiency is worthy of further research. These findings provided useful information for developing theoretical models for resilient bar structures.

ACKNOWLEDGEMENT

This research was jointly funded by the School of Engineering and Built Environment and Building Performance Centre at Edinburgh Napier University. The Faculty's technicians are thanked for their input during the experimental work.

REFERENCES

1. J.S. Bradley and J.A. Birta, A simple model of the sound insulation of gypsum board on resilient supports, *Noise Control Engng Journal* **49**(5), pp. 216-223, (2001).

2. J. Brunskog and P. Hammer, Measurement of the acoustic properties of resilient, statically tensile loaded devices in lightweight structures, *Building Acoustics,* **9**(2), pp. 99-137, (2002).

3. T.R.T. Nightingale, R.J.M. Craik and J.A. Steel, Statistical energy analysis applied to lightweight constructions, Part I: sound transmission through floors, *Canadian Acoustics,* **23**(3), pp. 41-42, (1995).

4. R.J.M. Craik and R.S. Smith, Sound transmission through double leaf lightweight partitions, Part I: airborne sound, *Appl. Acoust.* **61**(2) pp. 223-245, (2000).

5. S. Schoenwald and T.R.T. Nightingale, Measurement of structural intensity on plate structures, *Canadian Acoustics* **29**(3) pp. 102-103, (2001).

6. L. Cremer, M. Heckl and E.E. Ungar, Structure-borne sound, Springer Verlag, Berlin, 1988.

7. Structural Vibration Solutions A/S, ARTeMIS Tester & Extractor. Operational modal analysis software, Structural Vibration Solutions A/S, Aalborg East, Denmark, 2008.

8. S. Su, Structure-borne sound transmission through resiliently suspended ceilings in timber frame floor/ceiling assemblies, PhD thesis, Edinburgh Napier University, Edinburgh, 2009.

9. G. Maidanik, Response of ribbed panels to reverberant acoustic fields, *J. Acoust. Soc. Am.* **34**(6) pp. 809-826, (1962).

10. F.J. Fahy and P. Gardonio, Sound and structural vibration: radiation, transmission and response. 2nd Edition, Academic Press, Oxford, 2006.