Vibrational performance of metal-webbed timber floors

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VIBRATIONAL PERFORMANCE OF METAL-WEBBED TIMBER FLOORS

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ABSTRACT: Metal web engineered timber joists have been largely used nowadays to replace traditional solid timber joists for constructing intermediate-span timber floors in low-rise houses and long-span floors in commercial buildings. Vibrational criteria become crucial for serviceability design of timber floors and often control the design. This paper presents the study on the dynamic performance of the floors constructed with metal-web joists with focus on modal frequencies, modal shapes and damping. The studied parameters included spacing of joists, type, size, number and location of strongback, ceiling, etc. In general, joist spacing, strongback bracings and ceiling did not significantly influence the fundamental frequency and damping ratio for Mode 1-1, both required for the design of timber floors, but they did influence those of higher modes. The measured damping ratio for the fundamental mode was 0.87% on average, which is below the 1% recommended in Eurocode 5 and much smaller than the 2% recommended in the UK National Annex. The use of strongback, however, could considerably reduce the number of first-order modes below 40 Hz, which, used to determine the unit impulse velocity response, can thus be decreased notably.

KEYWORDS: Damping ratio, Frequency, Metal-web joists, Mode shapes, Timber floors, Eurocodes

1 INTRODUCTION [123]

With the rapid development of timber construction industries in the past few decades, metal web engineered timber joists have been largely used to replace traditional solid timber joists for constructing intermediate-span timber floors in low-rise houses and long-span floors in commercial buildings.

The metal web joist combines the lightness of timber flanges with the strength of strut steel web and spans far larger distances than alternative timber products, which provides unequalled design freedom across a wide range of applications for both floor and roof in domestic, industrial and commercial applications. Exceptional floor performance from a minimum fixing surface can ease floor construction, controls shrinkage, and reduces tiresome return visits and remedial work. Unique open web design provides an easy access for pipelines and electrical cables. Even on long spans, no herring-bone strutting is necessary with the metal web joist system. If the span exceeds 4.0 m, a strong-back is installed at mid-span. The metal web joist does not just joist floors and it can adequately span for flat and pitched roofs. Spanning capability and timber flanges make metal web joist a more desirable alternative to all steel systems.

In the Eurocode 5 Part 1-1 [1] and the corresponding UK National Annex [2], vibrational criteria become crucial for serviceability design of timber floors and often control the overall design [3, 4]. Those criteria include fundamental frequency, unit point load deflection and unit impulse velocity. The dynamic response of timber flooring systems has recently been extensively investigated at Edinburgh Napier University [5] and a project *Experimentally evaluating the vibrational performance of metal-web joist floors enhanced using strongback bracing* was conducted on behalf of the Metal Web Working Group, comprising ITW Alpine, Gang Nail Systems, MiTek Industries Ltd and Wolf Systems. The series tests on metal web joist floors were intended to experimentally evaluate the effects of joist spacing, strongback bracings and ceiling on the dynamic response modal parameters of the floors so as to assess Eurocode 5 Part 1-1 design criteria.

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2 EXPERIMENTAL WORK

Nine floors (Floors A to I) were included for this series of tests, with the variations on the following parameters: joist spacing, strongback (with or without), number and location of strongback, size of strongback, type of strongback and ceiling (with or without). Table 1 details the configurations of the tested floors.

Table 1: *Tested floors with various configurations*

Floor	Joist spacing (mm)	Strongback	Ceiling
A	600	None	None
B		47 × 147 mm TR26 at mid-span	
C		45 × 147 mm Kerto at mid-span	
D		35 × 97 mm TR26 at one-third points	
E		35 × 97 mm TR26 at mid-span	
F		35 × 97 mm TR26 at mid-span	Yes
G	400	None	None
H		35 × 97 mm TR26 at mid-span	
I		35 × 97 mm TR26 at mid-span	Yes

2.1 Floor Construction

All the tested floors were constructed with 5.25 m WOLF Easi-Joist metal web joists with 47 mm × 97 mm TR26 chords and MS250 steel webs, giving an overall joist depth of 254 mm. The deck was formed from 22 mm T&G Caberboard P5 moisture resistant chipboard sheets of 2400 mm × 600 mm fixed to the metal web joists and to the end bracing which was in turn fixed to the ends of the joists, with Twinquik Plusdrive single threaded countersunk steel woodscrews 8g × 50 mm long at 300 mm centres.

The C16 timber end bracings of 47 mm × 222 mm were fixed to both ends of the metal web joists flush with the top surface of the joists, with 3 no 5.0 × 100 mm Speed-Drive countersunk head woodscrews through the bracing into the end noggings. The continuous bracings saved cutting noggings between the joists which are securely fixed to the support structure.

Ceiling noggings of 47 mm × 72 mm solid timber were fixed to the metal web joists using Cullen UZ/47 clips and 3.75 × 30 mm square twist nails at plasterboard-joist joints. The ceiling of 12.5 mm Gyproc wallboard was fixed to the joists and noggings with Gyproc drywall screws at 150 mm centres along the perimeter of the sheets and at 230 mm centres where ceiling crosses internal joists.

The material, size and location of a strongback varied with the test but were fixed to strongback noggings. The noggings of 47 mm × 72 mm solid timber were cut 1 mm short of the gap between top and bottom chords and fixed to both chords with 2 no 5.0 × 100 mm Speed-Drive countersunk head steel woodscrews. The strongback was then placed tightly against the underside of the top chord and fixed to the strongback noggings with 3 no 5.0 × 100 mm Speed-Drive countersunk head steel woodscrews.

The tested floors were fixed onto the support structures at both ends using woodscrews, with an effective span of 5.15 m. The support structure for the floors, manufactured by Donaldson Timber Engineering, comprised two 2-ply chord girder walls of 1.2 m × 5.0 m and ten 45° triangular outriggers to support walls, 5 for each end. The top chords of the girder walls were manufactured from 47 mm × 147 mm solid timber and the bottom chords and bracings were from 47 mm × 72 mm solid timber. The outriggers had a cross-section of 35 mm × 72 mm. All the chord girder walls and outriggers were directly connected to the concrete floor. Figure 1 shows a typical metal web joist floor (Floor A).

Figure 1: *A typical metal web joist floor (Floor A)*

2.2 Procedure for vibrational test

Dynamic tests were conducted on all the floors to obtain the required information with regard to the vibrational performance of metal web joist floors. The dynamic testing consisted of an output-only modal analysis, which was carried out on all the metal web joist floors to obtain vibrational parameters, including modal frequencies, damping ratios and modal shapes.

The equipment used for the dynamic tests included a TEAC LX-10/10L data recorder, Pinocchio vibraphone AX 150 V sensors, a laptop with the ARTeMIS Testor and Extractor modal analysis software package, and a trolley with attached weight.

A grid of 5 × 5 = 25 equally distributed node points was drawn on the floor surface, including points along the central lines and edges. The node points served as measurement points. This grid was also drawn to scale in the ARTeMIS Testor software programme, which was used for conducting the vibration tests. Five roving sensors were used to cover all 25 measurement points after 5 measurements (see the green arrows in Figure 2).

Additional two sensors were placed as references at two pre-fixed locations where all vibration modes of interest could be detected (see the blue arrows in Figure 2). Here, x-axis indicates the span direction and y-axis indicates the transverse direction which is parallel to the support line.

The floor was excited to vibrate by using a specially designed trolley. The trolley consisted of a squared wooden board of 350 mm × 350 mm, four small plastic wheels and a long wooden handle, and was loaded with bagged aggregates, forming a total weight of 5.0 kg. This trolley was pushed up to the central line of the floor from the floor edge and pulled back while moving it from one side of the floor to the other side, until the whole floor area was fully covered to excite the different vibrational modes. The time duration for each measurement was set to be 100 seconds. The Pinocchio Vibraphone sensors transformed the vertical vibrational movements of the floor into electrical signals, which were recorded by the data recorder.

The recorded signals were processed using two different analysing techniques embedded in the ARTeMIS Extractor software: the Enhanced Frequency Domain Decomposition (EFDD) and the Stochastic Subspace Identification (SSI). In the EFDD the signals were processed by a Fast Fourier Transform (FFT) to obtain the spectral densities in the frequency domain and an inverse FFT was applied to the spectral densities for the modal parameter estimation, while in the SSI a pure time domain approach is used. Both methods had been used so as to verify the results [5]. Those obtained by the SSI are presented in this report because of its smaller variations. Further information and validation on the SSI can be found in the publications by Brincker and Andersen [6] and by Peeters and De Roeck [7], respectively.

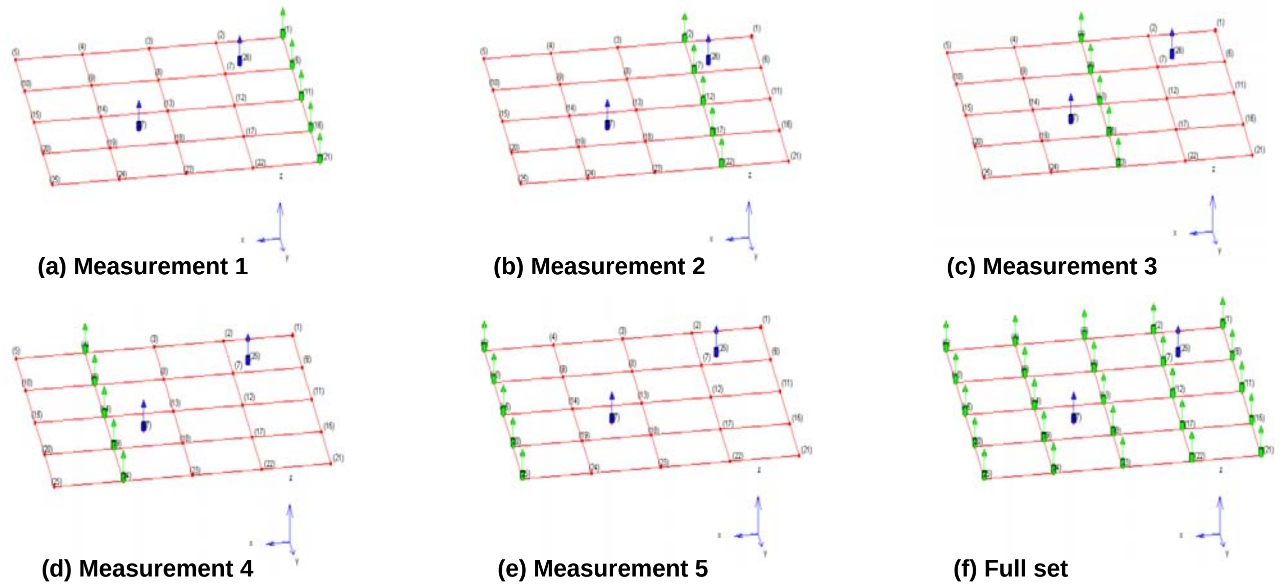


Figure 2: *Arrangement of vibration sensors on the metal web joist floor*

3 TEST RESULTS AND DISCUSSION

Table 2 presents the results of vibrational parameters, including all first-order modal frequencies up to 40 Hz and the corresponding damping ratios. A first-order mode implies that there is only one (half sine) wave along the floor span direction. The first subscript for the frequency f and the damping ratio ζ stands for the number of waves in the floor span direction and the second subscript stand for the number of waves in the transverse direction (along the support direction). For example, $f_{1,2}$ stands for the frequency of the mode with one (half sine) wave in the floor span direction but two waves (one full sine) in the transverse direction. The measured fundamental frequencies and corresponding damping ratios (Mode 1-1) are highlighted. In Eurocode 5 Part 1-1, a parameter n_{40}, the number of first-order modes with natural frequencies up to 40 Hz, is defined for calculating the unit impulse velocity v, and the measured n_{40} for each tested floor is also summarised in Table 2. Table 3 lists the values of damping and the frequencies up to 40 Hz of the second-order modes. Further higher modes were hardly found for the frequency range up to 40 Hz.

Figure 3 shows the first-order mode shapes of a typical floor (Floor F) and Figure 4 shows the corresponding second-order mode shapes. The shape of Mode 1-6 appeared to be similar to the one of Mode 1-4 due to the number and location of measurement points used.

3.1 EFFECT ON MODAL FREQUENCIES

Varying joist spacing and adding ceiling or strongback bracings varied the mass and stiffness properties of the floors. The effect of both on natural frequencies was reverse, but the influencing degree can however vary. Such effects on the metal web joist floors are presented in this paper and further detail of the test results will be published separately in the future.

Table 2: Frequencies and damping ratios of first-order modes up to 40 Hz

Floor	$f_{1,1}$ (Hz)	$\zeta_{1,1}$ (%)	$f_{1,2}$ (Hz)	$\zeta_{1,2}$ (%)	$f_{1,3}$ (Hz)	$\zeta_{1,3}$ (%)	$f_{1,4}$ (Hz)	$\zeta_{1,4}$ (%)	
A	**14.42**	**0.88**	16.01	0.95	18.07	0.79	20.60	0.88	
B	**14.59**	**0.83**	16.23	0.70	21.22	1.08	28.40	1.03	
C	**14.55**	**0.88**	16.21	0.77	21.27	0.91	28.27	1.34	
D	**14.49**	**0.87**	16.18	0.80	20.09	0.85	25.27	1.15	
E	**14.53**	**0.79**	16.21	0.83	19.63	0.90	24.10	1.43	
F	**13.43**	**0.99**	15.52	0.85	19.78	0.83	25.12	1.38	
G	**15.54**	**0.77**	16.99	1.05	18.80	1.13	20.97	1.39	
H	**15.47**	**0.94**	17.02	0.73	19.87	1.01	23.97	1.11	
I	**14.25**	**0.80**	16.16	0.73	19.74	0.98	24.69	1.19	
Mean		**0.86**		0.82		0.94		1.21	
Floor	$f_{1,5}$ (Hz)	$\zeta_{1,5}$ (%)	$f_{1,6}$ (Hz)	$\zeta_{1,6}$ (%)	$f_{1,7}$ (Hz)	$\zeta_{1,7}$ (%)	$f_{1,8}$ (Hz)	$\zeta_{1,8}$ (%)	n_{40}
A	23.71	1.03	27.28	0.85	31.34	1.18	35.26	1.20	8
B	37.09	1.15	-	-	-	-	-	-	5
C	37.08	1.30	-	-	-	-	-	-	5
D	33.81	1.29	-	-	-	-	-	-	5
E	30.47	1.37	37.24	1.40	-	-	-	-	6
F	32.17	1.59	39.35	1.28	-	-	-	-	6
G	23.77	1.46	27.37	1.24	30.92	1.17	34.23	1.05	8
H	30.04	0.96	36.72	1.22	-	-	-	-	6
I	31.69	1.36	39.13	1.18	-	-	-	-	6
Mean		1.28		1.19		1.18		1.12	

Table 3: Frequencies and damping ratios of second-order modes up to 40 Hz

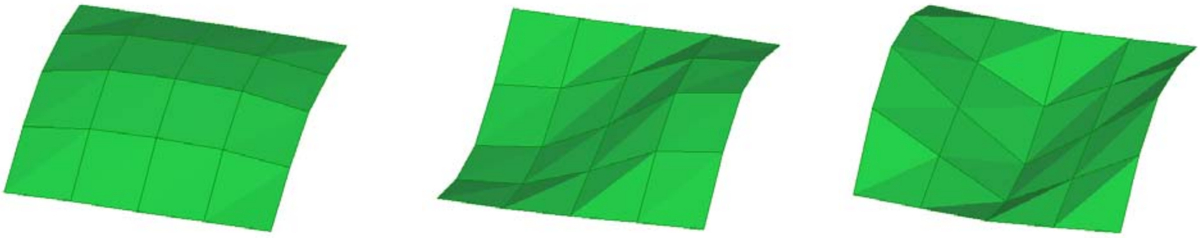
Floor	$f_{2,1}$ (Hz)	$\zeta_{2,1}$ (%)	$f_{2,2}$ (Hz)	$\zeta_{2,2}$ (%)	$f_{2,3}$ (Hz)	$\zeta_{2,3}$ (%)	$f_{2,4}$ (Hz)	$\zeta_{2,4}$ (%)
A	34.20	1.73	37.16	1.86	39.07	1.19	-	-
B	35.19	1.93	37.73	1.41	(40.09)	(1.03)	-	-
C	35.17	1.63	37.95	1.50	(40.08)	(1.56)	-	-
D	34.82	1.45	37.60	1.23	(41.14)	(1.15)	-	-
E	35.52	1.70	37.71	1.60	39.95	1.43	-	-
F	31.74	1.77	33.45	1.40	36.63	1.24	39.76	1.51
G	37.87	1.84	40.68	1.14	-	-	-	-
H	38.07	1.68	40.63	1.11	-	-	-	-
I	34.57	2.68	37.60	1.40	39.60	1.60	(42.27)	(0.79)
Mean	34.20	1.73	37.16	1.86	39.07	1.19	-	-

3.1.1 Joist spacing

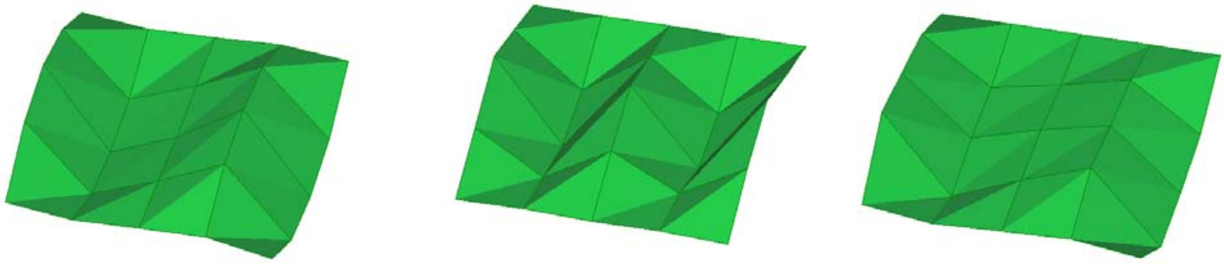
The test results showed an increase in the first three modal frequencies for smaller spacing. In particular the increment for the fundamental frequency (Mode 1-1) varies from 0.8 Hz to 1.1 Hz. For higher modes, a decrease in joist spacing slightly decreased the corresponding frequencies for the floors stiffened by strongback and ceiling. In general, smaller spacing would slightly increase the fundamental frequency because the increase in stiffness overwhelmed the increase in mass.

3.1.2 Ceiling

The test results showed a decrease in the first two modal frequencies for the floors with ceiling due to the extra weight of ceiling. The increase in the stiffness due to the composite effect could not compensate the increase in the weight. The drop for the fundamental frequency (Mode 1-1) was between 1.1 Hz and 1.2 Hz. For higher modes, the ceiling would increase the frequencies and for Mode 1-6 an increase of up to 2.4 Hz was found.

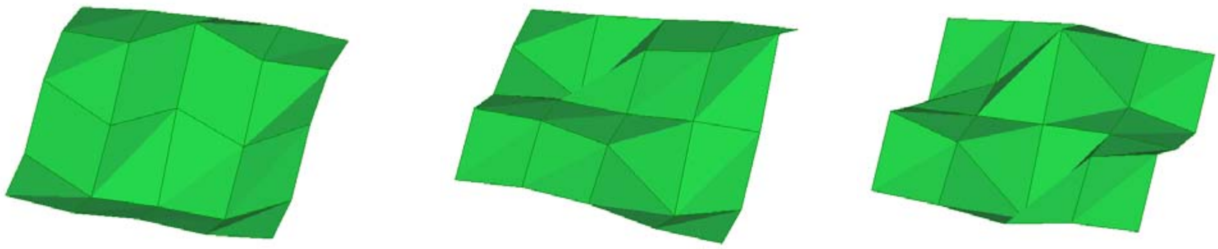


Mode 1-1: $f_{1,1}$ = 13.43 Hz, $\zeta_{1,1}$ = 0.99% **Mode 1-2: $f_{1,2}$ = 15.52 Hz, $\zeta_{1,2}$ = 0.85%** **Mode 1-3: $f_{1,3}$ = 19.78 Hz, $\zeta_{1,3}$ = 0.83%**



Mode 1-4: $f_{1,4}$ = 25.12 Hz, $\zeta_{1,4}$ = 1.38% **Mode 1-5: $f_{1,5}$ = 32.17 Hz, $\zeta_{1,5}$ = 1.59%** **Mode 1-6: $f_{1,6}$ = 39.35 Hz, $\zeta_{1,6}$ = 1.28%**

Figure 3: *First-order mode shapes of a typical floor (Floor F)*



Mode 2-1: $f_{2,1}$ = 31.74 Hz, $\zeta_{2,1}$ = 1.77% **Mode 2-2: $f_{2,2}$ = 33.45 Hz, $\zeta_{2,2}$ = 1.40%** **Mode 2-3: $f_{2,3}$ = 36.63 Hz, $\zeta_{2,3}$ = 1.24%**

Figure 4: *Second-order mode shapes of a typical floor (Floor F)*

3.1.3 Number of strongbacks

The test results showed that the existence of different numbers of strongback had little effect on the first two modal frequencies of the floors but largely influenced the higher modal frequencies. The increase in the number of strongbacks largely increased the higher modal frequencies. In particular, the use of two strongbacks could increase the frequency of the floors with 600 mm joist spacing by 4.7 Hz for Mode 1-4 and 10.1 Hz for Mode 1-5. Even a single strongback could also increase the frequency for Mode 1-6 by about 10 Hz for the floors with different joist spacings.

3.1.4 Size of strongback

The test results showed that the increase in strongback size had little effect on the first two modal frequencies of the floors but largely influenced the higher modal frequencies. The increase in strongback size largely increased the higher modal frequencies. For example, the use of a single 35 mm × 97 mm TR26 strongback at mid-span could increase the frequency of the floors with 400 mm joist spacing by 6.8 Hz for Mode 1-5 and 10.0 Hz for Mode 1-6. A larger single 47 mm × 147 mm TR26 strongback at mid-span also increased the frequency for Mode 1-6 by up to 13.4 Hz.

3.1.5 Type of strongbacks

Both strongbacks had similar size and stiffness (E_0 = 12669 N/mm^2 and 11200 N/mm^2 respectively) so similar dynamic behaviour could be expected. Little difference in frequency for all modes was found.

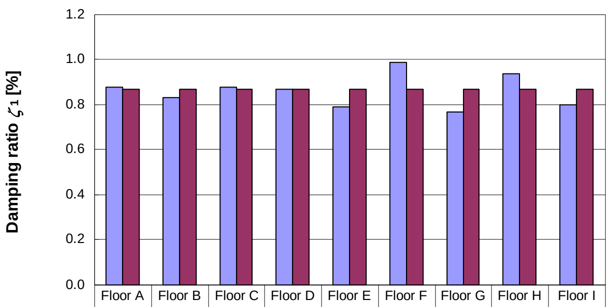
3.2 UNIT IMPULSE VELOCITY

In this study, damping and the number of first-order modes below 40 Hz were investigated as parameters for the design of metal web joist floors to the serviceability requirements for unit impulse velocity specified in Eurocode 5 Part 1-1. Damping is an intrinsic structural property of the flooring system and represents the ability to absorb and dissipate the vibrational kinetic energy. The higher the damping, the more rapidly the vibrational energy dissipates.

3.2.1 Damping

The variation in damping due to structural modifications is often inconclusive. There can, however, be certain structural configurations, whose damping characteristics definitely differ from others, such as metal-web joist floors' from timber I-joist floors' [5]. Damping is an important factor for the evaluation of dynamic responses and it is used in structural design, such as Eurocode 5 Part 1-1 [1]. The damping of the fundamental mode of vibration of the metal-web joist floors was 0.87% on average, which is below the recommended design values of 1% (Eurocode 5 Part 1-1) and 2% (the UK National Annex to this part), and the consequence of this was extensively investigated by Weckendorf [5], whose study also included the examination and consideration of damping corresponding to higher vibration modes and statistical analysis so as to identify suitable damping values for different aspects of floor design.

Figure 5 shows the measured damping ratios of metal web joist floors for Mode 1-1, which varied from 0.77% to 0.99% with an average of 0.87%.



	Floor A	Floor B	Floor C	Floor D	Floor E	Floor F	Floor G	Floor H	Floor I
Measured	0.88	0.83	0.88	0.87	0.79	0.99	0.77	0.94	0.80
Average	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87

Figure 5: *Measured damping ratios of metal web joist floors for Mode 1-1*

3.2.2 Number of first-order modes below 40 Hz

The number of first-order modes below 40 Hz, required for the calculation of the velocity response following Eurocode 5 Part 1-1, could be significantly reduced by the use of strongback bracings. The stiffer the strongback, the lower the value of n_{40}. The use of 47 mm × 147 mm TR26 and 45 mm × 147 mm Kerto S led to the lowest n_{40}. For example, the measured n_{40} value decreased from 8 for the floor without strongback bracings and ceiling, at 600 mm joist spacing, to 5, down by 3 or 37.5%. The use of ceiling decreased the measured n_{40} from 8 to 6, down by 2 or 25%. No difference was found in the measured n_{40} values for the floors with and without ceiling but with strongback bracings. Larger number of strongback bracings decreased the measured n_{40} but the joist spacing showed little impact.

4 CONCLUSIONS

Experimental investigations have been carried out on the vibrational performance of metal web joist floors and the enhancement using strongback bracings. Vibrational properties including modal frequencies and modal damping ratios as serviceability limit design parameters have been measured and analysed for varied joist spacing, number, size, location and type of strongback bracings, and ceiling. Joist spacing, strongback bracings and ceiling did not largely influence the fundamental frequency (Mode 1-1) but influenced higher modal frequencies. All tested floors had fundamental frequencies over 14 Hz which are greater than the threshold level of 8 Hz given in Eurocode 5 Part 1-1.

Joist spacing, strongback bracings and ceiling did not largely influence the damping ratio of the fundamental mode (Mode 1-1), which is used for calculating the unit impulse velocity limit for floor design. The average measured damping ratio of the fundamental mode was 0.87%. This is below the 1% recommended in Eurocode 5 Part 1-1 and much smaller than 2% recommended in the UK National Annex to the code.

Therefore, a damping ratio of 1% given in Eurocode 5 Part 1-1 may be a better option for the metal web joist floors because this value is closer to the measured ones. However, the value suggested in Eurocode 5 Part 1-1 should only be taken as long as not other damping values would be proven to be more appropriate. Tentatively, more purposeful damping ratios for the design are suggested in [5].

The increase in number and size of strongback bracings largely decreased the number of first-order modes with natural frequencies up to 40 Hz, which can in turn significantly decrease the unit impulse velocity and thus result in easier fulfilment of the velocity design criterion. Therefore, strongback bracings should be used to enhance vibrational floor performances, not only with respect to velocity response.

ACKNOWLEDGEMENTS

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