Experimental Characterisation of Dynamic Properties of an All-FRP Truss Bridge

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ABSTRACT

Fibre Reinforced Polymers (FRPs) have increasingly been utilised for construction of pedestrian bridges due to high strength- and stiffness-to-weight ratios, low maintenance costs and quick installation. Their relatively low mass and stiffness make these bridges potentially susceptible to vibration serviceability problems, which increasingly govern the design. Currently, the wider application of FRPs in civil engineering is hindered by the lack of experimental insight in dynamic performance of as-built structures. This paper presents an experimental investigation on a 25 m long glass-FRP truss footbridge in Italy. Ambient vibration tests were conducted to identify the dynamic properties. The peak-picking method and stochastic subspace identification approach were employed for modal parameter identification. The two methods produced very consistent results. Eight vibration modes were identified in the frequency range up to 10 Hz. Two lateral flexural vibration modes having natural frequencies of 5.8 Hz and 9.6 Hz were identified, as well as two vertical flexural modes (at 7.5 Hz and 8.1 Hz) and four torsional modes (at 2.1 Hz, 2.7 Hz, 4.8 Hz and 9.3 Hz). Damping ratios for all modes up to 10Hz except the eighth mode were above 1.2%.

Keywords: FRP truss footbridge, Dynamic properties, Ambient vibration testing, Peak picking method, Stochastic subspace identification method

1. Introduction

The Fibre Reinforced Polymer (FRP) composites have become a popular choice of structural material for footbridges and road bridges [1-5] thanks to their favourable properties, including high strength- and stiffness-to-weight ratios, good durability and short installation time. Owing to relatively low stiffness and proneness to large deformation, the FRP composites are usually limited to short- to medium- span beam bridges. Longer bridge spans could be achieved if the FRP composites were used in truss bridges, suspension bridges or cable-stayed bridges, in which materials can be utilised to their highest potential.

Vibration serviceability is increasingly found to govern the design of FRP structures. A sound knowledge and understanding of their dynamic characteristics is important for developing robust serviceability design procedures. Currently, there is lack of experimental data on the dynamic characteristics of FRP structures. Existing design guidance used in conventional material designs is usually employed in the design of FRP structures, which may lead to a conservative solution and compromise the benefits of using FRP composites. In addition, insufficient knowledge about the dynamic properties of FRP structures lowers the confidence of structural engineers, which hinders the wide application of this new material. Extensive and comprehensive experimental testing of dynamic performance of as-built FRP structures is required to inform design of FRP structures against dynamic loading. This paper provides a rare insight into the dynamic features of a truss footbridge at the outskirts of Prato, Italy.

The paper starts with a description of the FRP bridge in Section 2, followed by a description of the ambient-based modal testing in Section 3. Identified modal parameters are reported in Section 4 with conclusions from their evaluation made in Section 5.

2. Bridge description

The Prato Bridge is a simply supported 25m truss bridge for pedestrians and cyclists. It was open in 2008 and it crosses a busy dual carriageway at the outskirts of Prato, Italy (Fig. 1). The bridge is made of pultruded glass-FRP channel sections, with bolted connections consisting of stainless steel plates and bolts. FRP plates provide additional lateral bracing. The deck is 2.5m wide at the middle and 3.6 m at the ends and is made of a number of pultruded FRP planks, each 5m long and 500mm wide and 40mm deep, bolted at the ends as well as at the midspan to transverse members below. Additional beam elements provide contact support at the planks quarter points. A high metal mesh provides a barrier at the slides of the bridge. The bridge weighs a total of around 8 tonnes [6] and rests on two concrete piers, each 5.7m high from the ground (see Fig. 1 a).

(a) **(b)**

Fig. 1 The Prato Bridge: (a) side view; (b) deck view

3. Ambient vibration testing

The dynamic characteristics of the Prato footbridge were identified using ambient vibration testing, which requires measuring the acceleration responses of the deck under the natural excitation (in this case the wind and road traffic passing underneath the bridge). The testing programme was conducted by the University of Warwick (UK) and Iuav University of Venice (Italy) on 29 November 2016. The bridge was closed to pedestrian traffic during data recording.

To identify the vibration modes of the bridge, the measurement grid shown in Fig. 2 was employed, which includes 22 measurement stations on the deck at the location of each truss joint. Lateral and vertical acceleration measurement campaigns were carried out separately using two sets of different data acquisition systems and accelerometers. Vertical accelerations at all the MSs except the MS 54 were recorded using eleven PCB 393C accelerometers having nominal sensitivity of 1000 mV/g (Fig. 3 a). The vertical acceleration measurement campaign was divided into two set-ups. Lateral accelerations were recorded at the MSs 1, 3, 4, 6, 8, 9 and 11 using four Dytran accelerometers having nominal sensitivity of 500 mV/g (Fig. 3 b). Lateral and vertical accelerometers at MS 4 were used as reference vibration sensors, whilst the other accelerometers are the roving transducers. The duration for each measurement set-up was 10 minutes. The sampling frequencies for vertical and lateral acceleration measurement were 600 Hz and 256 Hz.

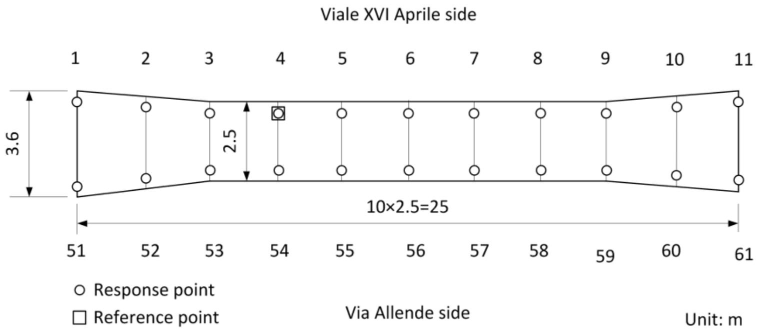


Fig. 2 Measurement grid on the deck

(a)

(b)

Fig. 3 Accelerometers on the deck: (a) Vertical: PCB 393C accelerometer; (b) Lateral: Dytran accelerator

4. Modal parameter identification

The modal parameters of the Prato footbridge were identified using the frequency-domain peak-picking method and the time-domain stochastic Sub-Space Identification (SSI) method. Whilst the peak-picking method was chosen to identify natural frequencies only, the SSI method was employed to identify natural frequencies, damping ratios and mode shapes.

4.1. Peak-picking method

Since certain modes may not be observable in the power spectrum density at a particular measurement station, the Averaged Normalised Power Spectral Densities (ANPSD) [7, 8] of all the measurement stations were used to identify the natural frequencies. Fig. 4 and Fig. 5 display the ANPSDs of the vertical and lateral accelerations, respectively. The peaks indicate the natural frequencies of the bridge. The analysis identified six peaks at frequencies of 2.1 Hz, 2.7 Hz, 4.8 Hz, 7.4 Hz, 8.1 Hz and 9.3 Hz that correspond to either vertical bending or torsional modes. By contrast, Fig. 5 shows that there are two lateral bending modes at 5.8 Hz and 9.6 Hz.

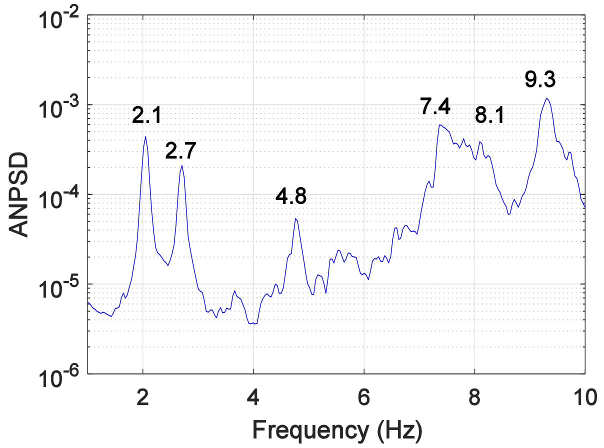


Fig. 4 ANPSD for vertical acceleration records

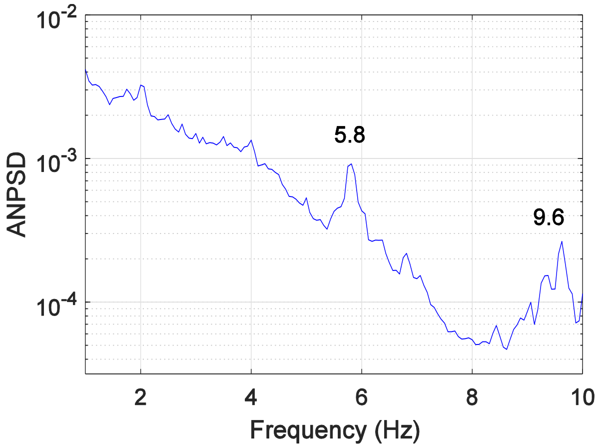


Fig. 5 ANPSD for lateral acceleration records

4.2. Stochastic subspace identification

A reference-based data-driven stochastic SSI algorithm, built in the Matlab toolbox MACEC 3.2 [9-12], was used for data pre-processing and modal parameter identification. The measured data were first visually inspected. It was found that the vertical accelerations corresponding to MS 10 and MS 59 were corrupted by intermittent spikes probably due to connection problems. These two abnormal signals were excluded from further signal processing. All the other measured data were de-trended before further analysis.

The vertical accelerations at the MSs presented in Fig. 6 were filtered using a low-pass filter with a cut-off frequency of 48 Hz and resampled at 60 Hz. The state-space model order parameter was set to 160. The stabilisation criteria were set to 1% for frequency, 5% for damping, 1% for modal assurance criterion and 0.8 for the low bound of the modal phase collinearity. Fig. 7 shows the stabilisation diagram from the vertical acceleration measurement at MSs 1 - 9 and 10, with the power spectral density of all the signals superimposed. Modes below 10 Hz were inferred by the stable poles depicted by large red circles. It can be seen that the stable poles for natural frequencies are clearly identified, except for the one around 8.1 Hz. In total six modes were identified using the vertical accelerations, including four torsional and two vertical bending modes, as illustrated in Fig. 8 - Fig. 13. All the vertical and torsional modes found by the peak-picking method are identified by the SSI method. The vertical bending modes shown in Fig. 11 and Fig. 12 are very similar. One of the possible reasons for the two similar vertical bending modes is that the whole bridge is a truss bridge but the test was only conducted on the deck. That is, the vertical bending modes might be parts of the global modes of the whole structure, including top chords.

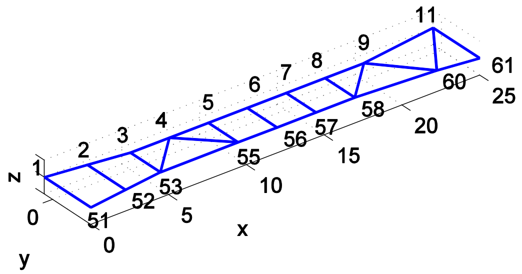


Fig. 6 MSs with vertical acceleration used for modal parameter identification

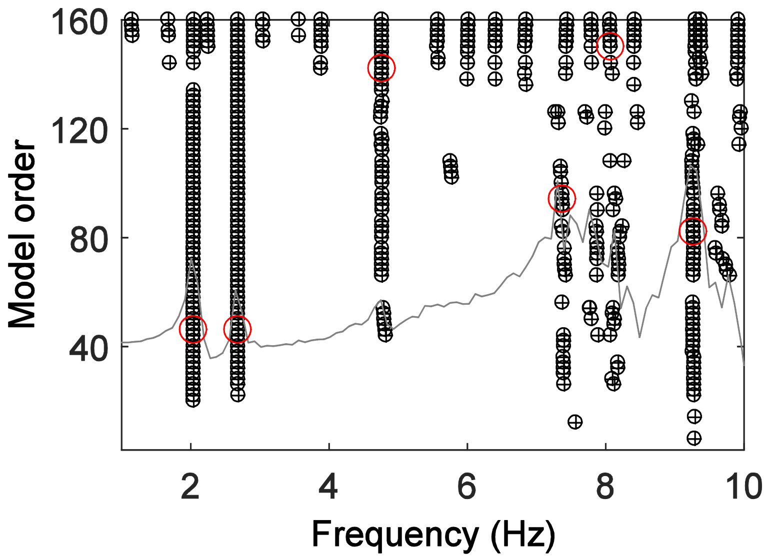
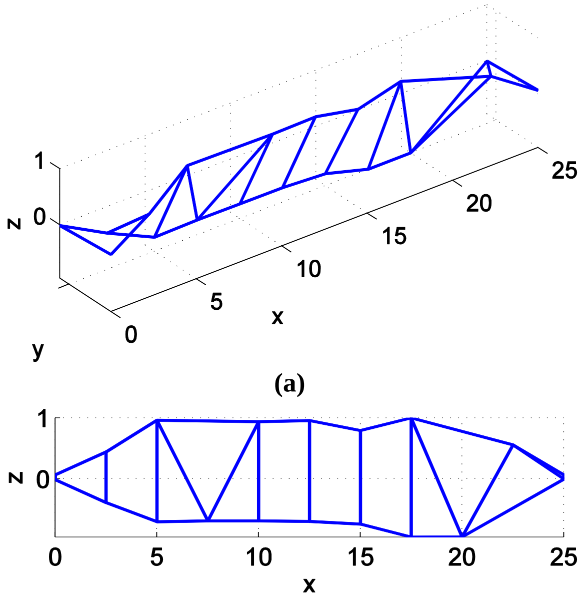


Fig. 7 Stabilisation diagram from the vertical acceleration measurement at MSs 1 - 9 and 10



(a)

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Fig. 8 First torsional mode ($f = 2.1$ Hz, $\zeta = 1.6\%$)

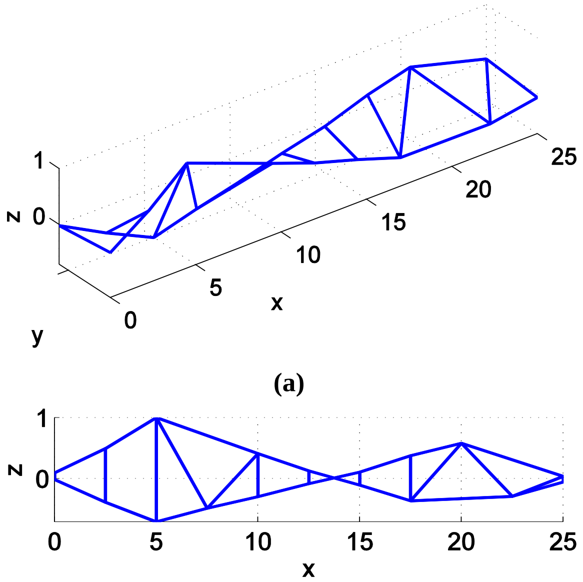

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Fig. 9 Second torsional mode ($f = 2.7$ Hz, $\zeta = 1.3\%$)

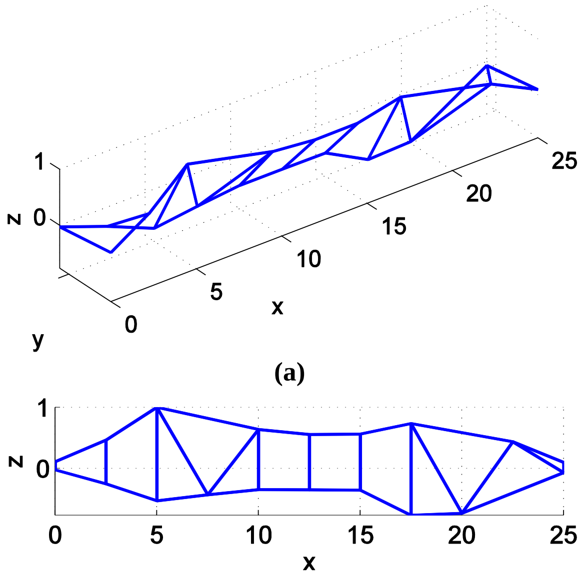

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Fig. 10 Third torsional mode ($f = 4.8$ **Hz,** $\zeta = 1.4\%$ **)**

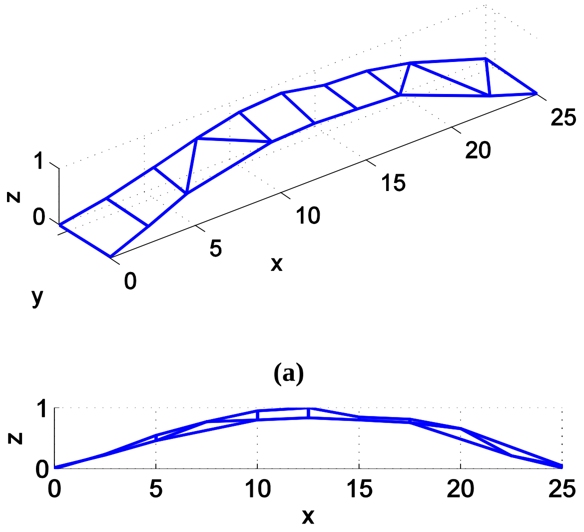

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Fig. 11 First vertical bending mode ($f = 7.5$ **Hz,** $\zeta = 2.6\%$ **)**

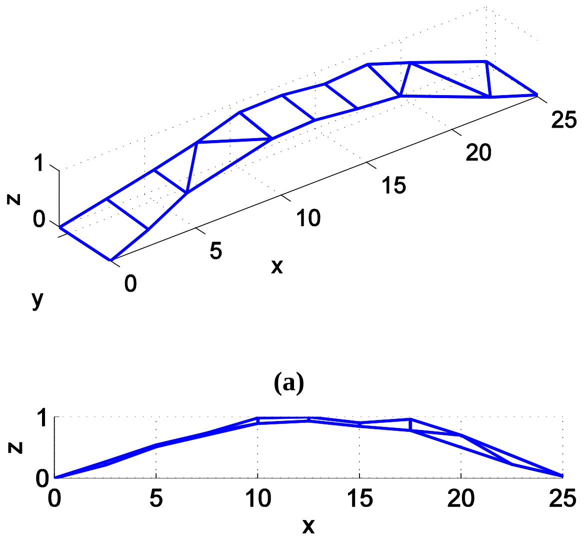

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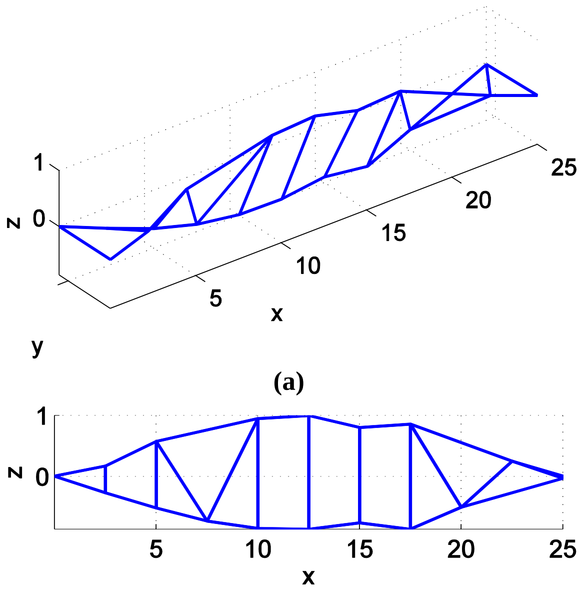
Fig. 12 Second vertical bending mode ($f = 8.1$ **Hz,** $\zeta = 1.7\%$ **)**



(a)

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Fig. 13 Fourth torsional mode ($f = 9.3$ **Hz,** $\zeta = 1.2\%$ **)**

Similarly, the lateral accelerations at the MSs 1, 3, 4, 6, 8, 9 and 11 (Fig. 14) were filtered using a low-pass filter with a cut-off frequency of 34.1 Hz (80% of the resampling frequency) and resampled at 42.7 Hz (a fifth of the sampling frequency). All other parameters for system identification were the same as those used in processing vertical accelerations. The lateral vibrations at the MSs 51, 53, 54, 56, 58, 59 and 61 are slave to those at the MSs 1, 3, 4, 6, 8, 9 and 11. Two lateral bending modes were identified, as shown in Fig. 15 and Fig. 16, which were also inferred by the peak-picking method.

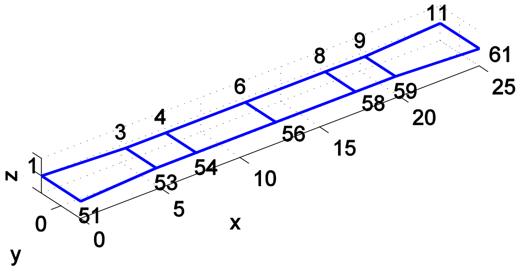

Fig. 14 Grid for lateral mode shape demonstration

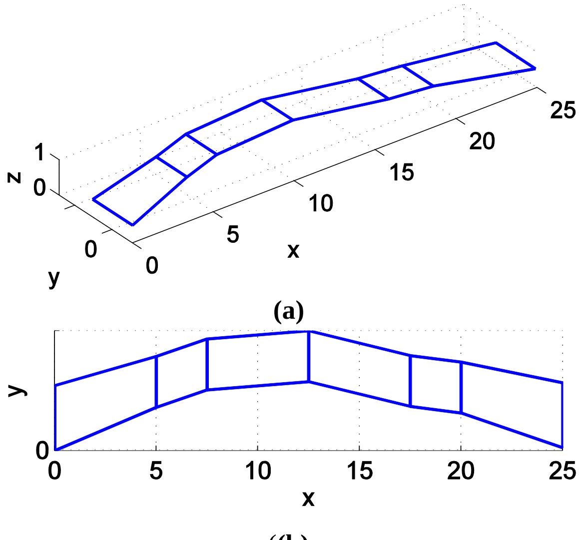

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Fig. 15 First lateral mode ($f = 5.8$ Hz, $\zeta = 1.8\%$)

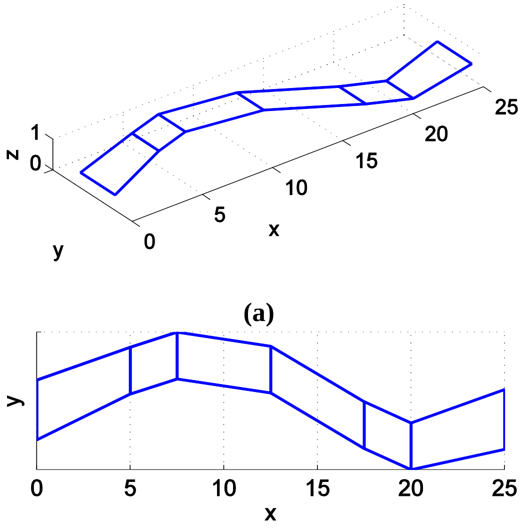

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Fig. 16 Second lateral mode ($f = 9.6$ Hz, $\zeta = 0.6\%$)

Table 1 Identified modal parameters of the Prato Bridge

No.	Mode description	SSI				Peak-picking	
		Vertical acceleration		Lateral acceleration		Vertical acceleration	Lateral acceleration
		Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Frequency (Hz)
1	1st T	2.1	1.6	/	/	2.1	/
2	2nd T	2.7	1.3	/	/	2.7	/
3	3rd T	4.8	1.4	/	/	4.8	/
4	1st LD	/	/	5.8	1.8	/	5.8
5	1st VD	7.5	2.6	/	/	7.4	/
6	2nd VD	8.1	1.7	/	/	8.1	/
7	4th T	9.3	1.2	/	/	9.3	/
8	2nd LD	/	/	9.6	0.6	/	9.6

VD: vertical bending mode; LD: lateral bending mode; T: torsional mode

The identified modes are summarised in Table 1. All the modes, including four torsional, two vertical bending and two lateral bending modes, inferred by the peak-picking method, were identified by the SSI method. The natural frequencies of the modes identified by both methods are in excellent agreement. The first torsional, lateral and vertical modes are of frequencies 2.1 Hz, 5.8 Hz and 7.5 Hz, respectively. The damping ratios of all the modes except the second lateral mode are no smaller than 1.2%. The frequency of the first vertical bending mode is a bit higher than those of traditional structures of the similar spans [13]. The averaged damping ratio for the eight modes is about 1.5%, indicating that the damping ratio of FRP structures might be comparable with those for structures made of reinforced concrete and higher than those for steel structures [14]. In addition, there is a relatively high density of torsional modes.

5. Conclusions

In this paper, the dynamic properties of a truss pedestrian bridge made of FRP components were measured using ambient vibration testing. The method of peak picking of the averaged normalised power spectral densities in the frequency-domain was employed to identify the natural frequencies, whilst the stochastic subspace identification method, in the time-domain, was employed to the identify natural frequencies, damping ratios and mode shapes. The two methods generated very consistent results in terms of the number of modes and natural frequencies. In total, eight modes were found in the frequency range up to 10 Hz. These include four torsional, two vertical bending and two lateral bending modes. The first torsional, lateral and vertical modes are of frequencies 2.1 Hz, 5.8 Hz and 7.5 Hz, respectively. The damping ratios of all the modes except the second lateral mode are no smaller than 1.2%. There is a relatively high density of torsional modes. Comparison between the fundamental frequency of the bridge and those of traditional footbridges indicates that for similar span lengths, the frequency of the first vertical bending mode is a bit higher than those of their traditional counterparts. Interestingly, the averaged damping ratio of the first eight modes is comparable with those of reinforced concrete structures but higher than those of steel bridges.

Acknowledgements

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