Effects of Pedestrian Excitation on Two Short-Span FRP Footbridges in Delft

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ABSTRACT

Reported in this paper is an evaluation of the vibration behaviour of two footbridges in The Netherlands having main spans of about 15m. Short-span footbridges over canals and rivers are embedded in the landscape of Delft and elsewhere. Increasingly, these bridges are made of Fibre-Reinforced Polymer (FRP) composites, utilising the high-strength and light-weight nature of the material, and taking advantage of fast installation and low maintenance costs. Due to low mass, these FRP bridges might be sensitive to dynamic excitation by human actions. This paper evaluates the vibration behaviour of two footbridges having main spans of about 15m. The main bearing structure consists of either two or four longitudinal beams made of vacuum infused FRPs with foam cores connected by an FRP deck. Modal testing revealed that fundamental vertical natural frequency of the two structures at 4.8Hz and 6.1Hz is in the range typical of similar structures made of concrete and steel, whilst the corresponding damping ratio for the wider, slightly cambered, bridge was exceptionally high at 7.9%. The vibration response to dynamic force by people walking was typically up to 1m/s^2. While both of these light-weight structures performed satisfactorily under the regular pedestrian loading, the higher frequency – higher damping structure represents an example of successful control of pedestrian-induced vibrations by means of longitudinal restraints at the end supports and slightly curved shape of the main structure.

Keywords: FRP composites, short-span footbridges, modal properties, vibration, walking

1. Introduction

Short-span footbridges made of high-strength, light-weight Fibre-Reinforced Polymer (FRP) composites are frequently employed in crossing canals and rivers in the Netherlands. These structures are fast to install and require little maintenance even in aggressive environments. The light-weight nature of the FRP material, with density that is about one-quarter that of steel, means that a 15m footbridge can weigh as little as two tonnes (2000kg), is easy to manipulate on site, and offers savings in energy use and cost of transport, lifting requirements and design of substructure foundations [1]. Whilst the low mass of FRP structures makes them increasingly popular choice in bridge engineering, it is the key factor that might lead to sensitivity to dynamic excitation by pedestrians.

There is little information in the public domain on dynamic performance of as-built FRP footbridges. There exists awareness that these structures might be lively under dynamic excitation. At the same time, the authors' experience with a number of short (e.g. 15-20m) span FRP structures is that they mostly exhibit acceptable vibration performance during typical loading conditions. Testing full-scale structures is a necessary step towards enhancing understanding of their dynamic behaviour and ensuring informed and confident structural engineering designs in the future.

To contribute to the above goal, the University of Warwick in collaboration with TU Delft conducted a programme of testing on two footbridges in Delft. This paper describes the two structures first, followed by description of experiments to determine the modal properties. Then the vibration performance of the two structures under single pedestrian excitation as well as groups of pedestrians is analysed. Finally, discussion and conclusions from the studies are presented.

The testing was conducted in cold weather conditions (air temperature 3-10 degrees Celsius, humidity 74-86%, light-to-gentle breeze) from the 6th to the 8th December 2016.

2. Description of two footbridges

Bridge 1 is a pedestrian bridge at the edge of TU Delft's campus. It consists of two (relatively) independent spans of 15m and 10m with deck width of 2m. Each span has two longitudinal beams made of vacuum infused FRPs with foam cores connected by an FRP deck, moulded as one piece, and resting on neoprene pads at the ends of each span. Surface is an epoxy layer with embedded gravel. Handrails are made of steel and they are continuous along the spans. Total mass of superstructure for the 15m span is estimated at about 4500kg. View of the two spans, as well as of the data acquisition station, is shown in Fig. 1.

Fig. 1: Bridge 1 – left: side view and right: data acquisition station

Bridge 2 is a 14.7m long by 4.5m wide pedestrian and cyclist bridge, with allowance for 12 tonne service vehicles. Structure is made of four vacuum infused FRP foam core beams connected by a composite cover. It has a slight camber and sits on concrete supports, with neoprene pads which also restrain it longitudinally. Hand railing is provided by a series of 1m composite posts bolted to side plates. Total mass is 6600kg. Fig 2. shows the bridge and the data acquisition station.

Fig. 2: Bridge 2 – left: side view and right: data acquisition station

3. Modal properties

To determine the dynamic properties (mode shapes, natural frequencies and damping ratios) of the two structures, the vertical vibration response of the deck was measured using three force balance accelerometers (model QA750 by Honeywell) having nominal sensitivity of 1300mV/*g*, where *g* is the acceleration of gravity. Two types of excitation were considered: natural (ambient) excitation due to wind and impact excitation applied manually using an instrumented impact hammer (Model 5803A by Dytran, nominal sensitivity 0.23mV/N). Since deck response due to natural excitation was very low, the decision was made to perform the modal testing using hammer excitation. This led to measuring Frequency Response Functions (FRFs). During the measurement periods the bridges were closed for pedestrian/bicycle traffic.

The force and response signals (in the vertical direction only) were recorded using four-channel data acquisition card (SignalCalc Quattro by Data Physics). The results of modal testing are presented in the reminder of Section 3.

3.1. Bridge 1

To test Bridge 1, a grid of 24 test points (TPs) on the deck, over the two spans, was utilised (Fig. 3). The 15m span accommodates TPs 1-7 and 51-57, whilst the remaining TPs belong to the 10m span. The longer span is of more interest for this study since it has the lower fundamental natural frequency. For this reason, the results from the 15m span only will be reported.

TP2 was chosen as a reference point to which the impact force was employed. The impact was applied five times in each measurement setup and each time the data acquisition window lasted 8s. The force and response signals were sampled at 1280Hz. The 8s data acquisition window resulted in sufficiently fine frequency resolution of 0.125Hz. An exponential window was applied to all signals to minimise the leakage and noise effects [2]. Three roving accelerometers were moved across the test grid until all 14 TPs were covered.

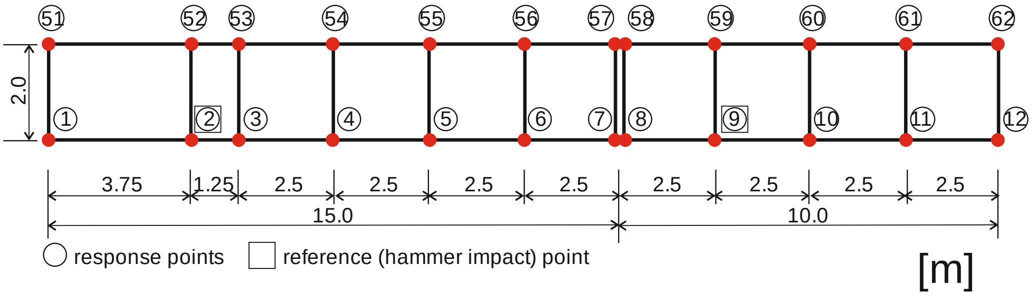
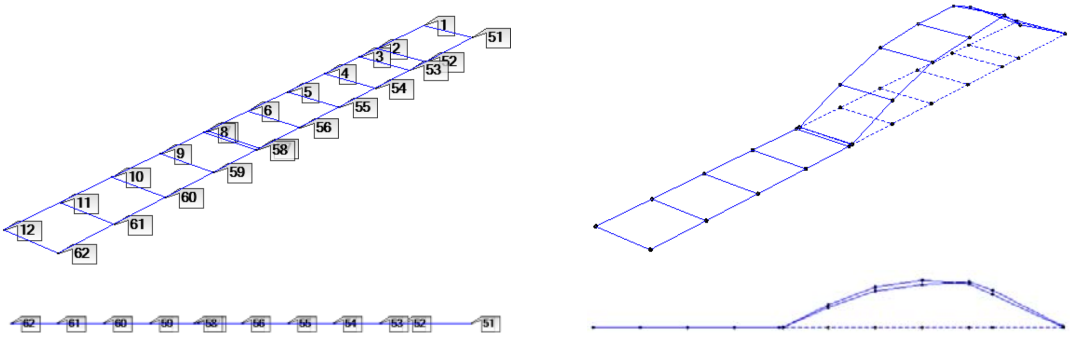


Fig. 3: Bridge 1 – measurement grid

The measured accelerance FRFs were analysed using ME'scope software [3] to identify modal properties of vibration modes in the frequency range up to 20Hz. Damping ratio for each vibration mode was corrected to eliminate the artificial damping introduced by applying an exponential window to the raw data records [4]. The identified vibration modes are shown in Fig. 4. The isometric and side views of mode shapes are presented, with the corresponding values for natural frequencies and damping ratios. Two vertical flexural modes resemble the shapes typical of a simple beam structure. The three torsional modes look similar; this is a consequence of apparent flexibility in the boundary conditions and potential vibration transfer between the two spans via the handrails. Fig. 4 shows that the supports engage in motion of either Mode 2 or Mode 3, whilst they are relatively stationary in Mode 4.

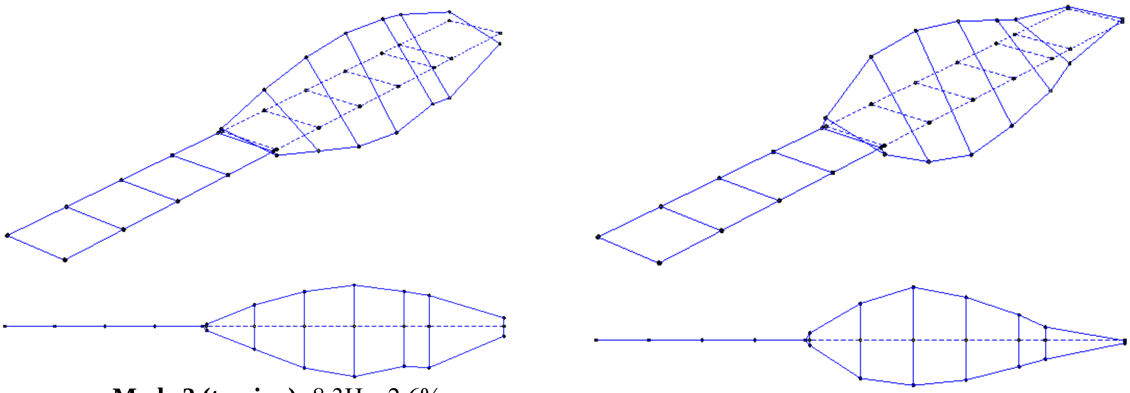
According to the Setra guidelines [5], only the first mode has potential to compromise vibration serviceability of the structure, due to its natural frequency being less than 5Hz. On the other hand, this mode, and all the others, have the damping ratio above 1.2%. This amount of damping is a positive feature of the bridge given that structures that exhibit excessive vibrations often have damping ratios well below 1%.

The actual damping ratio in the first mode is likely to be lower than the estimated 1.2% due to presence of the hammer operator on the bridge throughout the testing. To eliminate the operator's interaction with the structure and his influence on the modal properties of the first mode, the natural frequency and damping were calculated from the free decay response measured in the test in which a person walked at 2.4Hz to excite resonance in Mode 1. Using the logarithmic decrement method, the natural frequency was determined to be unchanged at 4.8Hz, whilst the damping ratio was lower at 0.7%, i.e. 58% of the value determined in the bridge – hammer operator dynamic system.



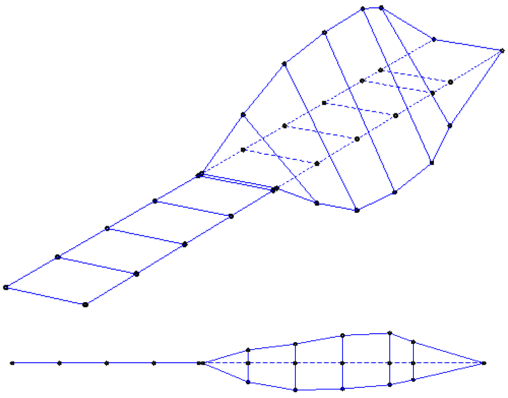
Test points in isometric and side views

Mode 1 (flexural): 4.8Hz, 1.2%

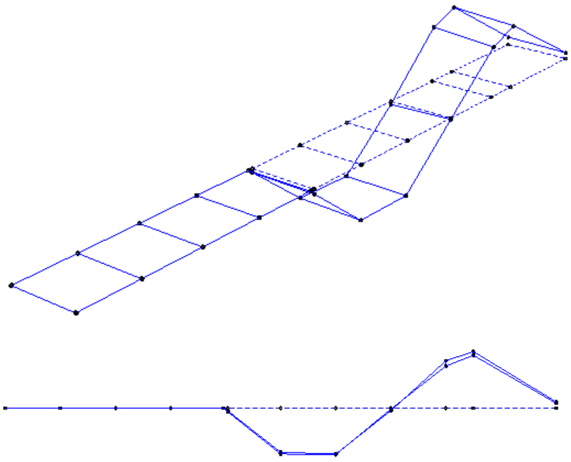


Mode 2 (torsion): 8.3Hz, 2.6%

Mode 3 (torsion): 9.5Hz, 2.0%



Mode 4 (torsion): 13.8Hz, 1.7%



Mode 5 (flexural): 17.1Hz, 1.2%

Fig. 4: Vibration modes for Bridge 1

3.2. Bridge 2

A grid of 21 TPs on the deck were utilised for testing Bridge 2 (Fig. 5). The reference point was TP3. The data acquisition parameters and the measurement procedure were the same as those implemented for testing Bridge 1. The vibration modes, identified using the same assumptions and methods as before, are shown in Fig. 6. The vibration modes of this bridge are all above 5Hz, and according to Setra guidelines [5], the risk of exciting resonance on this structure is negligible. In addition, the first two modes that, given their frequencies, might be excitable by higher harmonics of the human induced dynamic loading both have significant damping, reinforcing the conclusion that the vibration performance of this bridge is unlikely to be an issue in normal use. Note that interaction of bridge dynamics and that of the hammer operator is not of interest, due to inherent high frequency of vibration.

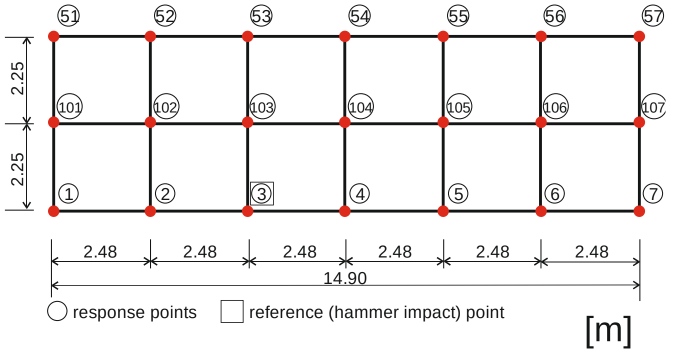
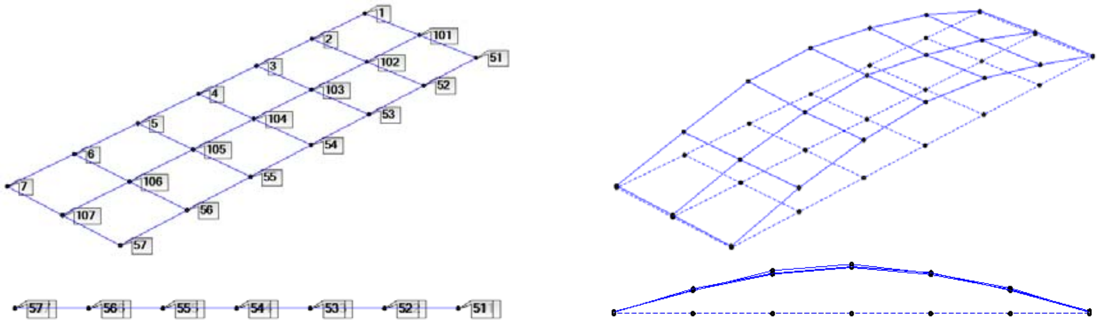
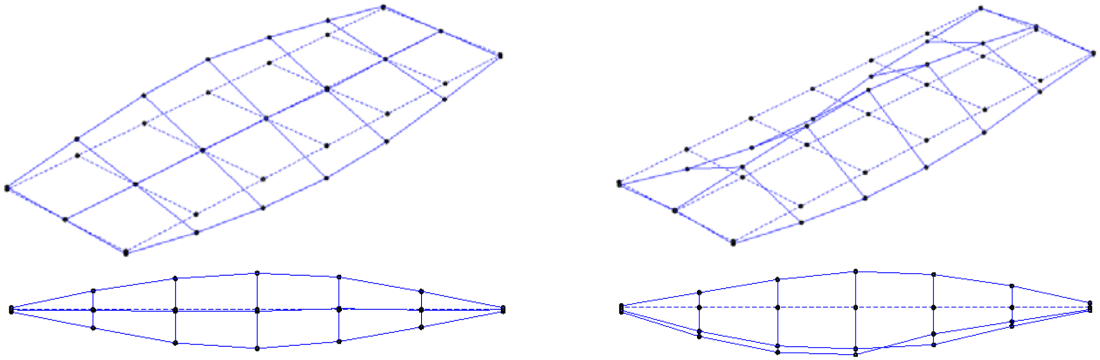


Fig. 5: Bridge 2 – measurement grid



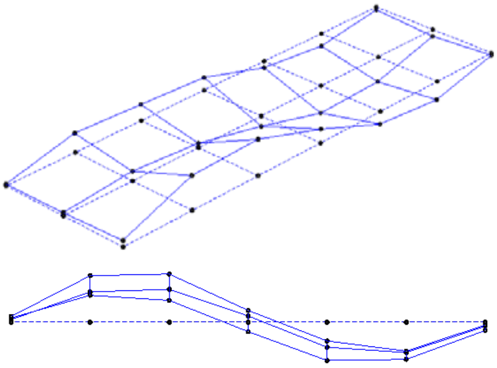
Test points in isometric and side views

Mode 1 (flexural-longitudinal): 6.1Hz, 7.9%



Mode 2 (torsion): 10.1Hz, 4.4%

Mode 3 (flexural-transverse): 17.1Hz, 1.0%



Mode 4 (flexural-longitudinal & transverse): 18.9Hz, 2.1%

Fig. 6: Vibration modes for Bridge 2

The two bridges have fundamental natural frequencies at 4.8Hz and 6.1Hz. This belongs to the natural frequency range of 3-7Hz typical of concrete and steel bridges having similar span length of 15-20m [6]. The damping ratio of Mode 1 of Bridge 1 is similar of data typical of reinforced concrete structures (that normally have higher damping than steel, composite steel-concrete or pre-stressed concrete structures), whilst the damping ratio of Bridge 2 is exceptionally high. This is believed to be due to this bridge having the structural engineering features of being slightly cambered and having longitudinal restraints.

4. Vibration performance

Two loading scenarios were considered for both bridges. First single pedestrian loading was applied. Tests were performed at controlled pacing rates by two members of the testing team. Second loading scenario involved groups of pedestrians walking. The test configurations and the measured vibration responses are listed in Table 1. The response was measured at TPs 3 and 4 on both bridges.

Table 1: Information on loading arrangements and corresponding vibration response

Test #	Loading	Pacing frequency [Hz]	Max. acceleration [m/s^2] (TP number)	Stongest response frequency [Hz]	Comment
			Bridge 1		
1	Walker 1	1.4-2.5 (in 0.1Hz steps)	1.2 (TP4)	4.8 (Mode 1)	Walking at 2.4Hz
2	Walker 2	1.4-2.5 (in 0.1Hz steps)	0.9 (TP4)	4.8 (Mode 1)	Walking at 2.4Hz
3	8 walkers	free	0.6 (TP4)	4.8 (Mode 1)	Walking for 10min
4	15 walkers	free	1.0 (TP4)	4.8 (Mode 1)	Walking for 10min
			Bridge 2		
5	Walker 1	1.4-2.5 (in 0.1Hz steps)	0.45 (TP3/4)	10.1 (Mode 2)	Walking at 2.5Hz
6	Walker 2	1.4-2.5 (in 0.1Hz steps)	0.35 (TP3/4)	10.1 (Mode 2)	Walking at 2.5Hz
7	8 walkers	free	1.5 (TP3/4)	10.1 (Mode 2)	

The response tests on Bridge 1 show that Mode 1 at 4.8Hz responded most to walking excitation by both single walker and groups of people. The second harmonic of the force generated by Walker 1 and Walker 2, when they walked at 2.4Hz, excited the resonance in Mode 1, which is the reason that walking at this frequency generated the highest vibration response. In free walking tests by the groups, strong vibrations were intermittent, and did not exceed 1m/s^2. According to Setra, this bridge provides mean comfort for its users, which is an acceptable comfort classification given the location and the usage of Bridge 1.

In walking tests on Bridge 2, the response in Mode 1 was very low owing to significant amount of damping in this mode. As a result, Mode 2 at 10.1Hz responded most; but this response was accompanied with response in higher modes and at multiple frequencies of the higher forcing harmonics. For such a high frequency content, the recorded peak response of 1.5m/s^2 to a group of walkers is not presenting the comfort challenge to pedestrians using the bridge. In the single walker tests, impulse response to each heel impact was easily identifiable in the data recorded, suggesting that this bridge exhibits dynamic behaviour similar to high frequency floors [7, 8]. Humans walking on this bridge cannot excite the resonance of the structure in any of the vibration modes, and the bridge is likely to provide very good comfort for its users.

It can be concluded that both bridges exhibit satisfactory vibration serviceability performance in normal use. If exposed to larger (so called vandal) dynamic loads, such as due to jumping, Bridge 1 has potential to respond strongly due to high likelihood of exciting resonance at 4.8Hz. On the other hand, the resonance response of Bridge 2 is extremely unlikely, and therefore this bridge is unlikely to be seen as uncomfortable even when exposed to extreme dynamic loads generated by human actions.

Some of the key features of the two bridges are observable in the measured FRFs, presented in the four plots in Fig. 7. For example, the first two modes of Bridge 2 (first two peaks in the magnitude graph in Fig. 7: right) are unusually broad and for highly damped situation. Bridge 1, on the other hand, exhibits complex behaviour in 9-15Hz frequency range (Fig. 7: left). This finding might be due to a strong interaction between the railings and the two deck spans. Finally, both bridges have a strong mode at around 17Hz. This relatively high frequency is unlikely to be of interest for evaluation of pedestrian comfort.

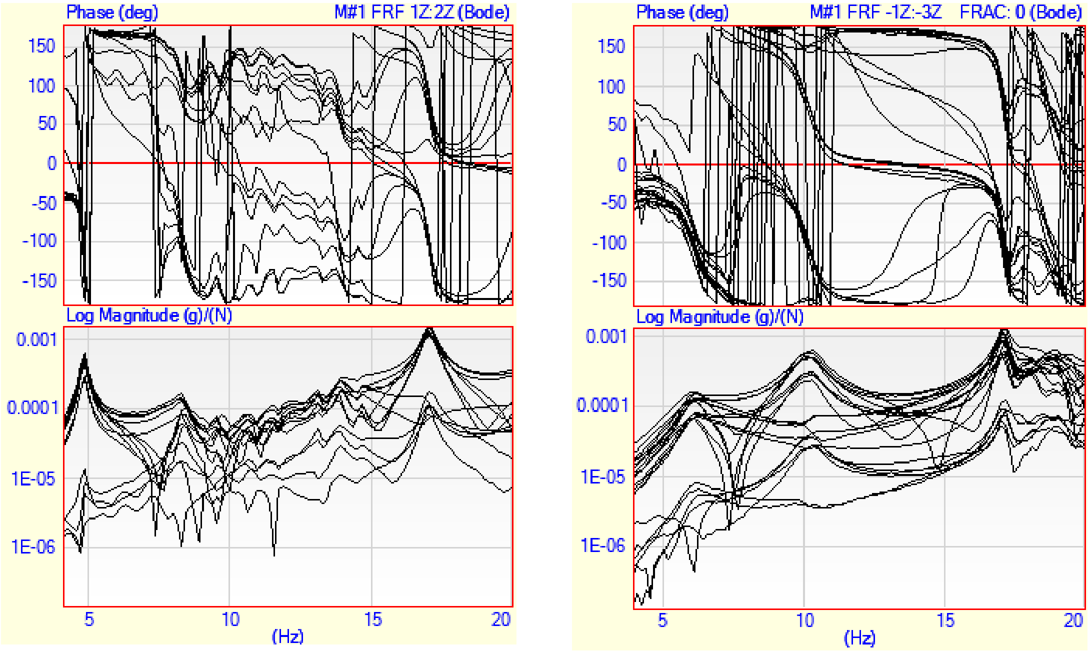


Fig. 7: Phase and magnitude of measured FRFs on – left: Bridge 1 and right: Bridge 2

5. Conclusions

The following conclusions can be drawn from the experimental analysis of the two short-span FRP bridges located in Delft:

- The fundamental natural frequencies of the two structures at 4.8Hz and 6.1Hz belong to the frequency range of 3-7Hz typical of the 15-20m span footbridges built of traditional construction materials, such as steel and concrete.
- Damping ratio of the two bridges is either similar to that seen in most damped traditional structures (0.7% for Bridge 1) or much higher (7.9% for Bridge 2).
- Both bridges exhibit satisfactory vibration behaviour in normal use, suggesting that the FRP composites are viable alternatives to traditional construction materials for bridging what is classified as short spans.
- The two bridges exhibit fundamentally different vibration behaviour, with Bridge 1 able to be excited in resonance, whilst Bridge 2 exhibits vibration performance similar to high-frequency floors in buildings.
- Careful choice of geometry of the bridge can result in high-frequency high-damping structure (e.g. Bridge 2) and serve as an excellent vibration control measure.

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