

Design and Performance of a Bespoke Lively All-FRP Footbridge

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ABSTRACT

This paper presents an overview into the design approach and challenges in constructing a very lively 20 m experimental bridge of Fiber-Reinforced Polymer (FRP) components. FRP composite bridges are an attractive option for footbridge construction since their lightweight nature offers engineering advantages. However, when combined with their low stiffness, such structures can result in being lively to human-induced loading conditions. Our bespoke footbridge structure was designed to consider human-structure interaction problems, as well as to develop the understanding of the dynamic response of FRP structures. Comparisons are made between the predicted design behavior and measured responses. Measured vertical bending modes are 2.53 Hz and 8.48 Hz, with a torsional mode at 3.36 Hz, agreeing with predicted design behavior. Walking tests on the bridge demonstrate that it responds strongly to typical human pacing frequencies and actions.

Keywords: Vibration, FRP Bridge, Human-induced loading, Modal testing, Bridge design

INTRODUCTION

Lightweight footbridges are becoming increasingly utilized as the reduction in material can lead to savings in fabrication and for installation. Glass Fiber-Reinforced Polymers, (FRPs) are an excellent option due to their low density and good strength to weight properties [1]. However, they typically have lower stiffness compared to traditional material, which when combined with their lower mass can lead to structures that are prone to vibration problems due to human induced loading [2,3]. To investigate this problem further, an experimental footbridge was designed and constructed at the University of Warwick. It was intended to be as lightweight as possible, with a vertical natural frequency within the range of typical human walking. Pultruded FRP sections were used to create the structure. Modal testing was conducted on the bridge to determine the frequencies, damping, modal masses and mode shapes. Finally, single pedestrian tests at set walking frequencies were conducted and the acceleration response measured.

BRIDGE DESIGN AND MODAL PROPERTIES

To achieve a flexible-lightweight footbridge with a low natural frequency, a shallow truss design is adopted. The truss has a depth of 475 mm between chord center lines and a span of 16.8 m. While this reduces flexural stiffness, it generates relatively high member forces, for which bolted connection strength controls the design. Overall the structure is 19.8 m long and 2.35 m wide, as shown in Figure 1. Top and bottom chords are of back-to-back EXTREN[®] 152x41x6.4 FRP channel sections with vertical and diagonal elements of EXTREN[®] 50.8x6.4 FRP box section. Channel sections are used also for the transverse beams support the FRP decking of SafPlank (51mm deep). Stainless steel bolts, with Nyloc nuts to reduce loosening from vibration actions, are used in all connections. Because sections of only 6.4mm thickness are required, the total weight is very low at 1400 kg, or 71 kg/m. The structure sits on four steel bearing supports, including a roller at one end, to create a simply supported condition (see Figure 1). Finite Element (FE) analysis was utilized to predict modal properties, deflections and member forces. Structural design is based on a maximum mid-span deflection of 100 mm, plus self-weight deflection, allowing for significant dynamic oscillations to occur. The key aspect is to ensure that the bolted connections has sufficient strength to prevent bolt bearing or net-tension failures in the FRP; to achieve this the channel's web in spliced joints was thickened with additional bonded FRP plating to increase local resistance. FE simulation predicted 2.5 Hz for first vertical

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bending mode, 3.6 Hz for first torsional and 8.7 Hz for second vertical. Because these resonant frequencies are in the range of interest for human-induced loading scenarios the design is considered fit for purpose.

In order to obtain the modal properties of the bridge, shaker testing was employed. An electromagnetic shaker was attached to the underside of the bridge by a thin strut. A PCB 208C03 load cell (nominal sensitivity 10 mV/lb) was used to measure the applied force and Honeywell QA750 accelerometers (nominal sensitivity 1300 mV/g) used to measure the response. A chirp signal between 1-25 Hz was applied for 64 s, including a free decay period, and the vertical accelerations at 30 test points (TPs) were considered for calculating the frequency response functions. Table 1 gives the modal properties identified up to 22 Hz and Figure 2 shows the first two mode shapes. The lowest vertical mode, at 2.53 Hz, is within the range of excitation due to human walking, and the close torsional mode also could respond to the 2nd walking harmonic. Both these modes have high damping ratios compared to traditional structures, however their low modal masses means that they are easily excited. Finally, the good design and construction of the bridge and its supports mean that the mode shapes (Figure 2) have a very smooth and predictable shape.



Fig 1 Photograph of the FRP Bridge. Left. Full view of the structure. Right. Support conditions

Table 1 Measured modal properties

Mode Description	Frequency (Hz)	Damping Ratio (%)	Modal Mass (kg)	Mode Description	Frequency (Hz)	Damping Ratio (%)	Modal Mass (kg)
1 st Vertical	2.53	1.69	650	1 st Torsional	3.36	1.18	572
2 nd Vertical	8.48	0.72	764.5	2 nd Torsional	11.3	0.52	588
3 rd Vertical	15.8	0.64	927.5	3 rd Torsional	21.9	0.66	651

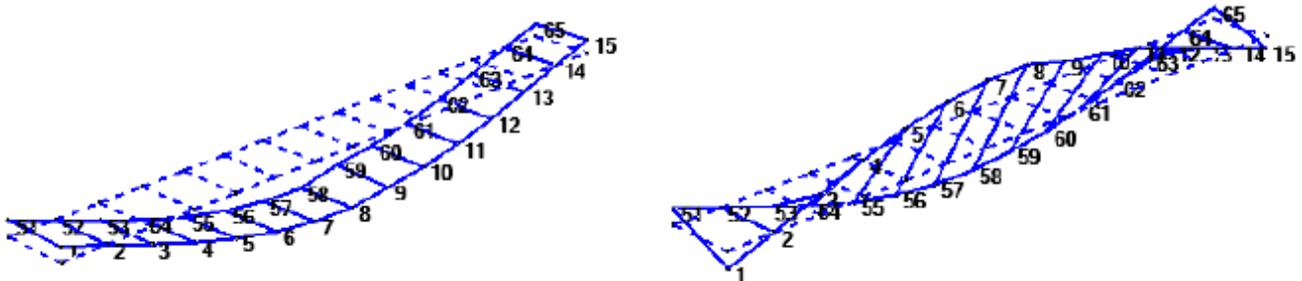


Fig 2 Mode shapes Left. First vertical (2.53 Hz). Right. First torsional (3.36 Hz). Test points are shown. Supports are at TP 2/52, 14/64

PEDESTRIAN WALKING TESTING

To consider the response of the bridge to human loading scenarios a single test subject walked across the centerline of the bridge at a set, metronome controlled, pacing frequency of 1.4 Hz. After the vibrations had died down, the test subject returned at the same frequency. Next the frequency was increased by 0.1 Hz and the test repeated up to a walking rate of 2.5 Hz. The vertical accelerations at the mid-span were recorded with a sampling rate of 512 Hz. The results were then low pass filtered at 20 Hz to focus on the modes of interest. Figure 3 show the results. From this it can be seen that with stepping rates of up to 2 Hz the peak acceleration was 1.11 m/s^2 . However, beyond 2 Hz the vibration levels increase significantly and at 2.5 Hz (the first vertical bending mode) a peak acceleration of 6.00 m/s^2 was recorded. It is clear that this bridge responds to single walking events, and therefore is of great interest for human-structure interaction problems. The low mass of the bridge means that relatively small input forces result in significant accelerations. It is also expected that the influence of the pedestrian on the structure will have a noticeable effect on the modal properties, which will be investigate in future research.

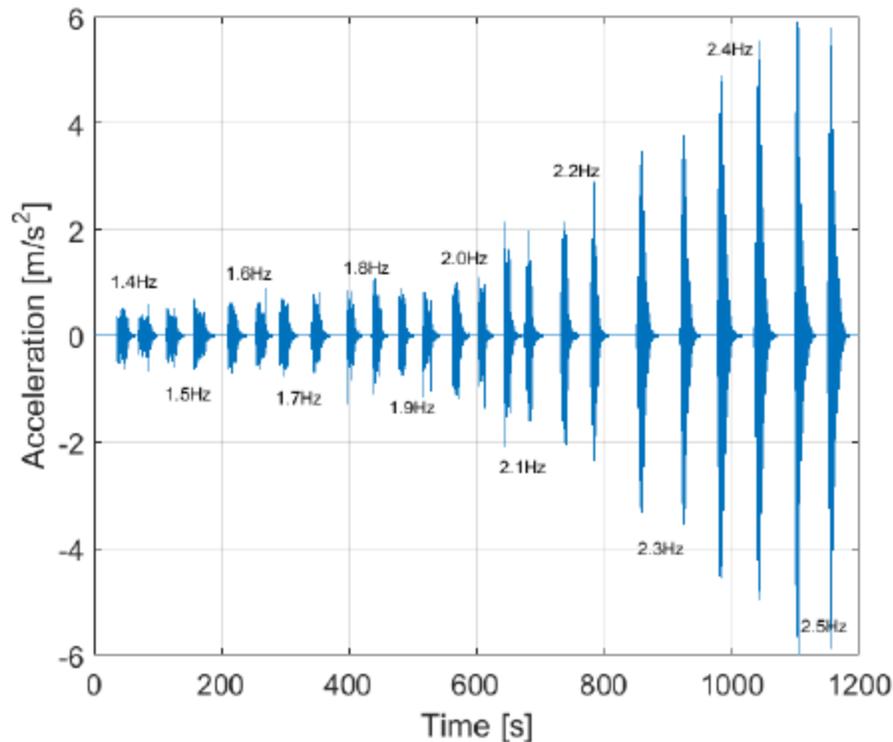


Fig 3 Mid-span acceleration response from a single pedestrian walking at set pacing frequencies

CONCLUSION

A very lively, lightweight FRP footbridge was designed and constructed at the University of Warwick. The large displacements expected during human walking scenarios meant that the bolted connections had to be checked carefully to ensure sufficient strength. The modal properties of the bridge were predicted using finite element analysis and measured with shaker testing. The well-defined boundary conditions and good joint construction resulted in smooth mode shapes and three vertical and three torsional modes were identified up to 22 Hz. The lowest of these, a vertical mode at 2.53 Hz is within the range of human walking frequencies and, because of the low modal mass associated with the mode, is very easily excited by pedestrians. This unique footbridge offers researchers an exceptional test structure for the characterization of human-structure interaction.

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