Material Testing, Design & Construction of a Laboratory-Scale FRP Composite Footbridge

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ABSTRACT

Pedestrian loading on flexible structures such as footbridges, grandstands and lightweight floors is an area, which is receiving significant attention from the research community of late. One of the key parameters in determining the structural response is the frequency of the bridge. Separately, fibre reinforced polymers (FRP) (typically referred to as advanced composites) represent the greatest innovation in structural materials in the recent past. These materials offer advantages over traditional materials such as steel, concrete and timber, which include improved durability performance, flexibility of design, improved quality assurance in production, potential for use of recycled materials, etc. However, perhaps the most significant advantage for civil engineering structures is the increased strength to weight ratios offered in comparison to more traditional materials. These materials are growing in popularity in innovative structures and are gaining increasing acceptance among designers internationally. One of the major barriers to greater use is the lack of design guidance on the use of these materials in load-bearing structures. The authors are currently researching pedestrian-induced loading on flexible structures and also the use of advanced composite materials (ACMs) in construction. This paper describes the amalgamation of these two discrete research interests by detailing the material testing, design and construction of a unique, laboratory-scale FRP composite footbridge.

INTRODUCTION

Pedestrian-induced vibrations in structures such as footbridges has been the topic of significant research in recent times due to a number of high-profile incidences of excessive vibration levels. Such vibrations can be vertical, lateral or torsional, (or a combination of these). The lateral vibrations caused by crossing pedestrians that occurred on the high profile London Millennium Bridge in 2000 resulted in extensive research into this phenomenon [1, 2]. Meanwhile, according to some, including Bocian et al. [3], the vertical vibration of footbridges is a more common occurrence. Two recent examples of this are the Eagles Meadow Bridge, Wales [4] and the Squibb Park Bridge, New York [5]. The more traditional method to avoid excessive vibrations on footbridges is to design the bridge to have a natural frequency outside the range associated with pedestrian walking rates. However, this approach has been shown to be inadequate, as many bridges with natural frequencies outside these ranges can be excited, while conversely, many bridges with frequencies in the critical spectrum have not experienced vibrations [6].

A major difficulty in advancing design guidance on flexible structures regarding human induced vibrations lies in the dearth of understanding of the true nature of pedestrian loads on a flexible structure. Many approaches for capturing this loading have been proposed.

Dang and Zivanovic [7] remark that pedestrians need to be modelled as part of a pedestrian-structure vibrating system. Further, they suggest that modelling the walking locomotion on a flexible surface is a challenge since it requires a departure from replicating the force waveform measured on a rigid surface. Ingolfsson [8] explains that the term 'human-structure interaction' covers the two way feedback within the human-structure system, which is formed when a pedestrian occupies a structure.. He cites Sachse et al. [9] by noting that occupants, intuitively add mass and damping to low frequency structures. However, Ingolfsson [8] does acknowledge that there is a scarcity of literature concerning walking pedestrians on the human-structure system, but cites Zivanovic et al. [10], Ohlsson [11], and Pimentel and Waldron [12] by suggesting that the dynamic load is smaller on a flexible floor than on a rigid one. Racic et al. [13] further this point, claiming there will be approximately a 10% reduction in force whilst walking on a flexible surface; he cites both Pimentel [14] and Baumann and Bachmann [15] whilst making this argument. In spite of these investigations, Racic et al. [13], similar to Ingolfsson [8], point out that experimental studies on the vertical walking forces induced on flexible structures are still very rare and limited. Claff et al. [16] contest that the best way to further understand pedestrian structure interaction on oscillating surfaces is to install force plates in the surface.

In addition to developing a greater understanding of the nature of loading, over the last 20 years, the structural engineer has been subjected to greater demands due to a wider variety of materials available. Among these, the structural performance of some advanced composite materials (ACM), which, although widely used, is not yet fully understood [17]. ACM have found particular prominence in the construction of footbridges. Potyrala [18] reports a total of 355 composite material bridges; both hybrid and composite varieties. Moreover, ACM footbridges have the ability to be long spanning (up to 300m), slender, and light weight [19]. This combination often yields natural frequencies in the range vulnerable to excitation from walking. The work reported on herein relates to the design and construction of a lightweight ACM footbridge, with a view to studying its response to dynamic pedestrian loading.

DESIGN OBJECTIVES

In order to further our understanding of the nature of the interaction between pedestrians and flexible structures, the structure must be excitable by pedestrian loading. This requires the structure in question to have a first vertical natural frequency of close to the pedestrian walking range of 1.6Hz to 2.4Hz. As this is to be a lightweight bridge, the mass of the pedestrians would influence the frequency of the overall pedestrian-structure system, so slightly higher natural frequencies of the empty structure would be acceptable.

Secondly, it is desirable to be able to alter the natural frequency of the bridge so that the effect of resonant response could be directly measured. In order to do this, it was decided to design the bridge so that the clear span could be altered – thus varying the natural frequency.

Thirdly, it was decided by the design team to utilise FRP composite structural members in the bridge as this would allow study of both pedestrian-induced vibrations and the structural performance of non-conventional structural materials.

Finally, and crucially, it must be possible to measure the forces exerted by pedestrians directly on the bridge. To this end, a force plate is to be embedded in the bridge at midspan.

GFRP TESTING AND MAKE-UP

The main structural members of the bridge were constructed from a glass fibre reinforced polymer (GFRP) composite. The authors constructed the sections using the hand lay-up method to produce planks, which are bonded together using a polyester resin to form I-beam sections. A montage of this procedure is presented in Figure 1.

Initially, seven 450mm long GFRP planks were developed for testing and mean values for their bending yield stress (263.6MPa), density (1,608.2kg/m^3) and flexural modulus (16.GMPa) were recorded.

Figure 1. Hand lay-up: Images showing the rolling and wetting process; right, finished planks.

I-BEAM DEVELOPMENT AND TESTING

The structural I-beams consist of three GFRP planks bonded together using polyester resin, and then reinforced using strips of alternating woven roving and shredded mat (Figure 1). Central cleats, offer a method to keep the beams ‘square’ and a prevention against early buckling. However, the earlier developed beams tended to separate between the tension flange and web before maximum bending strength was reached. This problem, was overcome by boring 5mm holes into the flanges prior to bonding and reinforcing. The premise of this was that the greater surface area produced by the borings would form a greater bond. The final I-beam (8mm x 60mm x 60xmm x 60mm) prototype, which was 1.5m in length revealed a yield stress of 847.5MPa, a flexural modulus of 15.5GPa and a density of 1605kg/m^3. Due to the success of this final prototype the final structural I-beams were developed using the same method. These I-beams (12mm x 60mm x 60mm x 100mm) were 9m in length. Figure 2 illustrates how the final I-beams were made, while Figure 3 presents the final I-beams.

Figure 2. Left 9m long mould; 2nd left, 9m lengths of WR and SM prepared; 3rd left, mould coated with PVA release agent; left centre, finished plank; right centre, plank's rough edges being filled off; 3rd right, 5mm borings in flanges; 2nd right I-Beam with cleats glued and held to set using G-clamps; right, I-beams reinforced with woven rovings and shredded mat

Figure 3. Finished 9m long I-beams

FEM OF LABORATORY SCALE FOOTBRIDGE

The proposed footbridge was modelled in ANSYS 16.1 finite element software, using the material properties determined from testing as input values. Static and modal analyses were carried out assuming an empty structure and one with an 80kg mass at midspan respectively. Table 1 presents the results of these simulations, indicating an expected natural frequency of the empty bridge to be 2.97Hz, reducing to 2.11Hz with the 80kg mass present for the 8.0m clear span. This was comfortably within the range excitable by human walking.

CONSTRUCTION OF FOOTBRIDGE

The plywood footbridge deck is 11m long and 900mm wide x 18mm thick. The deck is supported by two 100mm x 60mm x 60mm x 12mm GFRP I-beams, which are stiffened by 100mm x 12mm cleats at 400mm centres (Figure 4). There is a clear span that can be set to 8m, 7.5m, 7.0m or 6.5m on to two 1.5m timber platforms. The span is adjusted by use of adjustable supports. The bridge can be considered as rigid by use of an intermediate support. The beams, which were placed at 600mm centres are also braced every 800mm using 100mm x 12mm GFRP planks, and diagonally at the same points using 60mm x 60mm x 8mm GFRP L-beams. Finally, 1.5m lead-in/lead-out platforms were assembled from the 18mm plywood, and as these were 435mm high, steps were built-in to allow participants to step on and off.

Figure 4: left, lateral bracing construction; 2nd left, full bracing near completion; 3rd left and centre, GFRP and timber connections; 2nd right, decking of bridge; right, 1.5m walk rigid platform.

Figure 5. Left, pin connection for 8m span; centre left, opening and arrangement for pin connection for 6.5m to 7.5m spans; centre right, roller support top, and pin support bottom; right, rigid support arrangement

FORCE PLATE, ACCELEROMETERS, AND GRID PAPER (DATA COLLECTION)

A 502mm x 502mm x 45mm AMTI AccuGait balance platform (force plate) is embedded at the mid-point of the footbridge to record ground reaction forces: the top surface of the force plate is made flush with the top surface of the footbridge (Figure 6). In the vertical direction, Fz, the force plate has a natural frequency of 150Hz. Accelerometers are attached to the underside of the footbridge at mid-span and two third spans, respectively (Figure 8). Data from these are recorded through a virtual instrument (VI) developed in National Instruments (NI) LabView 8.5. These data are used to determine the time interval between consecutive footsteps on the rigid footbridge; and to determine the natural frequency of the flexible footbridge. The trial participants walking frequency during the flexible walking trials is also determined via video analysis. Grid paper measuring 4.2m x 0.6m and containing a 20mm x 20mm grid size was placed over the middle section of the footbridge to assist in recording the spatial parameters such as step length, step width, and foot landing position (Figure 7).

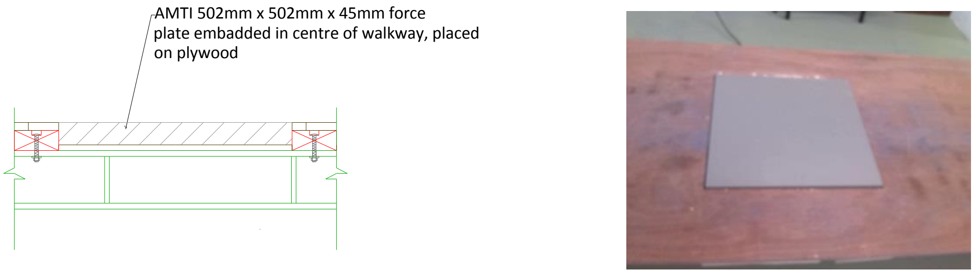

Figure 6: Left, schematic detail of embedded force plate (not to scale); right, actual force plate

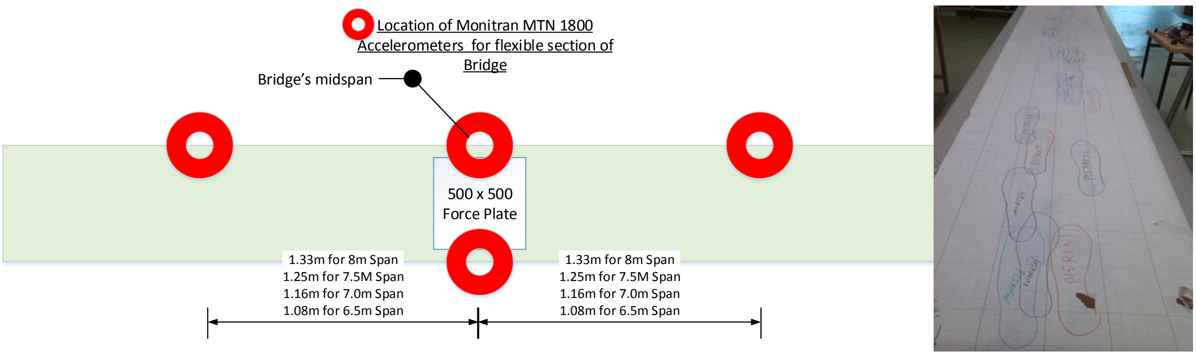

Figure 7: Left, location of accelerometers on bridge; right, grid paper ready to be measured

The completed bridge is shown in Figure 8.

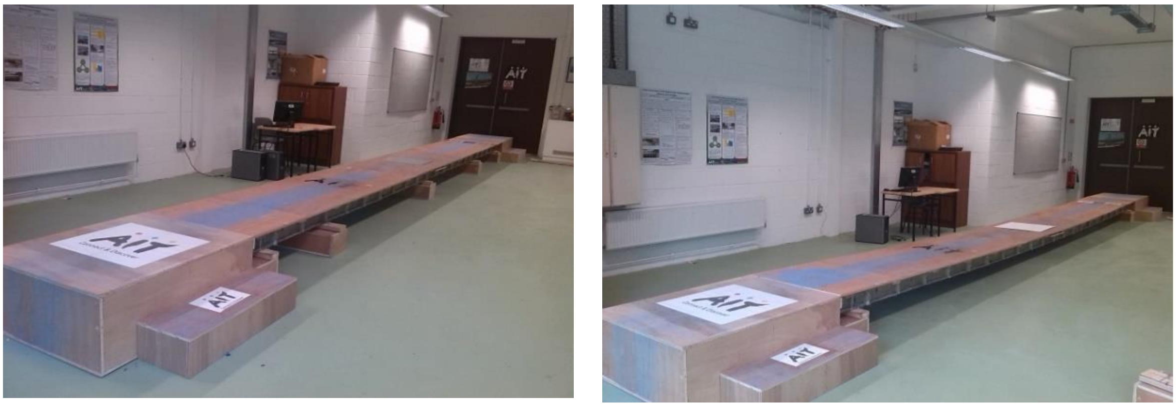

Figure 8. Left, footbridge set-up for rigid walking; right, flexible footbridge set-up

INITIAL BRIDGE TESTING

Once constructed, static and dynamic load testing was carried out on the bridge to determine its actual structural response. As with the FE modelling previously conducted, tests were carried out on the empty structure and when it was loaded with an 80kg mass at midspan. For static testing, midspan deflection was measured, while for dynamic testing, the free vibration response following an impulse load was recorded. This data was used to determine the natural frequencies of vibration. Testing was carried out for each of the achievable clear spans. Table 1 contains the results of the testing and compares the recorded values to those predicted by the FE model. Results show that the FE model (following some basic updating) is in good agreement with the physical structure with measured deflections within 5% of those predicted and natural frequencies within 8%. Moreover, the natural frequencies of the occupied structure are within the range critical for study of human-induced loading.

Table 1. Deflection, natural frequency, maximum load capabilities of bridge

	Self-weight						80kg Mass at mid-section					
Clear Span (m)	Measured Deflection (mm)	FE Predicted Deflection (mm)	Error	Measured Natural Frequency (Hz)	FE Predicted Natural Frequency (Hz)	Error	Measured Deflection (mm)	FE Predicted Deflection (mm)	Error	Measured Natural Frequency (Hz)	FE Predicted Natural Frequency (Hz)	Error
8	75	77	-2.6	2.97	2.73	-8.1	95	99	4.2	2.19	2.11	4.7
7.5	60	61	-1.6	3.28	3.10	-5.5	80	80	0.0	2.38	2.34	1.7
7	45	47	-4.3	3.59	3.55	-1.1	60	63	5.0	2.65	2.58	2.7
6	35	35	0.0	3.98	4.08	2.5	45	47	4.4	2.94	2.97	-1.0

CONCLUSIONS

Advanced composite material (ACM) footbridges are a form of bridge that are becoming more and more widespread, yet are neglected in terms of guidance within standards and codes of practice. The design and construction of an 11m test footbridge, with an effective flexible length of 8m has being described. More the flexible length of the bridge can be adjusted to be 8.0m, 7.5m, 7.0m, 6.5m, or rigid. The footbridge is structurally FRP based with plywood decking and plywood 1.5m lead-in and lead-out platforms. The bridge has a natural frequency, with a static 80kg person, of 2.11Hz at a flexible span of 8.0m, this coincides with that of an average person who generally has a frequency of between 1.76Hz and 2.20Hz. More, a force plate is embedded in the centre of the footbridge, which allows vertical forces to be measured; which is often neglected or ignored in some experimental studies. Other parameters that are measured include step length, step width and pacing velocity. Moreover, each walking trial will also be recorded, which will aid the study of pedestrian structure interaction, along with a method to calculate pacing frequency.

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