Thin-Walled Structures 117 (2017) 332–342

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Full length article

Dynamic behaviour of a GFRP-steel hybrid pedestrian bridge in serviceability conditions. Part 1: Experimental study

Mário F. Sá[a,*], Luís Guerreiro[a], Augusto M. Gomes[a], João R. Correia[a], Nuno Silvestre[b]

[a] CERIS, Instituto Superior Técnico, Universidade de Lisboa, Portugal
[b] IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Portugal

A R T I C L E I N F O

Keywords:
GFRP-steel hybrid footbridge
Pultruded multicellular deck panel
Dynamic tests
Vibration serviceability
Guidelines

A B S T R A C T

Glass fibre reinforced polymer (GFRP) composites are being increasingly used in bridge engineering in a wide range of forms, including pultruded thin-walled multicellular deck panels, which allow for the fast installation of lightweight and slender footbridges. The lightness and slenderness of these panels, together with the damping and low elasticity modulus of the pultruded GFRP material, render these bridge decks potentially more susceptible to human-induced vibrations when compared to other equally slender non-composite systems. However, very limited information is available about the serviceability dynamic behaviour of GFRP footbridges, in particular about composite deck-to-girder systems. In this context, this paper presents an experimental study about the static and dynamic responses of the St. Mateus footbridge (recently built in Portugal), representative of a typical GFRP-steel hybrid solution. The investigation included: (i) static load tests, (ii) modal identification tests, and (iii) vibration tests for different dynamic pedestrian load cases. In general, the acceleration-time records obtained attested an adequate structural responses of the footbridge, in terms of both vertical peak and root mean squared (RMS) acceleration values, even for the most severe load cases (deck loaded at 33% and crowded condition). In spite of relatively high acceleration peaks for pedestrians crossing in running mode, results obtained also show that there is low probability of user discomfort. In a companion paper (Part 2), the experimental results presented herein are used to assess the accuracy of conventional numerical models and analytical formulae in predicting the vibration response of the St. Mateus footbridge.

1. Introduction

The use of pultruded glass fibre reinforced polymer (GFRP) composites in bridge engineering applications has consistently increased in the past few decades, in either all-composite or hybrid new bridges or in the rehabilitation of existing infrastructure [1,2]. This stems from the well-known technical and economic benefits of GFRPs that include high strength- and stiffness-to-weight ratios, electromagnetic transparency, reduced maintenance requirements and improved durability [3,4]. Among the different pultruded GFRP members available for bridge applications [5], multicellular panel systems are particularly well-suited for both vehicular [6,7] and pedestrian bridge decks [8,9] due to their lightness and easy handling. In recent years, these deck systems have been provided with innovative mechanical joining systems [10] that significantly improve the deck assembly operations [11] and thereby their connection to the supporting structure [12], namely when compared with other heavier bridge slab systems. This has promoted the design and construction of more slender bridges, namely hybrid girder systems, with pultruded GFRP slabs connected to main girders made of traditional materials (*e.g.*, reinforced concrete, prestressed concrete and steel) [12].

Although providing important advantages, the lightness and slenderness also constitute one of the main concerns about the serviceability behaviour of pedestrian bridges, the same way as in slender footbridges made of conventional materials [13,14]. In addition, specific aspects of the pultruded GFRP deck material (*i.e.*, relatively deformable and with low damping [1,5,15]) associated with the possible low damping of the supporting girders (*e.g.*, about 0.4% for steel [14]), render that type of hybrid structural solutions potentially more susceptible to human-induced vibrations than other equally slender non-composite systems.

Therefore, especial attention must be given to the dynamic behaviour of GFRP footbridge decks under pedestrian loading, namely when design is governed by the human comfort requirements in service conditions. Regarding this particular aspect, very few studies have been published in the literature. Some of those studies focused mainly on the modal experimental identification of existing footbridges [16,17], not addressing the vibration response due to human activities. In this

* Corresponding author.
E-mail address: mario.sa@ist.utl.pt (M.F. Sá).

http://dx.doi.org/10.1016/j.tws.2017.05.013
Received 10 February 2017; Received in revised form 11 May 2017; Accepted 12 May 2017
Available online 25 May 2017
0263-8231/

Fig. 1. General view of the St. Mateus hybrid footbridge, Viseu, Portugal.

regard, the studies available focused (i) on all-composite footbridges [18,19], or (ii) on other types of hybrid structural solutions comprising pultruded GFRP girders supporting concrete slabs [20,21]. Although there are studies on the dynamic behaviour of vehicular bridges with GFRP components (*e.g.*, [22–25]), according to the authors' best knowledge, no information is available on GFRP-steel hybrid systems for footbridge applications.

In this context, the main goal of the study presented herein is to obtain a comprehensive understanding about the serviceability vibration behaviour under pedestrian loading of the St. Mateus footbridge, recently built in Viseu (Portugal). This footbridge, which stands as a representative example of typical deck GFRP-steel girder solutions (Fig. 1), is a 13.3 m span arched structure, comprising a 2.5 m width pultruded GFRP slab formed by assembling thin-walled multicellular deck panels. The structure weighs 3.33 kN/m of which only 25% corresponds to the panels [12].

This two-part paper presents results of experimental, numerical and analytical investigations about the dynamic behaviour of the St. Mateus footbridge for different pedestrian traffic densities, varying from single pedestrians to a stream/crowd. The present paper (Part 1) first presents a collection of the design guidance available concerning the comfort verification criteria for footbridges in general. Then, after a brief description of the bridge structure, the methods and results of a comprehensive *in situ* experimental campaign are presented and discussed; the experiments included static load tests, modal identification tests and vibration tests of the footbridge under pedestrian actions. In the companion paper (Part 2 [26]), the experimental data presented here is used to assess the accuracy of (i) a conventional numerical model and (ii) analytical formulae in predicting the dynamic behaviour of the St. Mateus footbridge under human-induced accelerations, considering the different traffic scenarios assumed at the design stage.

2. Overview of vibration design requirements for footbriges

In general, the existing design guidelines for pedestrian comfort in footbridges under serviceability conditions suggest the following types of verification criteria (one or both): (i) safety frequency criterion – indirect verification, and (ii) acceleration comfort criterion – direct verification. Table 1 presents a compilation of the vibration verification criteria for vertical accelerations recommended in the several standards, regulations and current design codes of practice.

The first criterion aims to prevent the risk of resonant responses on footbridges, by avoiding that their natural frequencies fall within certain frequency ranges, namely those close to the pedestrian walking frequencies. Almost all guidelines included in Table 1 adopt this indirect verification, setting a minimum frequency around 4–6 Hz, thus covering the most common human step paces. In this regard, it is worth stressing that some design codes consider different risk ranges for the natural frequencies in order to meet explicitly the influence of the 2nd harmonic of the pedestrian loads [30,33,35,39,40], which may assume particular relevance on very slender footbridges [13,14]. Note that some guidelines address the human comfort only by considering this indirect control, *i.e.* they do not set any limit value for the expected accelerations that the footbridge may undergo [33,35,38].

In most design codes the direct verification of the acceleration criterion is also considered for the human comfort assessment, when the indirect verification is not fulfilled. Most guidelines suggest single thresholds for an acceptable level of acceleration, often setting maximum limits (in general about 0.7–1.0 m/s^2) and, in some cases, defining them as a function of the footbridge's fundamental frequency [27,30,34,36]. It is worth noting that non-normative codes [39,40] propose different limit acceleration ranges (up to an singular limit of 2.5 m/s^2) related with various comfort levels to be selected by designers and owners, according to the typology/class and expected traffic

Table 1
Compilation of vibration verification criteria recommended by several codes.

Code/guideline	Safety criterion Frequency [Hz]	Comfort criterion Vertical acceleration [m/s^2]	Observations
BS 5400-2 [27]	< 5.00	$a_{lim} < 0.50 \times f_1^{0.5}$	Non-loaded structure.
NA BS EN 1991-2 [28]	< 8.00	$0.50 < a_{lim} < 2.00$	Non-loaded structure, a_{lim} calculation.
EN 1990-A2 [29]	< 5.00	$a_{lim} < 0.70$	Torsional modes exempted if $f_1 > 2{,}5$ Hz.
EN 1992-2 [30]	1.60–2.40 (α_1)	$a_{lim} < 0.50 \times f_1^{0,5}$	Linear reduction of acceleration (0–70%) for $4 \le f_1 \le 5$ Hz.
	2.50–5.00 (α_2)		
EN 1993-1-1 [31]	< 5.00	$a_{lim} < 1.00$	Including footbridges and others pedestrian structures.
EN 1995-2 [32]	< 5.00	$a_{lim} < 0.70$	Acceleration calculation depending of the motion type.
AASHTO [33]	< 3.00 (α_1)	–	1st and 2nd harmonics considered.
	< 5.00 (α_2)		
ONT 83 [34]	< 4.00	$a_{lim} < 0.25 \times f_1^{0.78}$	Control by acceleration.
CEB 209 [35]	1.60–2.40 (α_1)	–	1st and 2nd harmonics considered.
	3.50–4.50 (α_2)		
RPM-95 [36]	–	$a_{lim} < 0.50 \times f_1^{0.5}$	Control by acceleration.
ISO 10137 [37]	1.70–2.30	a_{RMS}[a] base curves	Single pedestrian, flows, and streams considered.
		(multiplying factors: 30 or 60)	
SBA 123/82 [38]	< 6.00	–	f_1 limited inferiorly for mass increase of 3 N/m^2.
HiVoSS [39]	1.25–2.30 (α_1)	Function of comfort levels:	Loaded structure.
	1.25–4.60 (α_2)	$a_{lim} < 0.50$ (max.)	1st and 2nd harmonics considered.
Sétra [40]	1.70–2.10 (α_1)	$0.50 < a_{lim} < 1.00$(mean)	
	1.00–1.70 (α_1)	$1.00 < a_{lim} < 2.50$ (min.)	Single pedestrian, groups, and streams/crowds considered.
	2.10–2.60 (α_1)		
	2.60–5.00 (α_2)		

f_1 – fundamental frequency (1st vibration mode). α_i – Fourier coefficient of the harmonic i = 1, 2.
[a] RMS – Root Mean Squared.