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Modal identification of a GFRP-concrete hybrid footbridge prototype: Experimental tests and analytical and numerical simulations

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ABSTRACT

The use of fibre reinforced polymer (FRP) structural elements, including glass fibre reinforced polymer (GFRP) pultruded profiles, has increased in the last few decades. The high potential of these materials for civil engineering structural applications, particularly for footbridges, stems from their high strength, low self-weight and good durability. However, when designing GFRP structures, the high deformability and the susceptibility to instability phenomena seldom allow the full exploitation of the GFRP material. In order to overcome these limitations, several hybrid structural systems have been proposed, namely GFRP-concrete hybrid systems. In this context, the evaluation of the dynamic characteristics of GFRP-concrete hybrid structural systems is very important, especially for footbridge applications, whose design is generally governed by pedestrian comfort criteria. This paper first presents modal identification experimental tests on a 6.0 m long and 2.0 m wide GFRP-concrete hybrid footbridge prototype, made of two I-shaped GFRP main girders and a thin steel fibre reinforced self-compacting concrete (SFRSCC) deck. The tests consisted of applying an excitation to the deck with an impact hammer and measuring both the applied excitation and the structure's response. The natural modes of vibration, frequencies and damping were determined using (i) a conventional input–output modal identification technique, based on the Rational Fraction Polynomial method, and (ii) a simple output-only method directly based on the Fast Fourier Transform (FFT) of the response (mode frequencies only). In the second part of the paper, experimental data are compared with analytical and numerical simulations in order to assess the accuracy of such design tools in predicting the dynamic behaviour of GFRP-SFRSCC hybrid structures, in terms of mode shapes and frequencies.

1. Introduction

In the last decades there has been an increasing use of structural elements made of fibre reinforced polymer (FRP) materials in general and of glass fibre reinforced polymer (GFRP) pultruded profiles in particular, owing to their high strength, low self-weight, ease of installation, corrosion resistance and electromagnetic transparency [1–3]. On the other hand, the high deformability, owing to the low elasticity and shear moduli, the brittle failure, the behaviour at elevated temperature and the lack of specific design codes are hindering the widespread use of these new structural materials [4–7].

The above mentioned mechanical disadvantages inherent to GFRP pultruded profiles, namely the high deformability, often lead to structural designs governed by the serviceability behaviour or instability phenomena, seldom allowing the full exploitation of the material high strength [8–10]. In this context, in order to overcome the aforementioned limitations hybrid structural solutions have been proposed by several authors (e.g. [11–18]), in which the GFRP profiles are combined with traditional materials, namely concrete and steel. Hybrid structures are particularly suited for footbridge structures due to the possibility of rapid and easy installation while reducing the structural slenderness (when compared to full GFRP structures), which is particularly important in these structures, whose design is oftengoverned by serviceability requirements, namely in what concerns pedestrian comfort [10,19,20].

The design of structures made of traditional materials (reinforced concrete, prestressed concrete, steel), unlike that of FRP structures, is generally governed by the material strength, leading to structures with higher stiffness and weight than comparable FRP structures. Although stiffness and weight have contrary effects in the vibration frequencies, structures made of traditional materials, especially concrete structures, tend to exhibit higher structural vibration frequencies than their FRP counterparts. On the other hand, the lower self-weight of FRP structures, in principle an inherent advantage, raises concerns about their dynamic behaviour

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Nomenclature

Symbol	Description
dx	infinitesimal length
f_{au}	tensile strength of the epoxy adhesive (MPa)
f_{bk}	tensile strength of the stainless steel bolts (MPa)
f_{cm}	compressive strength of the SFRSCC (MPa)
f_{cr}	tensile cracking strength of the SFRSCC (MPa)
f_{mu}	compressive strength of the epoxy mortar (MPa)
f_n	Vibration frequency of the *n*th-mode (in Hz)
$f_{tu,L}$	tensile strength of the GFRP for the longitudinal direction (MPa)
k'	ratio between shear area and total area of the beam
p_n	vibration frequency of the *n*th-mode (in rad/s)
t	time
x	longitudinal development of the beam
y	transverse displacement
$\bar{y}_n$	shape of the *n*th flexure mode
A_n to D_n	boundary dependent coefficients of the *n*th-mode shape
E	elasticity modulus
E_a	elasticity modulus in tension of the epoxy adhesive (GPa)
$E_{c,28}$	elasticity modulus in compression of the SFRSCC at 28 days (GPa)
$E_{L,t}$	elasticity modulus in tension of the GFRP for the longitudinal direction (GPa)
E_m	elasticity modulus in compression of the epoxy mortar (GPa)
$E_{T,c}$	elasticity modulus in compression of the GFRP for the transverse direction (GPa)
G	shear modulus
G_{LT}	shear modulus of the GFRP (GPa)
I	second moment of area of the beam section
I_p	polar moment of inertia
I_w	warping constant
J	torsion constant
L	beam length
M	bending moment
T	torque
V	shear force
β	distortional angle of the infinitesimal
θ	rotation angle of the infinitesimal
ρ	volumetric weight
τ_{mu}	shear strength of the epoxy mortar (MPa)
$\tau_{u,LT}$	in-plane shear strength of the GFRP (MPa)
υ	poisson's ratio of the SFRSCC (–)
ϕ	torsion rotation angle
$\bar{\phi}_n$	shape of the *n*th torsion mode

under human-induced loads, namely in footbridges. The relatively low material damping of FRP [21] also contributes to those concerns. When compared to full FRP structures, GFRP-concrete hybrid structural solutions present higher stiffness and damping (due to theaddition of concrete), thus mitigating the previous concerns and increasing their potential in footbridge structural solutions.

Modal identification tests have been an important tool in determining the dynamic characteristics of civil engineering structures, namely of the following modal parameters: (i) vibration frequencies, (ii) mode shapes, and (iii) damping values. The determination of these parameters is particularly important to validate the design models of structures that are particularly complex and/or involve non-traditional materials and structural systems, which is the case of GFRP-concrete hybrid solutions.

There are several examples in the literature of modal identification tests performed on civil engineering structures in general and bridge structures in particular (e.g. [22–26]). In order to determine the modal parameters by means of experimental tests, there are several methods of analysis available, namely input–output methods and output-only methods [27].

There are only a few studies reported in the literature regarding modal identification tests on FRP bridges. Bai and Keller [21] tested a two span full-GFRP truss footbridge, one of the spans presenting bolted connections and the other bonded connections. In this study, two different output only methods were used, namely (i) the peak peaking (PP) method, and (ii) stochastic subspace identification based on the state space model (SSI), to estimate mode shapes, frequencies and damping (only SSI). The two methods provided similar results. The experimental results were compared with analytical predictions based on the Euler–Bernoulli beam theory with a good agreement regarding mode shapes and frequencies. The authors showed that the connection between the pultruded elements considerably influences the dynamic behaviour, namely in what concerns the mode frequency and damping. Burgueño et al. [28] tested a bridge structural system constituted by carbon fibre reinforced polymer (CFRP) concrete filled tubular girders and a GFRP deck. This study confirmed the possibility of detecting and measuring damage in this type of structural system by means of modal identification tests. Experimental results were predicted with a good accuracy using finite element (FE) models.

The study presented herein concerns the modal parameter identification of a GFRP-concrete hybrid footbridge prototype. The structure's cross-section is comprised of two I-shaped GFRP pultruded profiles and a thin deck made of steel fibre reinforced self-compacting concrete (SFRSCC). These elements are connected by an epoxy adhesive layer combined with stainless steel bolts. The footbridge prototype, with a total length of 6.00 m, was tested in a simply supported span. The experimental data was analysed in order to retrieve the modal parameters of the first four vibration modes with (i) an input–output identification algorithm based on the Rational Fraction Polynomial method [29] and with (ii) a simpler output-only method directly based on the Fast Fourier Transform (FFT) of the structural response. The first method allowed the determination of the mode shapes, frequencies and damping ratioswhile the latter method was used to provide only the mode frequencies. The experimental results were then compared with predictions from analytical and numerical models, in order to assess the quality of these simulation tools for GFRP-concrete hybrid structures.

2. Experimental programme

2.1. Characteristics of the footbridge prototype

Fig. 1 shows the cross-section of the footbridge prototype used in this study, which presents a total length of 6.00 m, a width of 2.00 m and a simply supported span of 5.50 m, as shown in Fig. 2.

The hybrid structural system comprises two I-shaped pultruded profiles (200 × 100 × 10 mm), used both as main and secondary girders, and a thin (40 mm thick) SFRSCC deck on top constituted by precast slabs (2.0 m wide × 1.0 m long). The connection