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# Dynamic response under pedestrian load of a GFRP–SFRSCC hybrid footbridge prototype: Experimental tests and numerical simulation

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ABSTRACT

The use of glass fibre reinforced polymer (GFRP) pultruded profiles in civil engineering structures has known considerable growth in recent years due to their high strength, low self-weight and corrosion resistance when compared to traditional materials. However, the high deformability, the susceptibility to instability phenomena and the brittle failure are delaying the widespread use of this structural material. GFRP–concrete hybrid systems have been proposed as an alternative to fully composite structures in order to overcome some of those drawbacks, namely the deformability and instability problems. These hybrid solutions are especially attractive for footbridge structures whose design is often governed by serviceability requirements. Nevertheless, in order to make these structural systems standard solutions for civil engineering practice it is necessary to gather in-depth understanding about their structural behaviour, namely under dynamic loads, and to assess the ability of current design tools to predict their response. This paper presents experimental and numerical investigations concerning the dynamic behaviour under pedestrian induced loads of a 6.0 m long hybrid footbridge prototype comprising two GFRP pultruded profiles and a thin steel fibre reinforced self-compacting concrete (SFRSCC) deck. The results of dynamic tests and respective numerical simulations are compared in order to access the ability of conventional finite element (FE) models to predict the structural response of the hybrid footbridge, namely the accelerations as a function of time for different types of pedestrian loads. The experimental data are also compared with regulation requirements concerning human comfort. The results obtained show that the models developed using conventional numerical tools are able to predict the dynamic response of the footbridge prototype under pedestrian actions with fairly good accuracy. The comparison of the results with regulation requirements also attests the feasibility of the hybrid structural solution proposed.

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## 1. Introduction

In recent years glass fibre reinforced polymer (GFRP) pultruded profiles have been increasingly used as structural materials in a wide range of civil engineering applications. The high strength, low self-weight, ease of installation, corrosion resistance and electromagnetic transparency are the main advantages of this material [1,2]. In opposition, the brittle failure and the low Young's and shear moduli constitute major drawbacks regarding the structural use of GFRP profiles, with their design being often governed by deformability or instability phenomena, and seldom allowing the full exploitation of the material resistance [3,4].

In this context, several authors (e.g. [5–12]) have proposed different hybrid structural systems, in which GFRP composites are combined with traditional construction materials (such as concrete) in order to overcome the aforementioned limitations while maintaining the attractiveness of GFRP based structural solutions. Among the possible applications of GFRP–concrete hybrid systems identified earlier [1] are footbridges.

The design of footbridges is often governed by their serviceability behaviour, namely in what concerns the fulfilment of pedestrian comfort criteria [13,14] (*cf.* Section 2). Potential problems regarding the serviceability behaviour of footbridges rise with the slenderness of the structural solutions [14] and, therefore, with the use of more deformable materials, such as GFRP. Thereafter, it is particularly important to correctly assess and predict the structural behaviour of GFRP–concrete hybrid structures with available design tools, namely commercial finite element (FE) packages. However, there are very few published results on the dynamic behaviour and properties of fibre reinforced polymer (FRP) bridges (e.g. [14,16]) and, according to the authors' best knowledge, none about GFRP–concrete hybrid structures.

This paper presents experimental and numerical investigations about the dynamic response under pedestrian loads of a footbridge prototype comprising GFRP pultruded profiles and a very thin concrete deck made of steel fibre reinforced self-compacting concrete (SFRSCC) pre-cast slabs. This small-scale footbridge prototype was

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**Nomenclature**

| Symbol | Description |
|---|---|
| $E_{L,t}$ | elasticity modulus in tension of the GFRP for the longitudinal direction (GPa) |
| $E_{T,c}$ | elasticity modulus in compression of the GFRP for the transverse direction (GPa) |
| $G_{LT}$ | shear modulus of the GFRP (GPa) |
| $f_{tu,L}$ | tensile strength of the GFRP for the longitudinal direction (MPa) |
| $\tau_{u,LT}$ | in-plane sear strength of the GFRP (MPa) |
| $E_c$ | elasticity modulus in compression of the SFRSCC (GPa) |
| $f_{cu}$ | compressive strength of the SFRSCC (MPa) |
| $f_{cr}$ | tensile cracking strength of the SFRSCC (MPa) |
| $\upsilon$ | Poisson's ratio of the SFRSCC (–) |
| $E_a$ | elasticity modulus in tension of the epoxy adhesive (GPa) |
| $f_{au}$ | tensile strength of the epoxy adhesive (MPa) |
| $E_m$ | elasticity modulus in compression of the epoxy mortar (GPa) |
| $f_{mu}$ | compressive strength of the epoxy mortar (MPa) |
| $f_{bk}$ | tensile strength of the stainless steel bolts (MPa) |
| $\xi_n$ | damping of the *n*th vibration mode (%) |

built in laboratory and tested in a simply supported span of 5.5 m in order to investigate its structural behaviour and obtain in-depth understanding about the GFRP–SFRSCC hybrid system proposed. A full-scale footbridge, with a span of 10.5 m, will be designed and built in the campus of Minho University (Guimarães, Portugal) over a small river. It is worth mentioning that the prototype under study, being a small-scale model, is not required to perform according with design codes. One should also note that extrapolating results obtained from testing a small-scale prototype to the full-scale structure could be potentially affected by scale effects. Nevertheless, results obtained from the study of this prototype are essential to understand the feasibility and dynamic performance of the full-scale hybrid footbridge, particularly whether it fulfils serviceability and ultimate limit states design requirements.

The experimental investigations comprised (i) material characterisation tests on small-scale specimens, (ii) static flexural tests on the footbridge prototype, (iii) the definition of pedestrian loads, (iv) modal identification tests and (v) dynamic tests on the footbridge prototype under pedestrian loads. The numerical investigations included the development of a three-dimensional FE model of the footbridge prototype, in which the material properties derived from testing were used as input. The model of the prototype was first validated with the results of static flexural tests and modal identification tests and then used to simulate the dynamic tests under pedestrian loads.

## 2. Design requirements for comfort in footbridges

Regarding the design requirements for comfort in footbridges, the Eurocode 0 [17] recommends that structural accelerations under pedestrian actions shall not be greater than 0.70 m/s$^2$ and 0.20 m/s$^2$ for the vertical and horizontal directions, respectively, independently of the structure's principal frequency. Other design codes, relate the maximum acceleration limits with the structure's vibration frequencies [14,18]. According to Eurocode 0 [17], the explicit verification of those accelerations is not required if the first vertical vibration frequency of the footbridge is higher than 5 Hz.

Other standards addressing human comfort, namely BS 6472 [19] (in this case applicable for buildings), do not limit the maximum accelerations, but instead the maximum root mean square (RMS) of the expected accelerations. Such criterion takes into account not only the peak values of the response but also the overall structural response. Performance requirements are then set according to the structural frequency, the type of activity and the duration of the exposure to the vibrations. ISO 10137 [20] presents very similar recommendations to BS 6472 [19], but it also indicates parameters that are directly applicable to walkways or footbridges.

Many design codes, particularly the Eurocode 1 [21], do not specify which pedestrian actions shall be considered in the verification of design requirements, providing only frequency ranges for the pedestrian action. The absence of specific pedestrian actions, namely well-established load-time functions to be used in design means that comfort verifications are performed on a case-to-case basis, depending on the options of the designer and owner. Nevertheless, load-time functions and other relevant parameters of pedestrian actions are provided in the literature (e.g., Bachmann and Ammann [22]) and may be used in comfort criteria verifications. Fig. 1 shows the load-time functions proposed in [22] for slow, normal and fast walk, together with experimental curves derived from testing within the present study (*cf.* Section 4.4). Bachmann and Ammann [22] also recommend comfort verifications to be performed for a pedestrian weighing 70 kgf.

## 3. Structural concept and design of the footbridge

The main objective of hybrid structures is to fully exploit the material properties of each one of the components, maximising their advantages and overcoming their limitations. The hybrid structure proposed here, comprising GFRP pultruded profiles (200 × 100 × 10 mm, I-section) and a 40 mm thick concrete slab made of precast segments (Fig. 2), is to be used in simply supported spans, for which bending moments are (for most actions) positive. Thereby, the concrete elements that constitute the footbridge deck, being located at the upper part of the section, are basically subjected to compressive stresses, for which cementitious materials perform better. In opposition, the GFRP profiles underneath, used as main girders, are prevented to buckle by the deck and are subjected mainly to tensile stresses, for which GFRP materials behave better.

In order to avoid local failure of the webs over the support sections, concrete jackets (Figs. 3 and 4) are provided between the flanges, on both sides of the webs, with a length of 0.20 m, as suggested in [11]. Secondary girders are provided at midspan and at the support sections in order (i) to avoid local instability of the webs due to shear, (ii) to increase the torsional stiffness and (iii) to minimise the initial imperfections of the main girders. The secondary girders are made of GFRP pultruded profiles with the same cross-section as the main girders. The main and secondary girders are connected with small-length (160 mm) angle GFRP profiles (50 × 50 × 8 mm) using M10 × 55 stainless steel bolts. Fig. 4 shows the connection details for both the support and mid-span sections, including the cuts of secondary girders.

The connection of the SFRSCC slabs to the GFRP main girders is provided by a 2 mm thick layer of epoxy adhesive and stainless steel bolts. The adhesively bonded connection ensures full interaction between the materials, guaranteeing maximum stiffness and strength in the longitudinal direction [11]. The epoxy adhesive used in the shear connections was cured at room temperature

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