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Structural behaviour of a GFRP-concrete hybrid footbridge prototype: Experimental tests and numerical and analytical simulations

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ABSTRACT

Glass fibre reinforced polymer (GFRP) pultruded profiles are being increasingly used in the construction industry since the last few decades. The high potential of GFRP profiles for structural applications stems from their high strength, low self-weight and corrosion resistance. In opposition, the high deformability, the susceptibility to instability phenomena and the lack of specific design codes have been hindering a wider use of these advanced composite materials. Several hybrid systems in which GFRP materials are combined with traditional materials, namely concrete, have been proposed in order to overcome the aforementioned limitations of the GFRP material. This paper presents experimental, analytical and numerical investigations about the flexural behaviour of a GFRP-concrete hybrid footbridge prototype comprising two I-shaped GFRP main girders and a thin steel fibre reinforced self-compacting concrete (SFRSCC) deck. With the aim of limiting the structure's deformability, the footbridge features an external prestress system consisting of two ordinary steel rebars screwed tighten to the structure at the support sections. A small-scale footbridge prototype, 6.0 m long and 2.0 m wide, was built and tested in a 5.5 m simply supported span. The experimental programme included (i) serviceability tests, with and without the application of the external prestress system, and (ii) failure tests. Results of flexural tests proved the feasibility and advantages of the structural concept proposed: the judicious combination of GFRP and SFRSCC enabled the development of a lightweight, high performance and relatively inexpensive structural system for footbridges; furthermore, the external prestress system was very effective in limiting deflections. The analytical and numerical models developed in this study were able to predict with good accuracy (i) the linear elastic behaviour of the structure up to failure, (ii) the effects of the external prestress, and (iii) the failure mode and strength, proving to be accurate tools for the design of GFRP-concrete structural solutions.

1. Introduction

In the last few decades, the use of fibre reinforced polymer (FRP) materials in general, and of glass fibre reinforced polymer (GFRP) pultruded profiles in particular, has found a significant increase in civil engineering structural applications. In fact, these materials have high potential for both building and bridge structural applications owing to their high strength, low self-weight, chemical resistance, ease of installation and electromagnetic transparency [1–3]. However, the lack of specific standards dealing with the various aspects of the design, the brittle failure, the high deformability and the susceptibility to instability phenomena, which often govern design and seldom allow the full exploitation of the materials' resistance [4–6], have been delaying the widespread use of these materials [7–10].

Several hybrid structural systems combining GFRP elements with traditional materials have been proposed in order to overcome the aforementioned limitations while maintaining the main attractiveness of advanced composite structures. In those systems, the careful combination of GFRP with concrete in flexural members has proven to be particularly effective, namely in reducing short- and long-term deformability and in delaying instability phenomena (*e.g.* [11–19]).

The research presented in this paper is part of a broader research project – *PONTALUMIS* – a collaborative study between Instituto Superior Técnico (IST), Minho University (UM) and composites manufacturer *ALTO, Perfis Pultrudidos, Lda.* This project aims at developing a lightweight, durable and maintenance-free hybrid footbridge made of two I-shaped GFRP pultruded profiles acting as main girders and a steel fibre reinforced self-compacting concrete (SFRSCC) deck. In order to fully understand the feasibility and structural behaviour of the structural system proposed, the research project included the construction of a small-scale prototype, with a length of 6.0 m, approximately half of the length of the

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Nomenclature

Symbol	Description
a, b	geometrical parameters of the 4-point bending load configuration
b_p	width of the GFRP profiles' flanges
d	distance between the theoretical support and the rotation point of the rebars
e	eccentricity of the prestress rebars with respect to NA
f_{au}	tensile strength of the epoxy adhesive
f_{bk}	characteristic tensile strength of the stainless steel bolts
f_{cm}	compressive strength of the SFRSCC
f_{cr}	tensile cracking strength of the SFRSCC
f_{mu}	compressive strength of the epoxy mortar
$f_{tu,L}$	tensile strength of the GFRP for the longitudinal direction
h_c	thickness of the SFRSCC slab
h_p	height of the GFRP profiles
h_t	total height of the cross-section
i	number of element
kA	Timoshenko shear area
l	free length of the rebars
t_f	thickness of the GFRP profiles' flanges
t_w	thickness of the GFRP profiles' webs
x	longitudinal development of the structure
z	vertical distance to z_g
z_g	neutral axis height with respect to the mid-line of the GFRP bottom flanges
z_{gi}	vertical position of the stiffness centre of element i
A_i	area of element i
A_s	area of the steel rebars
A_w	area of the GFRP webs
E_a	elasticity modulus in tension of the epoxy adhesive
E_c	elasticity modulus in compression of the SFRSCC
E_i	elasticity modulus of element i
EI	flexural stiffness of the cross-section
$E_{L,t}$	elasticity modulus in tension of the GFRP for the longitudinal direction
E_m	elasticity modulus in compression of the epoxy mortar
E_s	elasticity modulus of steel
$E_{T,c}$	elasticity modulus in compression of the GFRP for the transverse direction
F	applied load in the 4-point bending load configuration
$F_{cu,L}$	compressive strength of the GFRP for the transverse direction
F_u	failure load
G	shear modulus
G_{LT}	shear modulus of the GFRP
K	average midspan stiffness
L	Span
$M(x)$	bending moment at position x
M_F	bending moment due to the applied load F
M_{max}	maximum bending moment
M_u	ultimate bending moment
M_{SW}	bending moment due to the self-weight
NA	neutral axis position measured from the top fibre of the cross-section
P	prestress force
S	shear strength in the plane 1–2
$V(x)$	shear force at position x
V_F	shear force due to the applied load F
V_{SW}	shear force due to the self-weight
V_u	ultimate shear force
X	axial strength in direction 1
Y	axial strength in direction 2
$\delta(x)$	deflection at position x
δ_{ms}	average midspan deflection
$\delta_{ms1\text{-}2}$	midspan deflection measurement positions
$\delta_{ms\text{-}u}$	midspan deflection at failure
$\delta_P(x)$	upwards deflection at position x caused by the prestress load P
$\varepsilon_{c1\text{-}3}$	midspan strain measurement positions on the SFRSCC
$\varepsilon_{f1\text{-}2}$	midspan strain measurement positions on the GFRP flanges
$\varepsilon_{w1\text{-}2}$	midspan strain measurement positions on the GFRP webs
θ_L	rotation of the support section due to vertical loads
θ_P	rotation of the support section due to prestress loads
θ_T	total rotation of the support section
ρ	volumetric weight
$\sigma(x,z)$	axial stress at position x, z
σ_1	axial stress in direction 1
σ_2	axial stress in direction 2
σ_F	axial stress due to the applied load F
σ_L	axial stress in longitudinal direction
σ_{SW}	axial stress due to the self-weight
σ_T	axial stress in transverse direction
$\tau(x,z)$	shear stress at position x, z
τ_{12}	shear stress in the plane 1–2
τ_F	shear force due to the applied load F
τ_{LT}	shear stress in the plane defined by the longitudinal and transverse directions
τ_{mu}	shear strength of the epoxy mortar
τ_{SW}	shear stress due to the self-weight
$\tau_{u,LT}$	in-plane shear strength of the GFRP
υ	Poisson's ratio of the SFRSCC
χ	curvature of the cross-section
Δ	elongation of the rebars
ΔP	additional force on the rebars caused by the vertical loads

full-scale prototype. Previous studies were already performed in order to investigate the structural behaviour of this small-scale prototype, namely in what concerns the following aspects: (i) performance of different shear connection systems used at the GFRP–SFRSCC interface [20]; (ii) modal (dynamic) identification [21]; (iii) dynamic response of the footbridge under pedestrian loads [6]; and (iv) creep behaviour of the footbridge under sustained loads [19].

This paper presents experimental, analytical and numerical investigations about the short-term static behaviour up to failure of the hybrid GFRP–SFRSCC small-scale footbridge prototype. The remainder of the paper is organised as follows. Section 2 describes the underlying structural concept of the footbridge prototype and details its geometry. Section 3 presents the experimental programme, which included the construction of the footbridge prototype, material characterisation tests on the constituent materials and 4-point bending flexural tests, which aimed at evaluating both the serviceability and failure responses of the prototype, as well as to assess the efficacy of an external prestress system in limiting the deformability of the hybrid structure. Sections 4 and 5 present analytical and numerical simulations of the structural behaviour of the footbridge, in which simple analytical formulae and a three-dimensional finite element model, respectively, were used to predict the serviceability and failure responses of the hybrid footbridge structure.