A FULL-SCALE INNOVATIVE GFRP-CONCRETE HYBRID FOOTBRIDGE: DESCRIPTION AND TESTING

José SENA-CRUZ, Joaquim BARROS, Luís RAMOS, Delfina GONÇALVES
Associate Professor, Full Professor, Assistant Professor, Researcher, ISISE, University of Minho, Portugal
jsena@civil.uminho.pt, *barros@civil.uminho.pt*, *ramos@civil.uminho.pt*, *delfinagoncalves@civitest.com*

José A. GONILHA, João R. CORREIA, Fernando A. BRANCO
PhD student, Assistant Professor, Full Professor, ICIST, Instituto Superior Técnico de Lisboa, Portugal
jose.gonilha@ist.utl.pt, joao.ramoa.correia@tecnico.ulisboa.pt, fbranco@civil.ist.utl.pt

ABSTRACT: The present paper describes the construction process of a full-scale innovative GFRP-concrete hybrid footbridge, and summarizes the main tests performed. This footbridge is 11 m long, 2 m wide, simply supported, and composed of two pultruded I-shaped GFRP girders (0.2 m × 0.4 m) and a 0.04 thick deck in steel fiber reinforced self-compacting concrete (SFRSCC). To evaluate the static and dynamic behavior of this footbridge, short and long-term load tests, and dynamic tests were performed.

1. Introduction

Fiber reinforced polymer (FRP) materials have been explored in both existing and new constructions due to several advantages pointed out in the literature, such as the high strength, lightness and resistance to harsh environments (Correia 2008). Pultruded FRP materials have the potential to replace conventional steel profiles in housing and infrastructures. In this context, the predominant use of glass FRP (GFRP) composites is justified by its competitiveness when cost and technical aspects are considered (Correia *et al*. 2011).

Fiber reinforced self-compacting concrete (FRSCC) consists of the addition of fibers (typically, steel fibers or synthetic fibers) to a self-compacting concrete composition, whose characteristics are optimized to consider the influence of fibers in the skeleton organization of the aggregates. FRSCC can be used to produce thin shell elements without using conventional steel reinforcement and compaction process, which has relevant benefits in terms of lightweight, time-execution, durability, and costs-maintenance.

A three-year research project, funded by ADI (Portuguese Innovation Agency), was carried out for the development of an innovative footbridge using a Steel FRSCC (SFRSCC) deck and GFRP girders. The team was composed by researchers from the University of Minho and IST/Universidade de Lisboa, and the company *ALTO, Perfis Pultrudidos, Lda*. The present paper describes the material/structural concept of this footbridge, its design and construction process, and summarizes some of the performed tests.

2. Design, Construction and Material Properties

2.1. Design of the prototype

Fig. 1 presents the geometry of the proposed footbridge, with a total length of 11 m and 2.0 m of width. It is simply supported at the ends, with a span length of 10.5 m (L). The deck, of 0.04 m thickness, was made in SFRSCC. Two I-shaped pultruded GFRP main girders support the SFRSCC deck. Epoxy adhesive and steel anchors (Mendes *et al.* 2011) are used to connect the deck to the girders. To increase the stability of the system, five I-shaped pultruded GFRP secondary girders are used. These secondary girders are fixed to the main ones with stainless steel angles and bolts. To guarantee the shear resistance, at the extremities, in a length of 650 mm, the webs of the GFRP main girders were jacketed with SFRSCC, a procedure that had already been proved to be effective (Correia *et al*. 2009).

The footbridge was designed by considering, mainly, the Eurocodes' recommendations. For that purpose, a live load (LL) of 5 kN/m^2 was used. In terms of serviceability requirements, the value of 0.70 m/s^2 was considered as the maximum vertical acceleration to fulfill the pedestrian comfort criteria. Finally, the quasi-permanent combination of 30% of the LL was adopted for the evaluation of the long-term performance, limiting the deflection to L/500.

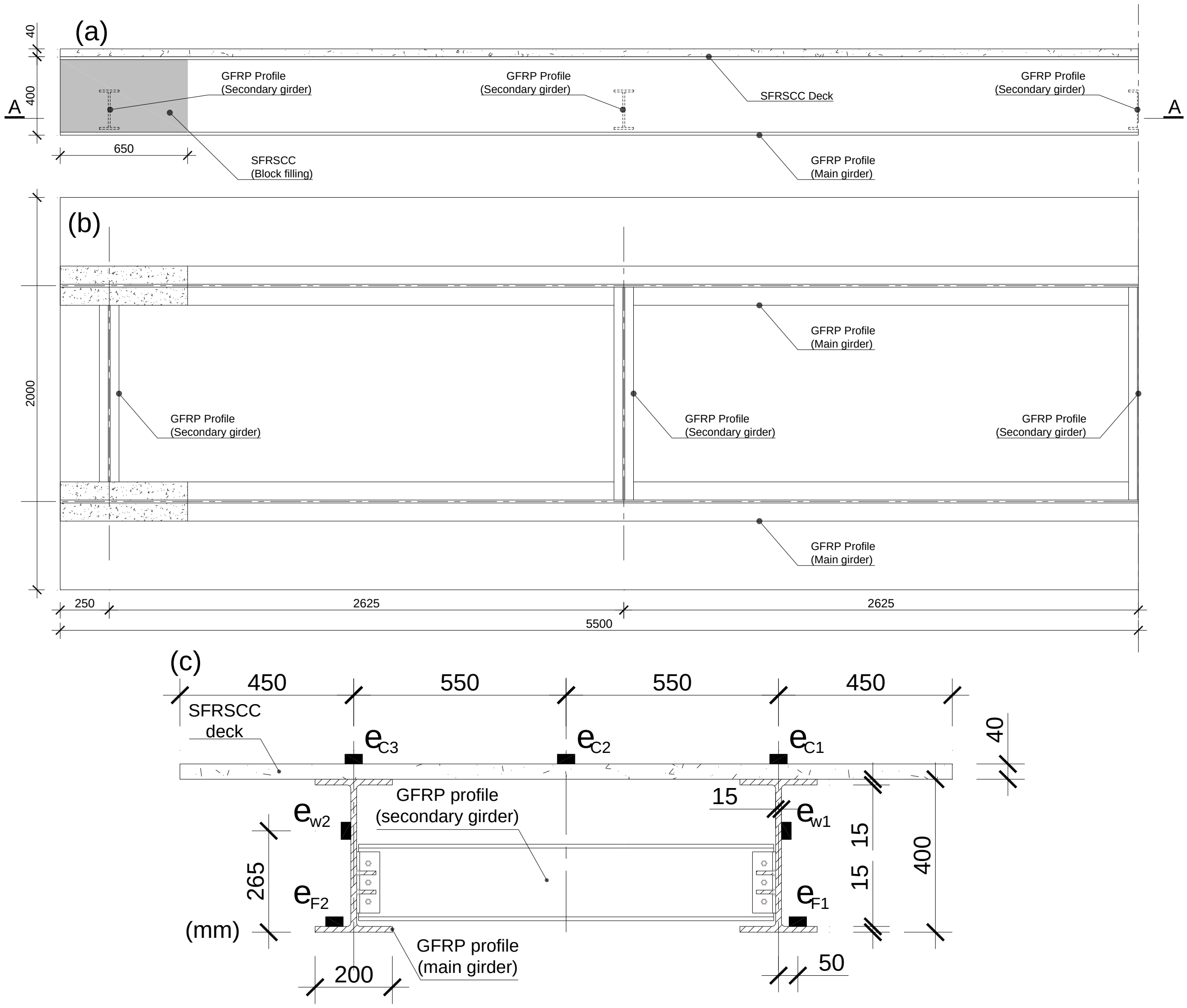


Fig. 1 – Developed footbridge: (a) longitudinal view (half of the bridge); (b) bottom view from A-A (half of the bridge); (c) cross-section at midspan

2.2. Construction of the footbridge

The construction of the footbridge involved several steps, mainly: (i) the manufacturing (pultrusion) of GFRP main and secondary girders (Fig. 2a); (ii) then, the GFRP girders were assembled and the resulting grid was delivered in a regular truck to the factory where the footbridge was built (Fig. 2b); (iii) the SFRSCC was manufactured and the thin deck was casted (Fig. 2c); (iv) holes were drilled in the deck and stainless steel M10×55 anchors were bonded with an epoxy adhesive (Fig. 2d); (v) after surface preparation, a thin epoxy adhesive layer was applied on the deck in the region where the main girders were to be connected to the deck (Fig. 2e); (vi) after assembling the GFRP grid to the SFRSCC deck, the prototype was kept in position enough time to assure a proper curing of the epoxy adhesive (Fig. 2f); (vii) finally, the footbridge prototype was rotated 180º in order to be placed in its final position. For that purpose, a special auxiliary system was designed and used (see Fig. 2g-h).

2.3. Material characterization

The SFRSCC used in the footbridge was developed by *CiviTest Company*, by assuring the required fresh and hardening properties with competitive cost. Table 1 shows the mixture composition of the developed SFRSCC that included 60 kg/m^3 of hooked ends steel fibers of 35 mm length, 0.55 mm diameter and 1100 MPa tensile strength. The methodology followed to formulate the SFRSCC composition can be found elsewhere (Barros *et al.* 2007). Table 2 presents the relevant mechanical properties of the SFRSCC obtained from compression (NP EN 12390-3:2003) and three-point bending tests (RILEM TC 162-TDF:2002 and Model Code 2010).

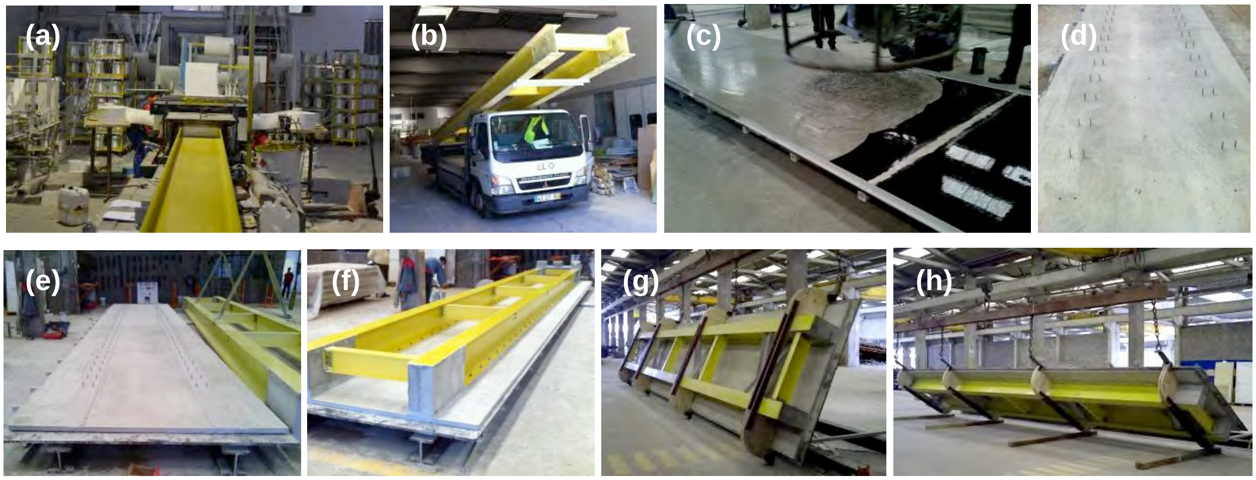


Fig. 2 – (a) Pultrusion of the GFRP profiles; (b) transportation of the GFRP grid; (c) casting the SFRSCC deck; (d) mounting the anchors; (e) applying the epoxy layer; (f) placing the GFRP grid; (g) and (h) rotating and placing the footbridge on the final position

The GFRP profiles used were produced by *ALTO, Perfis Pultrudidos, Lda*. by pultrusion and are composed by 65% in volume of E-glass fiber rovings and mats embedded in a polyester matrix (35%). The production speed of the GFRP profiles is 0.3 m/min at an average temperature and humidity of 180 °C and 55% in the die, respectively. The mechanical characterization was determined in samples extracted from the webs and flanges of the GFRP profiles. Table 3 presents the main properties obtained: in tension (EN ISO 527:1997); in compression (ASTM D 695:2002); in shear (Hodgkinson 2000). In this table $E_{L,t}$=longitudinal elasticity modulus in tension; $E_{T,c}$=transverse elasticity modulus in compression; G_{LT}=in-plane shear modulus; $f_{tu,L}$=longitudinal tensile strength; $\tau_{u,LT}$=in-plane shear strength.

Table 1 – SFRSCC mix proportion per cubic meter

Cement [kg]	**Limestone filler** [kg]	**Water** [kg]	**Superplasticizer SIKA 3005** [kg]	**Fine sand** [kg]	**River sand** [kg]	**Crushed stone** [kg]	**Fibers** [kg]
413	353	140	7.83	237	710	590	60

Table 2 – Mechanical properties of the SFRSCC (average values, COV in brackets)

f_{cm} [MPa]	$f_{ct,L}$ [MPa]	$f_{eq,2}$ [MPa]	$f_{eq,3}$ [MPa]	$f_{R,1}$ [MPa]	$f_{R,2}$ [MPa]	$f_{R,3}$ [MPa]	$f_{R,4}$ [MPa]
75.95 (13.2%)	6.21 (20.16%)	10.42 (23.24%)	10.56 (22.75%)	10.17 (21.24%)	10.27 (22.81%)	9.71 (23.26%)	9.01 (23.81%)

Note: f_{cm}=compressive strength (cubes with 150 mm of edge); f_{eq}=equivalent residual strengths; $f_{R,j}$ = residual flexural tensile strength corresponding with CMOD=CMOD$_j$.

Table 3 – Main mechanical properties of the GFRP profiles (average values, COV in brackets)

GFRP	$E_{L,t}$ [GPa]	$E_{T,c}$ [GPa]	G_{LT} [GPa]	$f_{tu,L}$ [MPa]	$\tau_{u,LT}$ [MPa]	ρ [kN/m^3]
Webs	23.98 (6.71%)	4.55 (11.43%)	3.49 (12.32%)	278.90 (8.55%)	20.42 (5.63%)	18.0
Flanges	35.71 (5.12%)	3.57 (10.08%)	-	336.94 (11.13%)	-	

The "S&P Resin 220" epoxy adhesive was used to bond the GFRP profiles to the SFRSCC deck, as well as to fix the metallic anchors. Sena-Cruz *et al.* (2012) characterized the tensile mechanical properties of this adhesive. After 7 days of curing at 22ºC, a Young's modulus of 7.7 GPa (CoV=3.1%) and a tensile strength of 20.7 MPa (CoV=9.9%) was obtained. According to the supplier, the "S&P Resin 220" epoxy adhesive presents a flexural tensile strength of 30 MPa, a compressive strength of 90 MPa and a bulk shear strength of 3 MPa.

3. Static and creep responses

3.1. Static load tests

To assess the flexural performance of the footbridge three distinct static load tests were executed. For that purpose closed water reservoirs with an average weight of 10.8 kN each and plan dimensions of 1.0×1.2 m^2 were used. Fig. 3 depicts the load configurations (LC) studied, while Fig. 4a shows a picture corresponding to the LC-I configuration static load test. A gap between reservoirs was adopted in order to avoid the arch effect. The load was applied as fast as possible in order to minimize creep effects. LVDTs and strain gauges were used to register the deflection along the bottom face of the main girders and the strains in different points of the midspan cross-section (see Fig. 1c), respectively. The maximum values obtained for the average deflection at midspan ($\delta_{\mathrm{ms,Avg}}$), the axial strains on the SFRSCC slab ($\varepsilon_{c,Avg}$), GFRP webs ($\varepsilon_{w,Avg}$) and bottom flanges ($\varepsilon_{f,Avg}$), and curvature (χ) at midspan measured in the static tests are presented in Table 4. The prototype exhibited linear elastic behavior in all the three static tests. As expected, the values obtained in LC-II are approximately half of those of LC-III. In spite of the highest load level in the LC-I (108.0 kN), the larger deformations were registered in the LC-II, due to the higher load concentration in the vicinity of midspan.

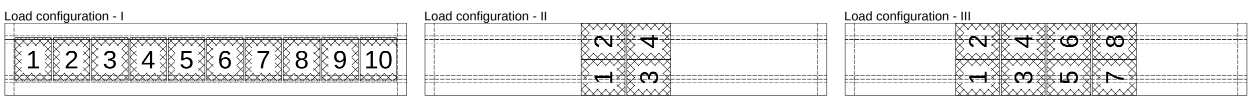


Fig. 3 – Static load test configurations

Table 4 – Main results obtained from the static load tests

Load configuration	$F_{total\ applied}$ [kN]	$\delta_{ms,Avg}$ [mm]	$\varepsilon_{c,Avg}$ [µm/m]	$\varepsilon_{w,Avg}$ [µm/m]	$\varepsilon_{f,Avg}$ [µm/m]	χ [10^4×m^{-1}]
I	108.0	38.07	-190	320	1102	30.62
II	43.2	23.27	-145	220	712	20.30
III	86.4	43.28	-252	392	1208	34.61

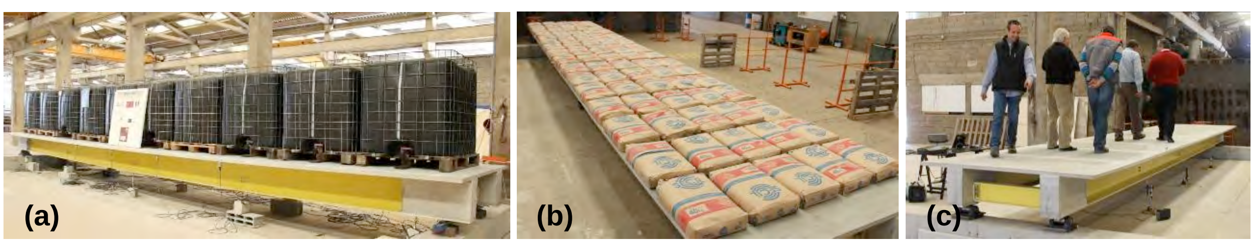


Fig. 4 – (a) Static load test; (b) Creep test; (c) Pedestrian test

3.2. Creep response

The flexural creep behavior was also analyzed by applying a uniform load of 1.52 kN/m^2 (about 30% of the live load) with cement bags – see Fig. 4b. The footbridge was subjected to this gravity load during 152 days (3670 hours), and then, it was unloaded. Two dial gauges placed at midspan (one per main GFRP girder) were used to continuously monitor the deflection. Fig. 5 includes the evolution of the midspan deflection, as well as the environment temperature and relative humidity in the vicinity of the footbridge. During the loading period the deflection due to creep effect reached 4.6 mm (about 40% of the elastic deformation due to the creep load). Based on the results obtained, the midspan deflection predictions using Findley's power law after 50 and 100 years are respectively 23.7 mm and 25.4 mm (about L/412).

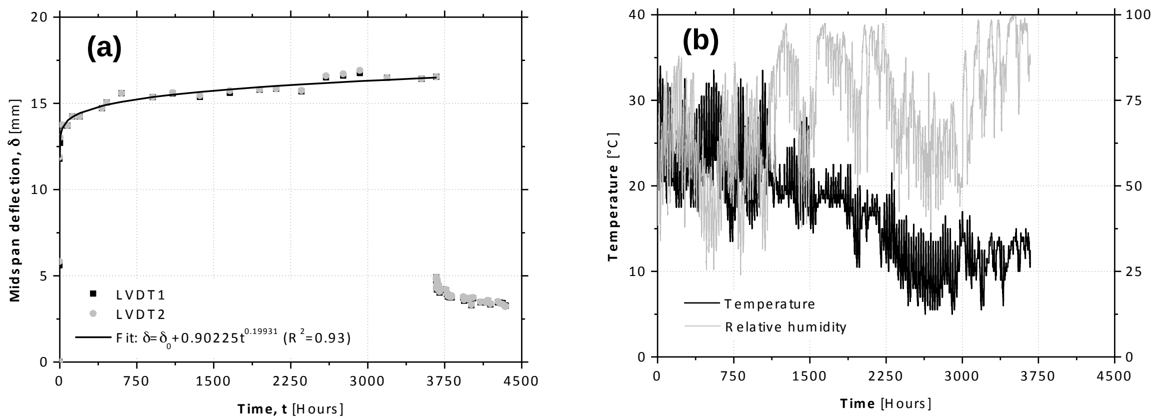


Fig. 5 – (a) Evolution of the deflection during the creep test; (b) Temperature and relative humidity

4. Dynamic response

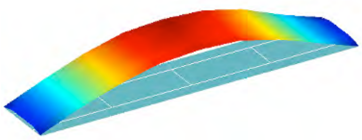
4.1. Modal identification

Dynamic identification tests were carried out to estimate the natural frequencies, mode shapes and damping coefficients. Accelerations were measured in eighteen points along the edges of the bridge, equally spaced by 1.31 m. Two directions were measured: the vertical and horizontal to identify the bending and torsional modes. Accelerations were recorded with piezoelectric accelerometers with a sensitivity of 10 V/g and a dynamic of ± 0.5 g. On each setup 5 minutes (circa 2000 times the first natural period of interest) ambient vibrations with small random impacts in time and on the surface of the concrete deck were recorded with a sampling frequency of 200 Hz.

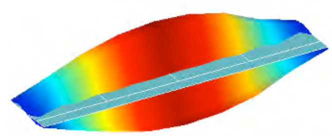
The Enhanced Frequency Domain Decomposition (EFDD) method was used to estimate the dynamic parameters. Fig. 6 shows the results in terms of mode shape configurations and values for the resonant frequencies and damping coefficients (only 6 are presented) – the fundamental frequency is 6.40 Hz. In total, 16 mode shapes were estimated, including vertical and horizontal bending modes and torsion modes. Concerning the quality of results, in general the coefficient of variation – CoV – (values between parentheses in Fig. 6) for frequency estimation is lower than 1%, with exception of modes 4 and 5, indicating a good estimation. Damping, however, presents a higher variability on the estimations, but an average value of 0.95% with a CoV equal to 20% can be established. To better estimate the damping, a free vibration test was carried out by suddenly releasing the structure from a static load of 90 kg (the weight of one person) positioned at midspan. The sudden release induces on the structure a transient excitation. By using the logarithm decrement method, the damping was estimated equal to 1.05%, which is quite close to the average value obtained by the ambient vibration test with small random impacts.

4.2. Pedestrian response

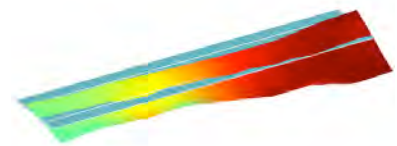
The pedestrian response of the footbridge was evaluated with two sets of dynamic tests: (i) tests with one pedestrian; and (ii) tests with several pedestrians simulating a crowd situation (about 0.3 pedestrians/m^2) – see Fig. 4b. The vertical accelerations were measured at quarter and mid-span of the edges of the deck. In general, all the load configurations used with one pedestrian did not exceed the maximum value of 0.70 m/s^2. Only one exception occurred for the case when the single pedestrian ran eccentrically along the longitudinal axis of the bridge. It should be stressed that this was, however, a single peak and did not affect the pedestrian comfort. The second set of dynamic tests predicted a very low probability of pedestrian discomfort, except for an exposure period over 16 hours, which is not expected in a 11 m long footbridge.



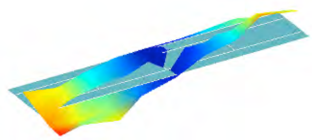
Mode 1: 1st vertical bending
f=6.40 Hz (0.28%); ξ=1.89% (18.69%)



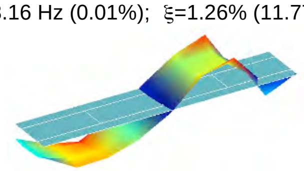
Mode 2: 1st torsional
f=8.16 Hz (0.01%); ξ=1.26% (11.77%)



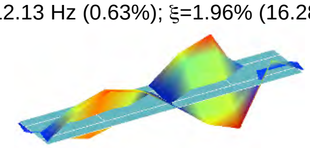
Mode 3: 1st lateral bending
f=12.13 Hz (0.63%); ξ=1.96% (16.28%)



Mode 4: 2nd torsional
f=20.78 Hz (12.28%); ξ=1.57% (62.08%)



Mode 5: 2nd vertical bending
f=22.16 Hz (6.14%); ξ=0.92% (20.59%)



Mode 6: 3rd torsional
f=23.74 Hz (0.09%); ξ=0.76% (11.65%)

Fig. 6 – Results of the system identification test with ambient excitation

5. Conclusions

The present work described the main features of the development of a full-scale innovative GFRP-SFRSCC hybrid footbridge, including design, construction and testing. Several static and dynamic tests were performed to evaluate its behavior for short and long actions. In general the tests showed a very good performance of the footbridge: the pedestrian bridge exhibited linear elastic behavior in the static load tests; based on the creep tests the predicted 100-years deflection is about L/412; the maximum vertical acceleration due to dynamic actions did not exceed of 0.70 m/s^2.

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7. References

BARROS, Joaquim, PEREIRA, Eduardo, SANTOS, Simão, "Lightweight panels of steel fiber reinforced self-compacting concrete", *ASCE Materials in Civil Engineering Journal*, Vol. 19, No. 4, 2007, pp. 295-304.

CORREIA, João R., "GFRP pultruded profiles in civil engineering: hybrid solutions, bonded connections and fire behaviour", PhD Thesis in Civil Engineering, IST, Technical University of Lisbon, 2008.

CORREIA, João R., BRANCO, Fernando, FERREIRA, João, "GFRP–concrete hybrid cross-sections for floors of buildings", Engineering Structures, Vol. 31, No. 6, 2009, pp. 1331-1343.

CORREIA, João R., BRANCO, Fernando, SILVA, Nuno, CAMOTIM, Dinar, SILVESTRE, Nuno, "First-order, buckling and post-buckling behaviour of GFRP pultruded beams. Part 1: Experimental study", Computers & Structures, Vol. 89, No. 21, 2011, pp. 2052-2064.

MENDES, Pedro, BARROS, Joaquim, SENA-CRUZ, José, Taheri, Mahsa, "Development of a pedestrian bridge with GFRP profiles and fibre reinforced self-compacting concrete deck", *Composite Structures*, Vol. 93, 2011, pp. 2969–2982.

SENA-CRUZ, José, MICHELS, Julien, CZADERSKI, Christoph, MOTAVALLI, Masoud, "Mechanical behavior of epoxy adhesives cured at high temperatures", Technical Report no. 880163, Empa, Switzerland, 2012, 30 p.