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Structural performance of iron-wood-FRP pedestrian bridge

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ABSTRACT: this research completes the information on the structural reinforcement of a footbridge in Venice, whose flexural stiffness was enhanced by using GFRP (Glass Fiber Reinforced Polymer) pultruded profiles. By inserting the composite profiles, a very good structural behavior as well as a reversible and not disturbing solution is guaranteed; furthermore, a high durability is assured by the composite material with polymeric matrix. This study highlights the benefits through all the installation steps especially granted by the low self weight of material. The structural project is then compared, through the finite element analysis, with reinforcement by traditional materials such as steel and aluminium. The final results show a very good static and dynamic performance considering the favourable ratio between mass and accidental load. The dynamic analysis was developed in the free vibrations field to control resonance phenomena through the man-induced vibrations.

1 INTRODUCTION

The favourable ratio between self-weight, mechanical parameters as well as durability of FRP pultruded profiles allow to define suitable application fields both for structural reinforcement and new structures all-FRP.

The most important applications of FRP profiles involve bridge engineering (Keller 2003). Several international researches show the excellence of this material in solving problems regarding mechanical strength, weight, durability, transport and assembling handiness, and resistance to aggressive environmental conditions.

Although the young age of the material, it's already possible to verify in some cases the static behaviour in serviceability state of GFRP structures, considering the long period and the repair activity, (Keller et al. 2005, Russo 2007). Some researches have been developed to analyse the dynamic behavior of FRP structure elements (Bastianini et al. 2007), and the all-composite structural system (Lestari & Qiao 2006). Although applications and researches mainly deal with all-GFRP structures, there are many examples showing the use of GFRP profile for structural rehabilitation (Borri & Giannantoni 2004). Because of its physical-mechanical characteristics, this material can be used for structural reinforcement so to assure the complete collaboration between the new structure and original material. In particular these applications are reversible and don't change the original structure configuration.

The design of structural reinforcement was illustrated in a previous research (Boscato et al. 2006). In this study, a new structural design with a new cross section is presented. The installation phase of the FRP structural elements and the analysis of the dynamic response to man-induced vibrations are illustrated in this research; this last topic was developed considering the natural frequencies of the bridge and a comparison was made with the frequencies of vertical and lateral vibrations to verify the resonance phenomena, (Bachmann et al. 1995, Zivanovic et al. 2004).

2 GENERAL DESCRIPTION

The “Paludo” bridge is in Venice town; the structure, built at the end of XIX century, has an arch static scheme; it is 12.7 meters long and 3.25 meters wide. The bearing structure is constituted by two iron longitudinal truss beams at the edges, linked through transversal iron profiles on which the wood deck is placed, Figure 1.

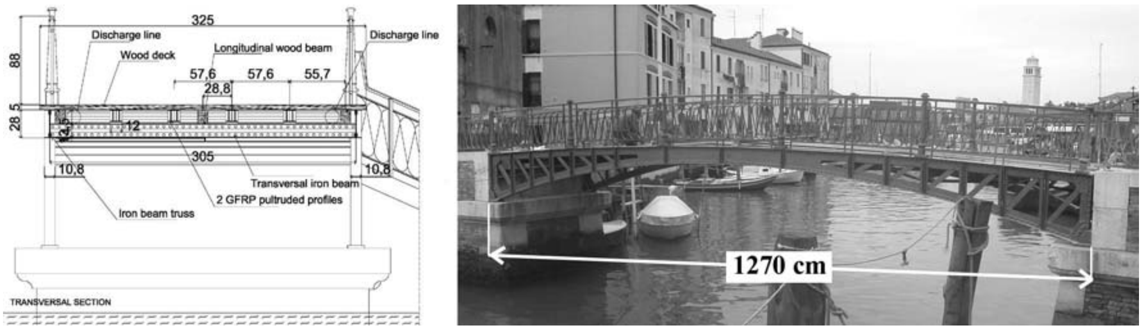

Figure 1. Transversal sections and general view

Structural reinforcement and a global restoration was found necessary because of the serious deterioration; the aggressive environment conditions was the main cause of the local rust and reduction of mechanical characteristics in wood beams, Figure 2.

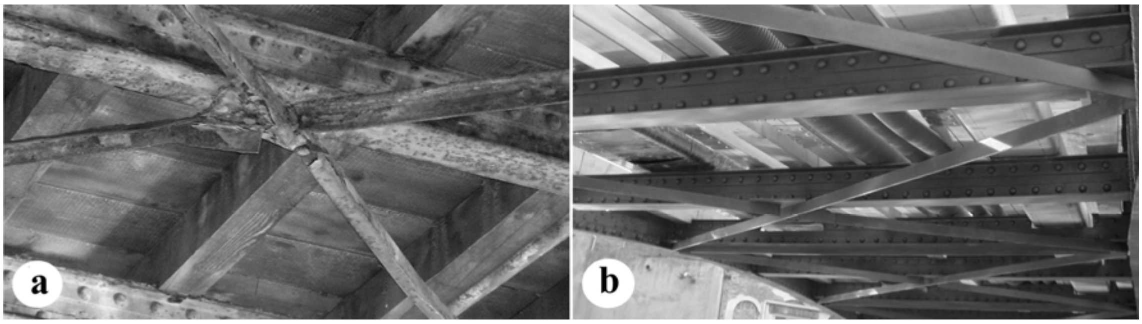

Figure 2. Detail of deck intrados, before (a) and during (b) the structural reinforcement

3 CHARACTERISTICS OF GFRP PROFILES

The mechanical and physical characteristics of pultruded GFRP profile are shown in Table 1; concerning the percentage of reinforcement the pultruded beams, had 48% in volume of glass fibers.

Table 1. Geometric and physic characteristics of GFRP material

Density	1600 – 2100 daN/m^3
σ_c (compression stress) - σ_t (tensile stress)	135 MPa
E_t (sample) - Modulus of Elasticity in tensile	20000 – 30000 MPa
E_c (sample) - Modulus of Elasticity in compression	14000 MPa
E_{fl} (sample) – Flexural Modulus of Elasticity	15000 – 20000 Mpa
E_{fl} (full-bending) – Flexural Modulus of Elasticity	25000 – 30000 MPa
G - Shear modulus	3000 – 5500 MPa
ν - Poisson coefficient	0.2 – 0.3

Figure 3 shows in detail the cross section of the GFRP beams realized by two “I” pultruded profiles (120x60x8mm) coupled by two GFRP plates (200x120x5.5mm), respectively in tensile and compression zone; the link is made of stainless steel bolts (Ø 10mm).

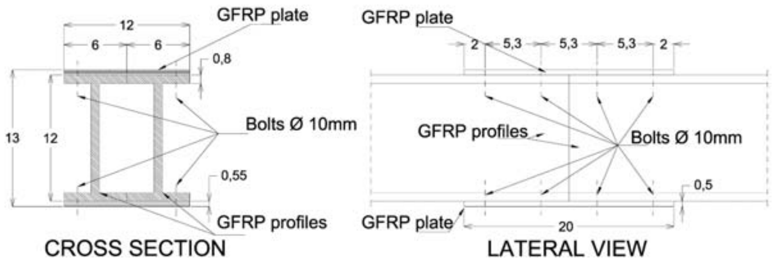

Figure 3. Details of cross section and beam-beam joint, cm dimension

4 ASSEMBLING AND INSTALLATION PHASE

This footbridge is an important link between a school and people residences; to substitute all the longitudinal wood beams, the bridge had to be out of service for only one day. This was possible because of the low self-weight of the FRP composite material - which made the executive phase easier (transport, assemblage and the installation). The photo sequence in Figure 4 shows the assemblage between the two "I" FRP profiles and the beam-beam joint of FRP pultruded plates and stainless bolts; this figure shows also the management, the positioning and finally the mechanical connection to the bridge abutments through the galvanic steel gussets. The workers' ease in making the cut, the holes and the final assemblage is evident. Such operations were necessarily carried out in yard during the positioning phase because some problems were to be solved directly in situ. In fact the bridge has a complex geometry, for the plan and elevation present two different radius of curvature.

Figure 4. Installation phase of GFRP pultruded profile

Figure 5 shows the complete installation phase of the longitudinal FRP and wood beams, and the final placement of wood deck.

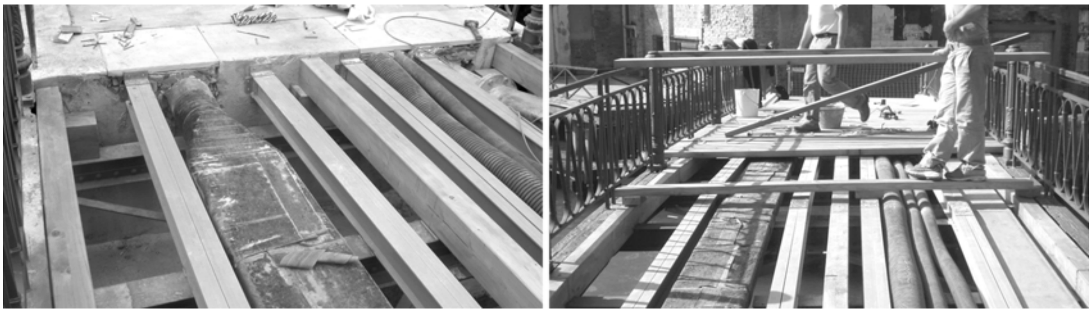

Figure 5. GFRP and wood longitudinal beams before wood deck phase

5 STRUCTURAL RESPONSE

The global structural behavior of pedestrian bridge was investigated under the point of view of static action and dynamic response in the free vibrations field. In the first analysis, a uniform distributed static load equal to 400 kg/m^2 was considered; about the dynamic response, the frequencies of first modes of free vibrations were defined, during the changing of the acting load, to verify any resonance phenomenon.

The analysis was led through finite elements modeling, considering a linear elastic behavior.

5.1 *Static behavior*

The maximum deflection value equal to 6.2 mm was obtained by numerical modeling, considering that the admissible maximum deflections, η_{max} /L $\leq$ 0.002, is equal to 7.4mm. Such displacement is similar to the previous configuration before the structural reinforcement.

The structural response results and the maximum stress values of GFRP profiles and wood beams of the new configuration (Wood-GFRP, scheme 1) are shown in Table 2. The initial configuration values (scheme 0) with the only wood longitudinal beams are shown to be compared in the same table. The values of GFRP beams (scheme 1) refer to one pultruded profile and not to the section with coupled profiles.

Table 2. Structural performance of cross sections and stress values

Scheme	η_{max} (cm)	Y_W (cm)	Y_G (cm)	σ_{cW} (Mpa)	σ_{cG} (Mpa)	σ_{tW} (Mpa)	σ_{tG} (Mpa)
0	0.63	10	-	-1.164	-	0.462	-
1	0.62	11.2	9.7	-0.830	-3.178	0.208	0.773

Where η_{max} is maximum deflection, Y_W and Y_G are the distance of neutral axis respectively of wood and GFRP elements, σ_c and σ_t are the stress values in compression and tensile zone of wood ($_W$) and GFRP ($_G$). Analysing the two configurations with equal applied load, the decrease of the maximum stresses in the tensile and compression zone of the wood beams is clearly visible - respectively equal to 55% and 28% from scheme 0 to scheme 1.

5.2 *Dynamic behavior*

The structural response to vertical and horizontal dynamic loads induced by human body motions was verified too. The analysis was developed considering the natural frequencies of the vibration modes with different accidental load to verify the resonance phenomena with external harmonic load. Table 3 shows the changing of the fundamental frequency with the increase in vertical load; in detail the comparison between the calculated frequency values of the dynamic responses of scheme 0 and scheme 1 are shown.

Table 3. Natural frequencies of fundamental flexural vibration for different live load

Scheme	Live Load					
	0 (kg/m^2)	100 (kg/m^2)	200 (kg/m^2)	300 (kg/m^2)	400 (kg/m^2)	500 (kg/m^2)
0	17.49Hz	11.72 Hz	9.4 Hz	8.08 Hz	7.19 Hz	6.54 Hz
1	17.08 Hz	11.64 Hz	9.39 Hz	8.09 Hz	7.21 Hz	6.57 Hz

We can see a similar dynamic behavior in both configurations; in the specific case, it has to be highlighted that with the increment of load from 300 kg/m^2, scheme 1 (Wood+GFRP) has higher in frequency values than scheme 0 (Wood). The frequencies of lateral vibration are shown in Table 4 for both analysed schemes.

Table 4. Natural frequencies of transversal lateral vibration for different live load

Scheme	Live Load					
	0 (kg/m^2)	100 (kg/m^2)	200 (kg/m^2)	300 (kg/m^2)	400 (kg/m^2)	500 (kg/m^2)
0	23.61	17.57	14.58	12.74	11.45	10.48
1	23.39	17.43	14.47	12.64	11.37	10.41

There are no resonance effects for either vertical and horizontal dynamic action induced by human body motions, as shown in the following Table 5.

Table 5. Vertical and horizontal forcing frequencies (Bachmann et al. 1995)

Vertical vibrations (Hz)			Horizontal vibrations (Hz)
Walking	Running	Jumping	
1.6-2.4	2.0-3.5	1.8-3.4	0.6-1.7

5.3 *Comparison with traditional materials and analysis of results*

To understand the real advantages of the use of FRP composite profiles, a comparison with steel (scheme 1S) and aluminium (scheme 1AL) profiles was made. These structural elements have the same length and an optimized section to assure an equivalent performance based on the maximum deflection value during linear elastic regime.

Table 6 shows the geometrical and physical characteristics of the traditional materials profiles, highlighting the percentage ratio between dead load and volume for GFRP, steel and aluminum.

Table 6. Geometrical and physical characteristics of steel and aluminum profiles and relations with GFRP material

Traditional-Materials	Cross Section dimension (cm)	J_{xx} (cm^4)	A_{TM} (cm^2)	A_{TM}/A_{GFRP} %	DL_{TM} (kg/m)	DL_{TM}/DL_{GFRP} %
Aluminum	9.1x4.55x0.6	125.26	10.34	57	0.028	84
Steel	6.9x3.45x0.46	41.24	5.93	33	0.046	140

Where J_{xx} is the moment of inertia, A and DL are respectively the section area and Dead Load of traditional material ($_{TM}$) and of GFRP profiles ($_{GFRP}$).

The static behavior shown in Table 7 emphasizes the optimum relationship between the static scheme first reinforced with traditional material (scheme 1S and 1AL) and then with FRP profiles (see Table 2, scheme 1).

Table 7. Structural performance of cross sections and stress values of steel and aluminum profiles

Scheme	η_{max} (cm)	Y_W (cm)	Y_{MT} (cm)	σ_{cW} (Mpa)	σ_{cMT} (Mpa)	σ_{tW} (Mpa)	σ_{tMT}(Mpa)
1S	0.62	10.8	6.31	-0.79	-16.36	0.24	1.52
1AL	0.62	11	7.75	-0.82	-6.8	0.22	1.19

Where $_{MT}$ is the subscript that indicates traditional materials (steel and aluminum).

The dynamic response results of scheme 1 is similar to the one of the section reinforced with steel and aluminum profiles; in detail, the variations are equal to 1-2% for vertical and horizontal lateral vibrations.

Generally speaking, the static and dynamic behavior is similar to the cases of reinforcement with traditional materials; thus the advantages in the use of GFRP must be evaluated in terms of durability and ease of assembling.

6 CONCLUSIONS

This research highlights that the use of FRP structural elements for the structural reinforcement assures important achievements in the static and dynamic behavior and suggests the following evaluations:

- the comparison with steel points out the optimum relation between structural strength and dead load of composite material. With the optimized section the use of steel material causes an increment of dead load 1.4 times higher than the reinforcement with GFRP profiles. The participant mass to total load (dead load + accidental load) of the composite material is equal to 6%, while for steel is equal to 9.5%. In the whole total load the FRP material, with its low self weight, allows a greater accidental load.
- Altogether, the maximum displacement values of analysed schemes are similar; with the applied load of 400kg/m^2, the maximum deflection is about 6mm for each verified scheme. Such a comparison must be evaluated considering the high resistance to the aggressive environment conditions of the composite material compared to traditional materials, the facility in moving and placing during the installation phase.
- The stress level in wood beams (in the wood-GFRP cross section) is 30% less than the stress level in only wood cross section.
- A relevant reduction of the compression stress level in wood beams – that prevents the material from entering the plastic phase – was assured by the use of GFRP beams.
- Regarding the general structural approach, the adopted reinforcement represents a good solution without increase of the deck's thickness and allows to reach low values of compression stress in GFRP profile.
- The global bridge stiffness, with the structural reinforcement, assures a good response to dynamic actions induced by vertical and horizontal harmonic loads.
- Finally, the structural response investigated by modeling analysis needs to be checked by static and dynamic experimental tests.

REFERENCES

Bachmann, H., Pretlove, A.J. & Rainer, H., (1995). Dynamic forces from rhythmical human body motions. *Vibration Problems in Structures: Practical Guidelines*, Birkhäuser, Basel, Appendix G.

Bastianini, F., Boscato, G., Russo & S., Sciarretta, F., (2007). Natural frequencies of pultruded profiles with different cross-section. *Proceedings of ACIC '07, Advanced Composites in Construction*, University of Bath, Bath, U.K.

Borri A. & Giannantoni A., (2004). Reinforcement of timber floors with FRP pultruded elements, *Mechanics of Masonry Structures Strengthened with FRP-materials: Modeling, Testing, Design, Control*, Venezia, Italia.

Boscato, G., Russo, S. & Siviero, E., (2006). The FRP Beams as Reinforcement of Pedestrian Bridge, *2nd International fib Congress*, Naples, Italy.

Keller, T., (2003). Use of Fibre reinforced Polymers in Bridge Construction, *Structural Engineering Documents n.7 IABSE International Association for Bridge and Structural Engineering*, Lausanne.

Keller, T., Bai, Y., Vallée, T., (2005). Long-term performance of a glass fiber reinforced polymer truss bridge. Manuscript CC/2005/022688, Composite Construction Laboratory (CCLab), Swiss Federal Institute of Technology Lausanne, Switzerland.

Lestari, W. & Qiao, P., (2006). Dynamic chracteristics and effective stiffness properties of honeycomb composite sandwich structures for highway bridge applications. Journal Composite for Construction. 10, 148.

Russo S., (2007). Strutture in Composito, Sperimentazione, Teoria e Applicazioni, Hoepli.

Živanović, S., Pavic, A. & Reynolds, P., (2004). Vibration serviceability of footbridge under humain-induced excitation: a literature review. *Journal of Sound and Vibration*, 279, 1-74.