Civil structures made enterely from FRP pultruded beams

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1. Introduction

The use of fibre reinforced materials for structural purposes is highly convenient in various fields of engineering, in particular mechanical, naval and aeronautical. In fact, their use not only reduces realization time and costs, but also increases corrosion and fatigue resistance as well as strengthens against fracture [1-3].

Over the last few years, FRP materials have also been used in civil engineering for structural applications both for the rehabilitation of existing reinforced concrete and masonry structures and for the realization of new structures. In particular, in order to diffuse their use in the field of civil engineering as structural materials for new civil constructions is necessary to study more in depth some aspects not be yet adequately investigated. Among them, the most important are the mechanical characterization of FRPs and the design procedures able to take into account their stability, viscosity and deformability [4-11]. Last but not least are the problems of design and verification of adhesively and bolted joints between composite elements.

It is worth taking into account that the literature on the FRP structural joints in the fields of aeronautical, mechanical and naval engineering cannot be directly applied to civil engineering. This is mainly due to the significantly different properties of the FRPs used in the various applications as well as the different geometric scales.

The aim of this paper is to present the main problems connected to the design of a civil structures made from composite materials, starting from the initial choice of the material up to the choice of the opportune procedure for designing and verifying the FRP elements [12].

Finally, the authors carried out an example of rehabilitation of a roofing structure consisting in replace totally the latter with a new one made entirely from FRP pultruded profiles. The new roofing structure is truss-frame type with a length equal to twelve meter whose connections are realized with steel bolts. The material used consists of glass FRP and the geometrical and mechanical properties are given by technical data sheets edited by the manufacturer.

2. Characteristics of FRP pultrudes and examples of realized structures

FRP structural elements used for the realization of new civil constructions take the shape of thin profiles made from thermoset resins strengthened with long glass fibres by the technique of pultrusion.

The pultrusion is a process completely automatic. It allows to obtain structures, similar to metal ones, constituted of flat sections, either L, U, T or I as well as I with wide flanges, tubular, etc. During the process, it is important to control the position of the strengthening in the section: the central web of the section is mainly constituted of fibres parallel to the longitudinal axes (*roving*), while the assembly of the section is given to the *mat*, with multi-directional fibres (orientated at 0°, 90° and ± 45°) which completely wind around the pultrude. The fibres are then prevented from appearing on the surface by a *surface veil* which is also realized from multidirectional fibres. It has the function of protecting the pultruded element from surface lesions as well as increasing the resistance to chemical agents, UV rays and humidity.

The mechanical properties of these materials depend on the type of matrix, the type of fibre as well as their volumetric fraction.

The pultrudes can be either bolted or bonded, but all the materials used in the joints should have the same characteristics.

In the following figures 1-4 four examples of realized structures concerning pedestrian bridges, buildings and roofing structures are shown.

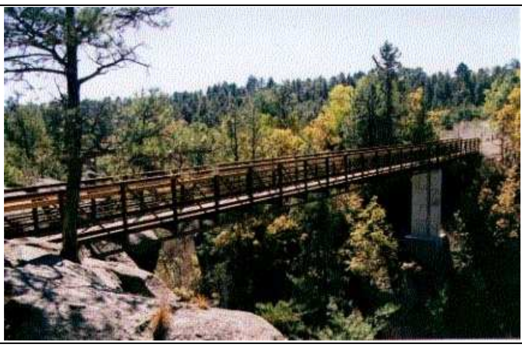

Fig. 1 - Pueblo Canyon Bridge, New Mexico

Fig. 2 - Fibreline Bridge, Denmark

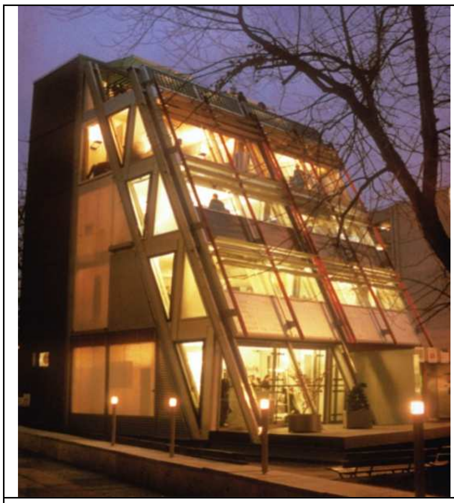	
Fig. 3 - Eyecatcher Building, Basil	Fig. 4 - Vila Moura, Portugal

3. Design problems

The design of FRP structure should take into account all the possible actions that could affect its service life. The risks to which it could be subjected to should be identified and, if present, either reduced or eliminated.

The basic requisites are considered satisfied when the following is guaranteed:

- an appropriate choice of materials;
- careful execution of structural details;
- definition of the appropriate procedures of design control, production, realization and use.

The design of the structure should also guarantee a constant performance over time, taking into account both the environmental conditions as well as the maintenance programme. The environmental conditions should be identified during the design phase in order to evaluate their influence on the durability of the structure, with any eventual measures being included to protect the material.

Verification of both elements and joints should be carried out in relation to both the serviceability limit states (SLS) as well as the ultimate limit states (ULS), as defined by the currently adopted regulations.

In this last case, the partial safety coefficient of the material and of the bolted joints takes into account the level of uncertainty in the determination of the properties of the materials and the appropriate caution in relation to the fragile behaviour of the FRP.

For bonded joints with structural adhesives, the safety coefficient of the material depends on the mechanical properties of the adhesive, the method of adhesive application, the load and the environmental conditions.

It is important to underline that the mechanical properties of several FRP pultrudes can become degraded in the presence of rheological phenomena which depend on the properties of the matrix as well as the fibres. In particular, viscosity appears to be more contained with an increasing percentage of fibres, while static fatigue can be mitigated by limiting the level service stress.

Under conditions of exposure to fire, the mechanical properties of the FRP can be significantly prevented from decreasing by either a covering of an appropriate thickness, or pultruded elements produced with special resins as well as active protection systems.

4. Application: a roofing structures

INSERIRE BREVE DESCRIZIONE DELLA STRUTTURA, DELLA SEZIONE DEI PROFILI DEI CORRENTI SUPERIORI ED INFERIORI, DELLE DIAGONALI E TABELLA CON LE PROPRIETA' MECCANICHE DEL MATERIALE (FIBERLINE

Fig. 5 – View of the roofing structures.

The mechanical properties of the material are summarized in tables 1 and 2.

Table 1 – Mechanical properties of FRP profiles (Fiberline).

Strength value		[MPa]
Tensile strength, 0°	$f_{Lt,Rd}$	97.5
Tensile strength, 90°	$f_{Tt,Rd}$	39
Compressive strength, 0°	$f_{c,d}$	97.5
Compressive strength, 90°	$f_{c,d}$	39
Shear strength	$f_{V,Rd}$	10.4
Pin-bearing strength, long. direction	$f_{Lr,Rd}$	150
Pin-bearing strength, tran. direction	$f_{Tr,Rd}$	70

Table 2 – Stiffness values of Fiberline FRP profiles.

Stiffness value		[MPa]	[-]
Modulus of elasticity, 0°	E_{Lc}	28000	
Modulus of elasticity, 90°	E_{Tc}	8500	
Modulus in shear	G_{LT}	3000	
Poisson's ratio	ν_{LT}		0.23
Poisson's ratio	ν_{TL}		0.09

It is supposed that the structure is subject to dead, live and snow loads. Their values are equal to ??, ?? and ??, respectively. In table 3 are reported the characteristic values of the maximum axial force in traction and compression acting in the frames.

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Table 3 – Maximum characteristic values of axial force.

Load condition	Axial force in compression $N_{t,Sk}$	Axial force in traction $N_{t,Sk}$
	[kN]	[kN]
Dead (G)	75	71
Live (Q_{live})	42	40
Snow (Q_{snow})	40	39

The corresponding design values for the load combination (ULS) have been obtained by adopting the partial factors suggested in [??] and they are summarized in table 4:

Table 4 – Design values of axial force for ULS.

Load combination	Axial force in compression $N_{c,Sd}$	Axial force in traction $N_{t,Sd}$
	[kN]	[kN]
ULS	90.25	-85.9

In the next sections will be presented the verification of the ultimate limit states of the pultrudes and joints, following the instructions of Italian National Research Council Technical Document CNR DT 205/2007 [12].

4.1 Verification of the ultimate limit states of the pultrudes

4.1.1 Elements under traction

The design value of the force, $N_{t,Sd}$, should satisfy the following limitation:

$$N_{t,Sd} \leq N_{t,Rd} = A \cdot f_{t,d} \,, \qquad (1)$$

where $f_{t,d}$ represents the design strength of the material and A is the area of the section.
In the example here examined the following values have been obtained:

$$N_{t,Sd} \leq N_{t,Rd} = A \cdot f_{t,d} = 194.3\ kN \,. \qquad (2)$$

4.1.2 Compressed elements

The design value of the compressive force, $N_{c,Sd}$, corresponding to each of the transversal sections, should satisfy the limitation:

$$N_{c,Sd} \leq N_{c,Rd} = \min\left\{N_{c,Rd1},\ N_{c,Rd2}\right\}. \qquad (3)$$

where $N_{c,Rd1}$ is the value of the compressive force of the pultruded element and $N_{c,Rd2}$ is the design compression value which provokes the instability of the element.
The value of $N_{c,Rd1}$ has been calculated through the following expression:

$N_{c,Rd1} = A \cdot f_{c,d}$,	(4)

where $f_{c,d}$ is the design compressive strength of the material. Moreover the value of $N_{c,Rd2}$ has been obtained from the relation:

$N_{loc,Rd} = A \cdot \frac{1}{\gamma_f} \cdot \min\{(f_{loc,k}^{axial})_f, (f_{loc,k}^{axial})_w\}$,	(5)

where $\left(f_{loc,k}^{axial}\right)_f$ and $\left(f_{loc,k}^{axial}\right)_w$ represent, respectively, the critical stress of the uniformly compressed flanges and web, whose expressions are reported in [12].
In the example here examined the following values have been obtained:

$N_{c,Sd} \leq N_{c,Rd} = \min\{227.00,\ 214.83\} = 214.83$ kN.	(6)

4.2 Verification of the ultimate limit states of the joints (plate)
4.2.1 Verification of net-section failure

The verification of normal stresses of the resistant section of the element weakened by the presence of the holes has been carried out in relation to the following limitations:

$V_{Sd} \leq \frac{1}{\gamma_{Rd}} f_{Lt,Rd} \cdot (w - n \cdot d) \cdot t$,	(7)

where γ_{Rd} is the partial model coefficient assumed to be equal to 1.11, V_{Sd} is the force transmitted by the bolt to the element, $f_{Lt,Rd}$ is the design traction resistances of the material along the fibre direction, t is the thickness of the FRP element and n is the number of holes (Fig.6).
In the example here examined the following values have been obtained:

$V_{Sd} = (\lvert 90.25\text{-}85.90 \rvert)\text{kN} \leq f_{Lt,Rd} \cdot (w - n \cdot d) \cdot t = 114.60$ kN .	(8)

4.2.2 Verification of bolt-shear failure

Verification of bolt-shear failure should be carried out following:

$V_{Sd} \leq f_{V,Rd} \cdot (2 \cdot e - d_b) \cdot t$,	(9)

being $f_{V,Rd}$ the design shear resistance of the FRP element.
In the example here examined the following values have been obtained:

$V_{Sd} = 85.9 \text{ kN} \leq f_{V,Rd} \cdot (2 \cdot e - d_b) \cdot t = 99.06$ kN .	(10)

4.2.3 Verification of bearing failure

In verifying bearing failure, the mean value of the pressure on the shank of the bolt on surface of the hole should satisfy the following limitations:

$$V_{Sd} \leq f_{Lr,Rd} \cdot d_b \cdot t \ , \qquad (11)$$

where $f_{Lr,Rd}$ is the design resistance to bearing failure of the material in the fibre direction.
In the example here examined the following values have been obtained:

$$V_{Sd} = 27.08 \leq f_{Lr,Rd} \cdot d_b \cdot t = 28.08 \text{ kN} . \qquad (12)$$

4.2.4 Verification of shear failure of a steel bolt

In the verification of shear failure of a steel bolt, the following limitation should be satisfied:

$$V_{Sd} \leq f_{Vb,Rd} \cdot A_b \ , \qquad (13)$$

where $f_{Vb,Rd}$ represents the shear design resistance of the bolt, as defined by the currently adopted regulations and A_b is the resistant area of the section of the bolt. In the example here examined the following values have been obtained:

$$V_{Sd} = 27.08\text{kN} \leq f_{Vb,Rd} \cdot A_b = 33.26\text{kN} . \qquad (14)$$

In addition to the verifications above described, the calculation of joint resistance has been carried out taking into account also the simultaneous presence of moment and shear in the plate.

5. Conclusioni

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