TIME DEPENDENT BEHAVIOUR OF GFRP PULTRUDED PROFILES AND POLYESTER PVC COATED FABRIC FOR BUILDING COMPOSITE ACTIVE TENSILE STRUCTURES

G. Carra[1*], A. Zanelli[1], P. Beccarelli[1], R. Maffei[1]

[1]*Department of Building Environment Science and Technology, Politecnico di Milano, Milan, Italy.*
**guglielmo.carra@mail.polimi.it*

Keywords: FRP profiles, Composite Active Tensile Structures, FRP textile building systems.

Abstract

An investigation dealing with the use of unidirectional fiber-glass profiles for building spatial structures is presented in this paper. The research aims to experiment the combination between a structural frame, made of pultruded E-glass/Polyester profiles, and a membrane, made of polyester PVC (PES/PVC) coated fabric, to create ultra-light building systems. The mechanical properties of pultruded GFRP profiles are suitable for large deflections, unlike conventional materials that yield (steel) or crack (concrete) for moderate deformations. For this reason the use of unidirectional profiles, mechanically pre-bended before the connection with the fabric, allows to obtain an elastic response that interacts with the membrane and constantly maintains the optimal pre-tension stress inside it. Stress relaxation and creep of the structural members are analyzed in order to estimate the behavior of the FRP-textile building system over time.

1 Introduction

1.1 Scope of the research

Fiber Reinforced Polymer composites (FRPs) appear only in recent years in the construction field and represent a valid alternative to traditional materials because of the excellent qualities of their physical and mechanical performance. Nevertheless applications of composite materials as structural elements remain exceptional, in comparison with concrete, steel or even wood and are often limited to infrastructural applications (as bars embedded in concrete or pultruded bridge decks) and a few structural applications in building construction (as pultruded structural profiles). Some features, among the others, suggest new fields in which explore the potentialities of these materials. In particular, because of the large elongation to failure allowed by both the fibers and the matrix, FRPs maintain an elastic response for large deflections and strains, unlike conventional materials that yield (steel) or crack (concrete) for moderate strains. Thinking about tensile structures and temporary architecture (10 years of service life) the use of unidirectional FRP profiles seems to open new interesting prospects, as recently demonstrated with the construction of FRP gridshells [1]. Other interesting applications can be the covering of archeological areas where large span and lightness are essential [2]. Main purpose of present research is to determine the behaviour of Glass Fiber Reinforced Polymer composites (GFRPs) when coupled to membranes for building Composite Active Tensile Structures [3]. In fact, the elastic response of the GFRP profiles, once inflected, guarantees a reaction force (that varies according with the geometrical dimensions of the profile) that can be applied directly to the membrane creating, within it, a force of tension. This phenomenon introduces scenarios that are different from what usually happens in tensile-structures, where the tension of the membrane is guaranteed by a process of mechanical pulling which, especially for wide areas of tissue, is very complex and requires a large amount of equipment and work force [4].

1.2 Application of FRPs to tensile structures

Typical mechanisms to tension membranes are realized by means of turnbuckles that, once put in place, act on the structure until it reaches the correct design stress. Typically it happens pulling the elements on the edge, usually wires or rigid metallic components, or through the rotation of rigid structural elements that are tilted from a vertical position, using tie rods, causing tension in the structure. In this article a different and innovative use of GFRPs is proposed. Inflected profile can move freely at one end; in this way the profile is able to dynamically interact with the rest of the structure (Figure 1). In case of application to tensile structures, the free ends of the inflected profile convey their reaction force directly to the membrane, putting it in tension through the elastic response of the profile.

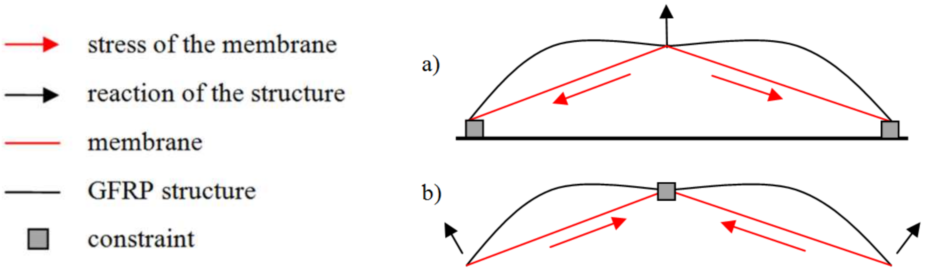

Figure 1. Schemes representing two mechanisms in which the GFRPs act as active structural systems.

Several advantages are related to this principle and, in particular, it introduces a possible solution to relevant issues, such as that of the initial tensioning and re-tensioning in tensile structures [5],[6]. The elastic response of GFRP members gives the appropriate values during the assembly phase but it does not guarantee to last in use, when the viscoelastic phenomena intervene generating a deformation of both the GFRP members and the cladding membrane. Present paper aims to study the time dependent behaviour of Composite Active Tensile Structures and, in particular, the dependency between the mechanical performance of the structural GFRP members and the viscoelastic phenomena that occur over time to both the composite members and the cladding membrane.

2 Experimental program

In order to determine the viscoelastic behaviour of fiber-glass pultruded members, when coupled to membranes in Composite Active Tensile Structures, they have been tested using two different processes. Firstly, relaxation stress of GFRP profiles has been evaluated testing three sets of specimens maintained in inflection for a long time period, exceeding 6000 hrs. This part of the experimental program aims to define the time dependent behaviour of the reaction force of the GFRP when maintained inflected at a constant strain. Secondly, the creep has been evaluated testing a single GFRP specimen coupled with the membrane. In this case the behaviour of the GFRP has been obtained throughout the preliminary quantification of the creep that occurs within the PES/PVC fabric.

2.1. GFRP profiles and PVC coated fabric

Different specimens were used for present investigation. GFRP specimens were pultruded tubes and rods made by E-glass fibers and Polyester Isophthalic matrix. The density of the material was 1800 kg/m^3 and the volume fraction (V_f), between fiber and resin matrix, was about 55% (data provided by the manufacturer). Main mechanical properties for the GFRP profiles were obtained through testing and are presented in Table 1. Relaxation test have been conducted using tubular profiles with an external diameter of 22 mm and an internal diameter of 17 mm; the tubes length (L) was 1 m and the buckling length during the test (L') was 0.8 m. A total of nine profiles have been tested.

Elastic modulus (GPa)	Tensile strength (MPa)	Ultimate tensile strain (%)
31.0	490.0	1,7

Table 1. Main properties for GFRP specimens.

Creep test was executed using a GFRP rod with a diameter of 20 mm, a length of 0.5 m and a buckling length of 0.4 m. A single rod has been used for the test.

According to the details described in Figure 4 the membrane sample was realised using a PVC coated polyester fabric. Main properties of the fabric are reported in Table 2. The sample was 650 mm long (T_1) and 300 mm wide (T_2). It was connected to the poltruded rod by means of a sleeve formed by folding over and welding the edge of the coated fabric. The opposite side of the sample was divided into three strips of fabric (100 mm wide and 250 mm) long in order to improve the stress distribution in the measured area. The end of each strip was folded over a wedge-shaped bar which was then clamped between two plates. Each grip was 100 mm wide and hold independently each strip of fabric.

Yarn (dtex)	Total Weight (g/m^2)	Tensile strength (N/5cm)	Tear resistance (N)
1100	670	2600/2500	300/300

Table 2. Main properties for PES/PVC fabric.

2.2 Stress relaxation test apparatus

A set of nine profiles have been tested: three profiles have been tested at a virgin stage, three profiles have been maintained inflected at a constant strain for 180 days (about 4300 hrs) and other three profiles have been maintained inflected at a constant strain for 270 days (about 6500 hrs) and then tested in the testing apparatus described in Figure 2. The tubes have been inflected at constant temperature of 20 °C and 80% UR, using a bending length consistent with the real use within composite active tensile structures. Tests were conducted at constant displacement and results have been compared to the performance of the virgin specimens in order to evaluate the reduction of the reaction force of the profiles over time.

The testing apparatus consisted in a compression machine with a load cell sensitivity of 10 N. The specimens were connected to the machine using two steel plates, acting as cylindrical hinges. Specimens have been tested to compressive and bending stress due to an axial force that intervene after the initial bending of the profile due to the gravity force (F_g). Displacement along the longitudinal axis (s) and reaction force (R) of the specimens were monitored. The tests have been conducted till failure applying a displacement, along the longitudinal axis, at a rate of 2 cm/min. Figure 3 shows a GFRP tube during bending test.

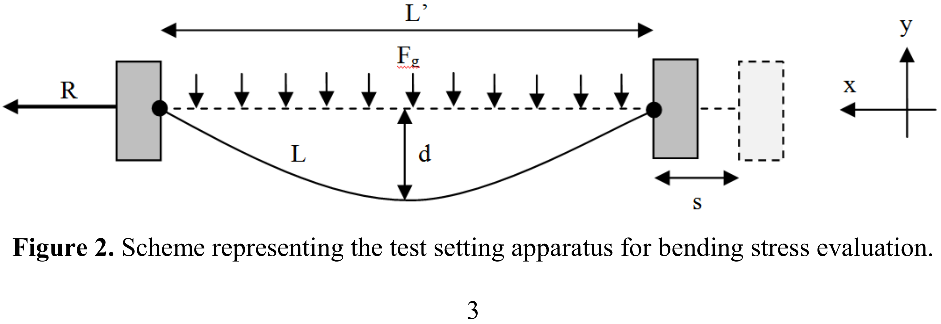

Figure 2. Scheme representing the test setting apparatus for bending stress evaluation.

Figure 3. GFRP profile before failure under compressive and bending stress.

2.3 Creep test apparatus

A composite rod has been tested coupled with PES/PVC fabric in order to better understand the reciprocal interaction between the GFRP structural members and the cladding system and simulate the real condition in use in a composite active tensile structure. The coupled specimens of GFRP and PES/PVC were tested within a biaxial machine at the Politecnico di Milano. Displacement of the rod was recorded along with the elongation of the membrane.

The load was applied by means of three actuators which were free to move along the frame in the transverse direction of the applied load and free to rotate around an axis perpendicular to the sample plane. The actuators are based on a brushless motor which is coupled with a Planetary Gearbox. The rotational motion is transformed into linear motion through a ball screw mounted on an axis providing a maximum tension force over 25kN for each strip of material 100 mm wide. Each actuator is equipped with a S shape load cell able to measure forces between 1N and 25kN. The global displacement of the system, composed by the GFRP and the membrane, has been monitored through the actuators (d_1, d_2, d_3).

The membrane strain was obtained through three linear potentiometers ($\varepsilon_1, \varepsilon_2, \varepsilon_3$) Penny & Giles MOD. SLS095/0030/1.2K/R/50 mechanically fixed to the fabric at an initial distance of 100 mm. The GFRP rod was connected to the frame of the biaxial machine using a metal plate acting as a joint.

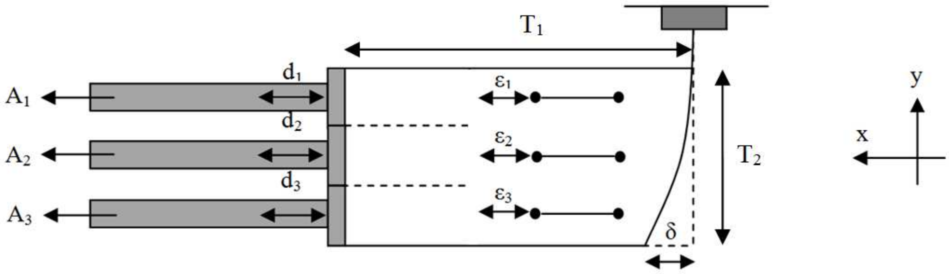

Figure 4. Scheme of the test settings for GFRP and PES/PVC creep evaluation within the biaxial machine.

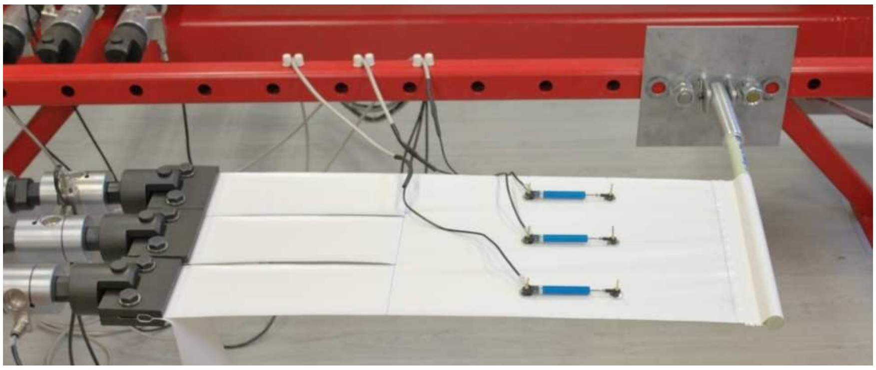

Figure 5. GFRP rod and PES/PVC membrane coupled together during the creep test within the biaxial machine.

The load was applied to the system from the three actuators following an increment of 50 N/min. Once reached a load of 0.5 kN for each actuator (this value represents an optimum pre-tension stress for a tensile structure in practice) it was maintained for 5 hours in order to evaluate the creep phenomena that occurred to the system. Load increments are reported in Figure 6.

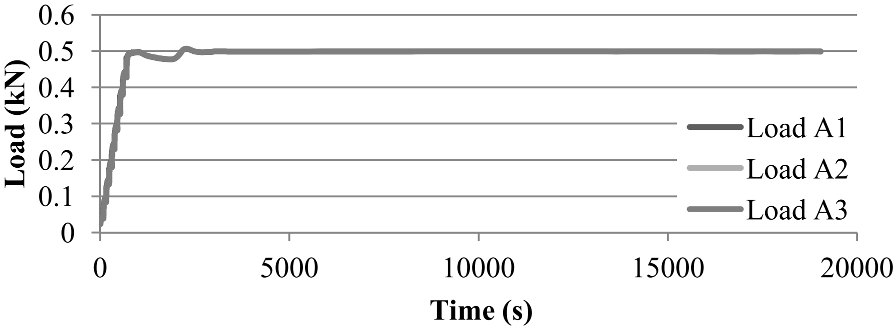

Figure 6. Load increments during creep test.

3 Experimental results and discussion

3.1 Stress relaxation evaluation

Following are reported the results obtained from the testing of the GFRP tubes to compression and bending load. Results show a reduction for the reaction force of the GFRP members due to the stress relaxation phenomena that occurs over time. Figure 7 shows, on the left, a displacement/reaction force diagram for the GFRP tube instead, on the right, it has been reported the reaction force (R) decrement for the three sets of tested specimens. A 14 % reduction is registered after 180 days of inflection at fixed displacement. A total 30% reduction is registered after 270 days. Data are presented in Table 3.

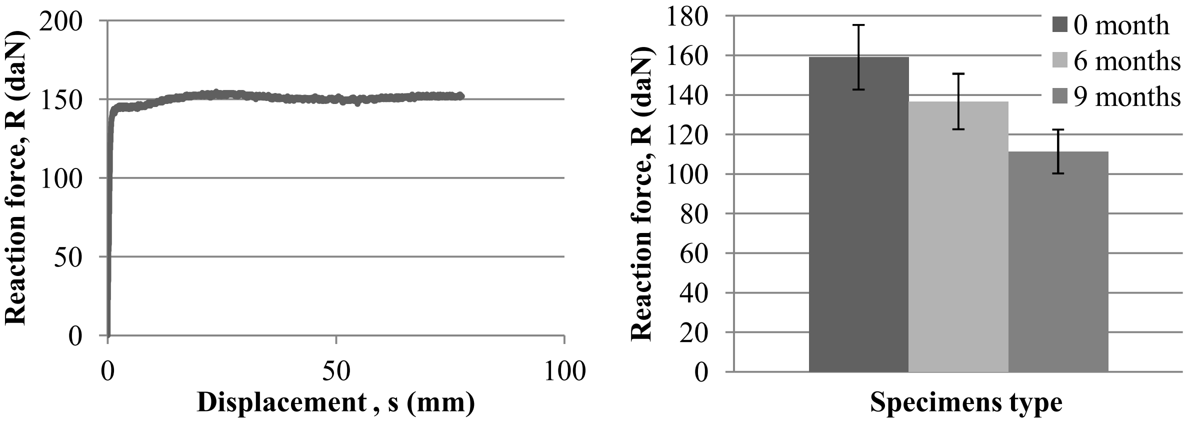

Figure 7. Left, diagram displacement/reaction force for a GFRP tube under compressive and bending load. Right, comparison among the reaction force (R) for different specimens after sustained inflection.

	Reaction force [daN]			**Average [daN]**	**St. Dev.**	**Reaction force decrease [%]**
Specimen n°	1	2	3			
0 month	155,00	177,00	145,00	159,00	16,37	-
6 months	148,00	121,00	141,00	136,67	14,01	*14,05*
9 months	123,00	110,00	101,00	111,33	11,06	*29,98*

Table 3. Present table shows the values for the specimens subjected to sustained displacement and comparison with the virgin specimens.

Values of the reaction force (R) of the GFRP change over time due to the sustained inflection. They could be expressed by the following formula:

$$R\ (t) = R_0\ e^{-t/\tau} \tag{1}$$

where R_0 is the initial reaction force, t is the time of inflection and τ represents a constant value that can be experimentally determined. A confront between theory and practice shows a substantial agreement (Figure 8).

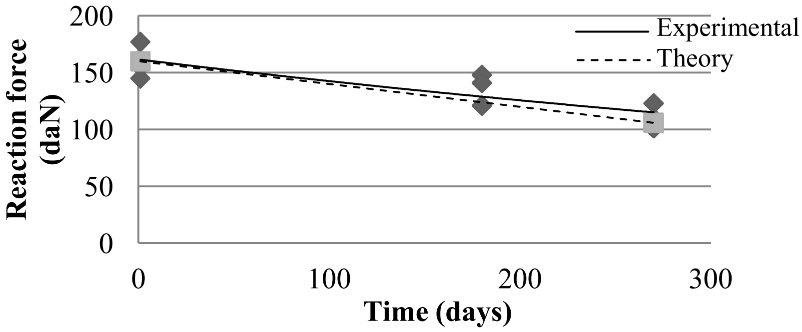

Figure 8: Decrement of GFRP reaction force due to stress relaxation after sustained inflection.

3.2 Creep evaluation

The displacement of the three actuators (d_1, d_2, d_3) has been compared with the fabric strains (ε_1, ε_2, ε_3). In this way it has been possible to distinguish between the global displacement of the system, composed by GFRP and PES/PVC, and the membrane elongation. Figure 9 shows the membrane strain. Figure 10 shows the displacement of the actuators.

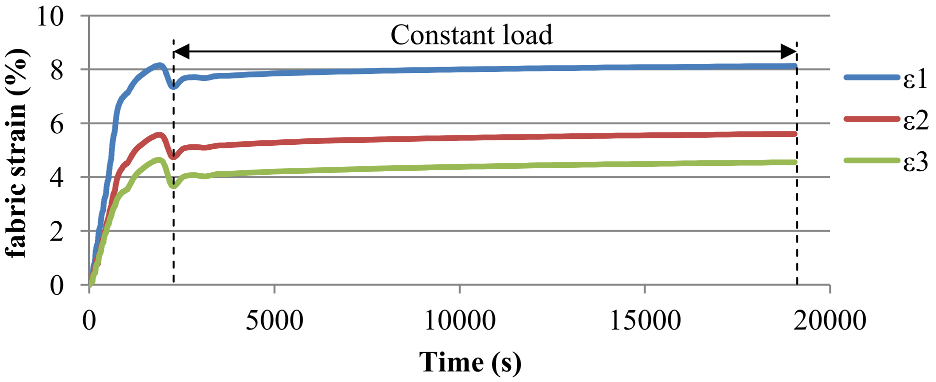

Figure 9. Diagram Time/Strain for the PES/PVC fabric.

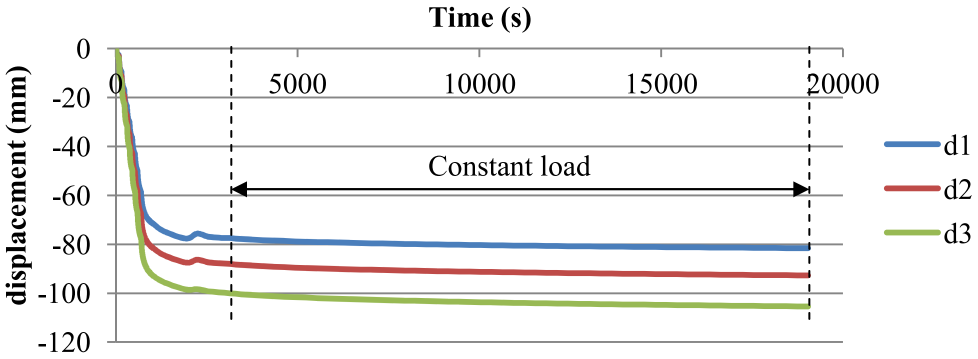

Figure 10. Diagram Time/Displacement for the actuators.

The displacement of the actuators is composed by the sum of the PES/PVC fabric creep and a part of GFRP bending and subsequent creep. The strain of the membrane augment close to the joint because of the highest rigidity of the system. Creep deflection of GFRP can be expressed by the following equation, as a difference between the displacement of the actuators (d_i) and the tissue elongation (ε_i*T_1):

$$\delta_{comp,i} = |d_i| - (\varepsilon_i * T_1) \qquad \text{where } i{:}1,2,3 \tag{2}$$

T_1 is the membrane length. δ_{comp} can be expressed by the simplified Findley model [7], [8]:

$$\delta_{comp\ (t)} = \delta_{(0)} + m\ (t/t_0)^n \tag{3}$$

where $\delta_{(0)}$ is the time-independent initial deflection and m and n are respectively the stress and time dependent creep coefficients for deflection creep and stress-independent material constant for deflection creep. Figure 11 shows the creep deflection of the GFRP under a constant load of 0.5 kN for each actuator.

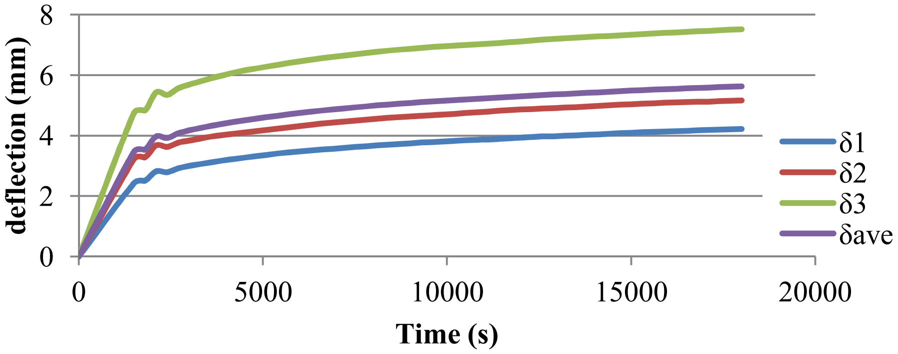

Figure 11. GFRP creep under deflection at a load of 0.5 kN for each actuator.

Referring to the average deflection and using a logarithmic expression it is possible to determine the values of the parameter *m* end *n* that are unknown in the expression. Equation 4 expresses the (3) in logarithmic form:

$$\log\ (\delta_{comp\ (t)} - \delta_{(0)}) = \log m + n \log\ (t/t_0) \tag{4}$$

Using data from (4) it is possible to define the value of *n*, that is equal to 0,18, and represents a stress independent constant for the material. Regression curve for the deflection is presented in Figure 12.

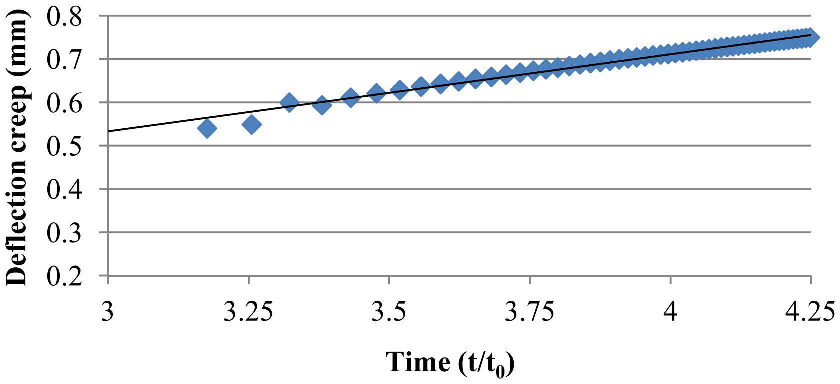

Figure 12. Deflection creep for the tested rod.

Conclusions

An experimental investigation dealing with the behavior over time of GFRP tubes and rods when coupled to PES/PVC membranes for building Composite Active Tensile Structures has been presented in this paper.

Present research shows that the viscoelastic phenomena deeply affect the global response of the GFRP members due to applied loads and imposed deflection when coupled to membranes. Both long lasting inflection and sustained stress affect the elastic response. For this reason geometrical dimension of GFRP profiles and, in particular, inflection length should be accurately defined during the design stage, along with the tension and pre-tension stress in the membrane that should be set-up according with the GFRP behavior. The reduction of 14% and 30% for the reaction force respectively after 6 months and 9 months of sustained inflection, due to stress relaxation, suggests to apply adequate coefficients to account the reduction of the elastic response of the profiles. Creep deflection has been calculated according to the simplified Findley model and it has been possible to distinguish between the membrane creep and the viscoelastic creep for composite. Calculus of n, that represents an independent constant for the material, permits to extend the creep evaluation to a large set of cases that can be encountered during the design of Composite Active Tensile Structures.

Further research should be done to analyze the coupled behavior of GFRP members and architectural fabrics. Some interesting applications, as roofing and building systems, generate interest for such structures and increase the importance of the research. Main features of these systems are lightness, easiness in transportation and installation and a low need for workforce during the installation phase. Due to the decrement of the elastic response specific applications can be found in temporary and emergency architecture.

Acknowledgments

The authors gratefully acknowledge Topglass Spa that supplied the GFRP profiles and Serge Ferrari SaS and F.lli Giovanardi Snc which supplied PES/PVC fabric used in present research. The biaxial testing equipment was provided by the multidisciplinary research cluster on Innovative textiles “clusTEX” at the Politecnico di Milano.

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