An experimental study on the long-term behavior of CFRP pultruded laminates suitable to concrete structures

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ABSTRACT: The rheological behavior of structural materials has a significant role indeed in Civil Engineering, where concrete and FRP materials undergo creep in normal environmental conditions, while steel exhibits a sizable creep only at high temperature (above 400 °C). With reference to RC structures strengthened by means of FRP laminates, FRP creep generally coexists with concrete cracking. The interaction between these phenomena should be taken into account in order to evaluate the structural durability. Here, the first results of a research program on creep in composite pultruded laminates used in Civil Engineering are presented, under various stress levels and in constant environmental conditions (many theoretical and experimental studies on creep have been performed so far in the aerospace and naval fields, but not as many in Civil Engineering). The specimens tested in this project are made of high-modulus carbon fiber-reinforced polymer – CFRP, whose mechanical properties are tailored for Civil Engineering applications. The tests are still in progress in the Materials and Structures Testing Laboratory of the Civil Engineering Department of the University of Salerno (Italy).

1 INTRODUCTION

In the field o.f Civil Engineering the rheological behavior of materials has an important role. One aspect that is particularly relevant is the creep phenomenon, since the continually increasing strain can compromise the durability of structural elements.

The viscous effects result particularly sizable in the case of fiber reinforced composite materials (FRP – Fiber Reinforced Polymer), due to the polymeric matrix, that is sensitive to viscous phenomena.

Nowadays these innovative materials are mainly utilized in the rehabilitation of damaged Reinforced Concrete (RC) and masonry structures.

Current international guidelines regarding the design of FRP strengthening applications confirm the importance of this problem. In fact, suitable limits have been introduced on the FRP stress state in Serviceability Limit State, in order to limit viscous effects (ACI Committee 440 2000, CEB-FIP 2001, CNR-DT 200/2004 2004).

Both theoretical and experimental studies on the viscous behavior of composites used in the aeronautical and naval fields have been performed (Barbero & Harris 1998, Dutta & Hui 1997, Maksimov & Plume 2001, Pang et al. 1997, Petermann & Schulte 2002, Scott & Zureick 1998).

The main aim of these studies has been to formulate constitutive laws for these materials under different stress states, as well as in different environmental conditions.

The studies developed on composite materials for civil engineering applications, and in particular on their secondary creep are less numerous. As it is well known, the secondary creep mainly occurs during the service life of a structure.

So far, the authors of the present paper have produced several theoretical studies based on the effects that secondary creep has on the long term behavior of RC beams strengthened with FRP laminates. The first results show a sizable influence of the viscous effects on the mechanical behavior of the strengthened structures. This leads to a consistent migration of FRP stresses towards the RC beam. The subsequent increase of the stress state in RC beams may compromise the efficacy of the strengthening technique and produce damage and cracking in the concrete (Ascione & Berardi 2003, Ascione et al. 2004, Berardi et al. 2003).

Therefore it is necessary to develop further theoretical and experimental analyses on this topic, starting from a better characterization of creep properties of FRP laminated composites used in civil applications.

The objective of this work is to present the results of the creep test program on several CFRP pultruded laminates subject to different stress values, in constant environmental conditions. The tests are currently being carried out at the Material and Structures Testing Laboratory of the Civil Engineering Department of the University of Salerno.

2 CREEP BEHAVIOR

The viscous behavior of FRP materials mainly depends on:

- matrix type;
- fiber type;
- fiber volume fraction;
- fiber orientation;
- load history;
- temperature and humidity.

This behavior can be identified by creep tests. A sample is subject to a constant tensile force and its elongation is monitored over time (Fig. 1). In the first part of the test a phenomenon, well known as primary creep, can be investigated. The initial elastic elongation is followed by fast-growing deformations. After this phase, the elongation goes on with an approximately constant rate over a time period longer than the previous one (secondary creep). Finally, if stress or temperature values become very high, the specimen may break (tertiary creep).

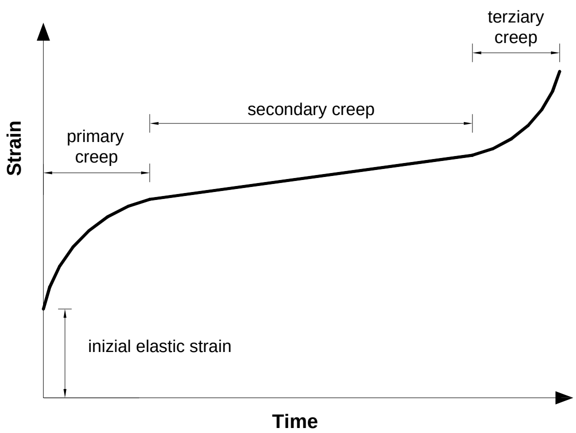

Figure 1. Creep deformations over time.

From a theoretical point of view FRP laminates are classified as ortotropic viscous materials, whose long term behavior should require the characterization of all the in-time mechanical properties.

In Civil Engineering applications the FRP mechanical behavior is in one-dimension (along one of the natural directions) and the stresses are less than forty per cent of the ultimate values.

These peculiarities simplify FRP long-term analysis, allowing the modeling of these innovative materials through linear viscoelastic one-dimensional models. These models are based on either mechanical analogies or experimental data (Barbero & Harris 1998, Dutta & Hui 1997, Maksimov & Plume 2001, Pang et al. 1997, Petermann & Schulte 2002, Scott & Zureick 1998).

At the moment, there are no constitutive laws of general validity for composite materials.

3 EXPERIMENTAL SET-UP

A creep test program on CFRP unidirectional laminates is being carried out at constant temperature.

The CFRP specimens, characterized by high value of longitudinal Young modulus, are subjected to constant different stress values along the longitudinal natural direction.

The experimental equipment includes:

- two identical testing devices able to apply constant loads;
- a data acquisition system.

More specifically, the thickness of all the CFRP laminates is equal to 1.4 mm and their mechanical properties, certified by the producer, are shown in Table 1, where E_f is the longitudinal Young modulus, f_{fk} is the characteristic tensile strength and ε_{fu} is the ultimate strain.

Table 1. CFRP certified mechanical properties.

E_f [N/mm^2]	f_{fk} [N/mm^2]	ε_{fu} [%]
≥300000	1450	0.45

3.1 *Testing mechanical device*

The dissipation-free testing device allows the application of axial loads to CFRP specimens set through a lever arm.

It is a steel lever arm, whose ends are linked respectively to a dead load and to the CFRP specimens series. Furthermore it includes a fixture composed of a steel structure with roller bearings functioning as the fulcrum (Fig. 2).

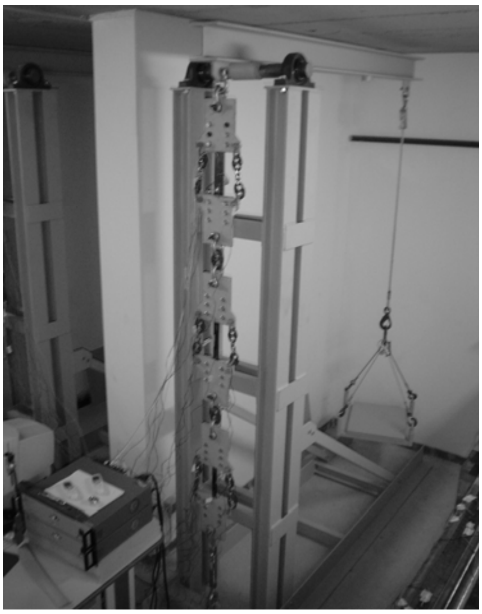
Figure 2. Testing device.

The lever arm has been designed to magnify the load applied to the specimens by a factor of 10.

The device is capable of loading three laminates simultaneously at a desired constant load.

The running system requires an efficacious load transfer from the end of the lever arm to the composite specimens. With this aim, the specimen anchorage devices consist of two suitable steel plates glued to the laminates and then bolted to each other.

The link between two successive specimens consist of chains and hooks (Fig. 3).

Figure 3. Specimens link.

The two end anchorages of each specimen are connected also by means of chains, in order to ensure a link in the case of an accidental sliding of the specimen between the anchorage plates.

Table 2. Testing stress values.

Testing device			1	2
Specimen	F	[N]	15225	22838
	B	[mm]	50	30
Top	σ	[N/mm^2]	217.5	543.8
	σ/f_{fk}	[%]	15	37.5
	B	[mm]	30	25
Middle	σ	[N/mm^2]	362.5	652.5
	σ/f_{fk}	[%]	25	45
	B	[mm]	25	15
Bottom	σ	[N/mm^2]	435	1087.5
	σ/f_{fk}	[%]	30	75

The axial force applied at the top of CFRP series (F), the CFRP specimen width (B) and the corresponding normal longitudinal stress value (σ), are summarized in Table 2 for each testing device.

3.2 *Data acquisition system*

The data acquisition system consists of electrical strain gages glued to the external surface of the specimens, thermocouples, scanner and a database management software.

The equipment can automatically record the data corresponding to fixed time steps.

Furthermore the system can correct the strain data by taking into account the temperature effects.

Each specimen is equipped with six electrical strain gages, symmetrically bonded with respect to the middle plane, in order to take care of the measurement errors and of the accidental flexural deformation. In particular, three strain gages are applied on each face, as shown in Figure 4.

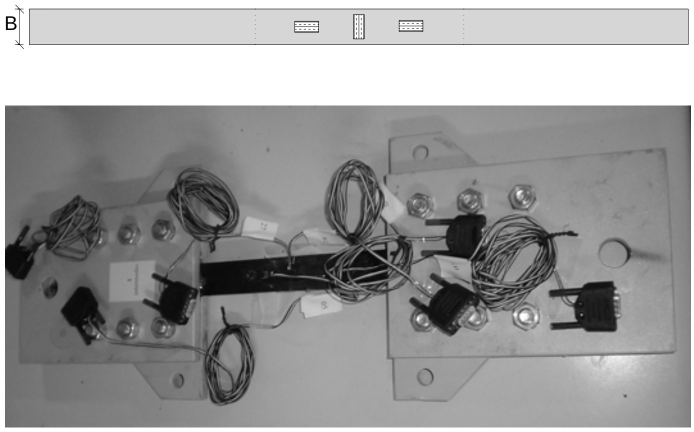

Fig. 4. CFRP specimen.

This strain gages layout allows both longitudinal and transverse strains to be measured as well as evaluate the Poisson ratio variation over time.

4 EXPERIMENTAL RESULTS

The creep tests on six CFRP specimens, subjected to different tensile stress values, are still being performed through two testing devices (§ 3.1).

The CFRP strains and the environmental temperature values have been recording since the start time of the test by means of a data acquisition system (§ 3.2). The test temperature is held constant (20 °C) by using an air-condition system.

Starting from the recorded elastic strains values, the average value of Young longitudinal modulus, E_{3m}, and Poisson ratio, ν_{32m}, have been obtained: $E_{3m} = 413383$ N/mm^2, $\nu_{32m} = 0.34$.

With reference to CFRP specimens tested by the testing device n.2 (Table 2), after about thirty-two hours a sudden rupture of the specimens occurred.

This accidental failure seems to have been caused by a microcrack produced in one of the samples during the cutting phase. A new creep test is being performed on another specimen using the above mentioned testing device.

The average values of specimen longitudinal strains recorded over time, expressed in days, are plotted in Figures 5-6.

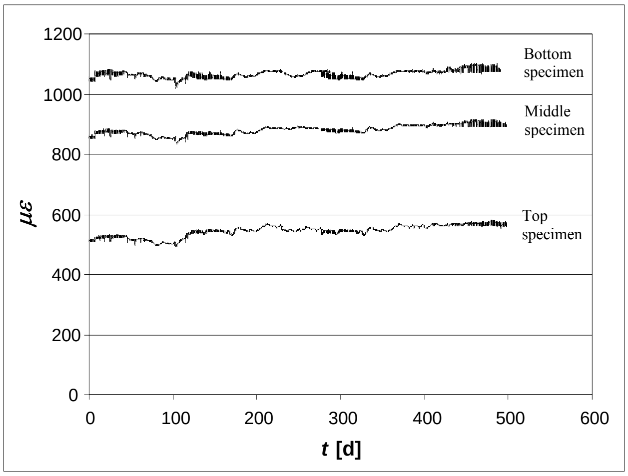

Figure 5. Longitudinal strain over time (testing device n.1).

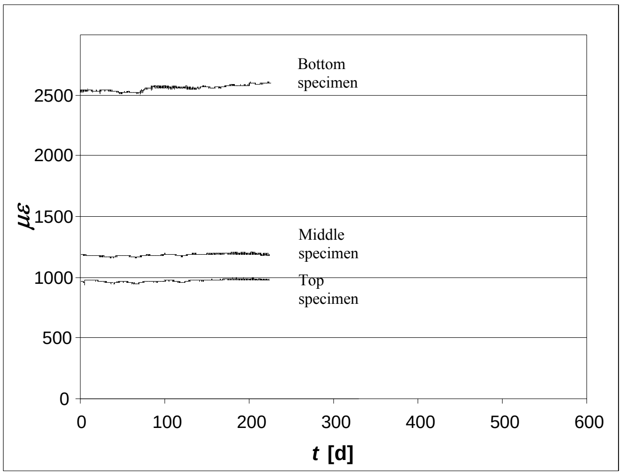

Figure 6. Longitudinal strain over time (testing device n.2).

5 CONCLUSIONS

In this paper an experimental study on the creep behavior of CFRP pultruded laminates has been presented.

In particular, several creep tests are being performed for different stress values at a constant temperature.

Experimental data relative to the first hours show a limited longitudinal strain variations for the tested specimens, revealing a negligible primary creep phase.

These data confirm the efficacy of carbon fibers in limiting the primary creep strains of CFRP laminates, characterized by high longitudinal Young modulus and high fiber volume fraction, as well known in literature.

The subsequent records for testing device n.1 have highlighted a maximum strain variation after about thirty days (Ascione et al. 2005), starting from the reference time instant t = 28500 s (≈ 8 h), which represents the assessment time of the data acquisition system.

Table 3. Maximum longitudinal strain variation.

	Specimen	σ/f_{fk} [%]	$\Delta\varepsilon/\varepsilon_{i}$ [%]
Testing device 1	Top	15.0	-
	Middle	25.0	1.35
	Bottom	30.0	1.63
Testing device 2	Top	37.5	1.66
	Middle	45.0	1.71
	Bottom	75.0	1.93

The average percent longitudinal strain variations for the middle and the bottom specimens are equal to 1.35% and 1.63%, respectively (Table 3). With reference to the top sample, its strain values, being smaller than the others, are affected by higher measurement errors, and then it is not possible to evaluate with high precision the strain variations. In any way, the test results have highlighted that the creep rate is negligible.

The experimental data recorded until about 500 days have not shown any further relevant increases of the longitudinal strains for all the specimens of testing device n.1.

With reference to the specimens of the testing device n.2, the maximum strain variations with respect to reference time instant, t = 0 s, have been recorded after about 76 days. The percent longitudinal strain variations for the top, the middle and the bottom specimens are equal to 1.66%, 1.71% and 1.93%, respectively (Table 3).

The subsequent records for testing machine n.2 have not highlighted any further relevant strain increases.

Starting from the above experimental results, the viscous behavior seems to be depleted, due to the creep rate being negligible.

They would confirm that the CFRP pultruded laminates with high longitudinal Young modulus and high fiber volume fraction highlight limited creep strains.

The analyses above shows the application rules prescribed in the CNR Guidelines about the FRP viscous behavior are confirmed.

They allow one to realize FRP retrofitting by avoiding damage and cracking of the concrete related to the viscous behavior of the composite materials.

The data are still being acquired in order to verify the effective attenuation of creep phenomena.

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