An experimental analysis on the time-dependent behaviour of a CFRP retrofitting under sustained loads

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ABSTRACT: Over the past few years, the strengthening of concrete structures with fibre reinforced polymer (FRP) composites has become increasingly user-friendly among engineers worldwide. Within this field one of the most relevant topics concerns the durability and the reliability of such materials, depending strongly on their viscous properties. FRPs, in fact, are made up purely of elastic fibres embedded in highly creep sensitive matrices. Most of the data available in literature about FRP creep tests deal with aeronautical/aerospace or mechanical applications, while only few concern civil purposes. In this paper the authors present some experimental results relative to the time-dependent behaviour of FRP pultruded laminates under sustained loads. The experimental set-up simulates the actual bonding conditions occurring in typical retrofitting interventions. The results present a part of a two year long experimental programme going on at Salerno University (Italy).

1 INTRODUCTION

Over the past few years, the strengthening of concrete structures with fibre reinforced polymer (FRP) composites has become increasingly user-friendly among engineers worldwide.

Nowadays, composite materials are used by civil engineering for structural rehabilitation together with traditional materials, like steel.

Within this field there is a great interest in investigating the durability and the reliability of such materials, mainly with respect to their viscous properties. FRPs, in fact, are made up purely of elastic fibres embedded in highly creep sensitive matrices.

All current international guidelines for the design of FRP strengthening interventions assess the importance of the above problem. In fact several limitations on FRP stresses at Service Conditions are usually introduced in order to control viscous effects (ACI Committee 440 2000, CEB-FIP 2001, CNR-DT 200/2004, English translation 2006).

Both theoretical and experimental investigations on the viscous behaviour of composites used in the aeronautical and naval fields can be found in many technical papers or textbooks (Barbero & Harris 1998, Dutta & Hui 1997, Maksimov & Plume 2001, Pang et al. 1997, Petermann & Schulte 2002, Scott & Zureick 1998). The common aim is to introduce constitutive laws accounting for different stress levels as well as different environmental conditions.

Instead, few studies concerning the time-dependent behaviour of composite materials used in civil engineering fields are available in literature. In these types of applications the most relevant phenomenon is the so-called secondary creep.

Many theoretical investigations designed to study the effects of secondary creep on the long-term response of Reinforced Concrete (RC) beams strengthened with FRP laminates have been developed by the authors. They show the possibility of relevant stresses migration from the FRP reinforcement to the former core of the RC beam as time passes. The consequent increase of the stresses level in the RC beam may compromise the efficacy of the strengthening technique (Berardi et al. 2003, Ascione et al. 2004).

Therefore it seemed very interesting to further investigate by experimental analyses, the time-dependent behaviour exhibited by FRP laminates commonly used in civil applications.

The aim of this paper is to present the experimental results of creep testes carried out on some CFRP retrofitting systems.

Such results are part of a two year long experimental programme currently underway at the University of Salerno.

2 CREEP BEHAVIOUR

When dealing with aged concrete structures, the rate of the viscous effects in the concrete can be considered equal to zero. Consequently, only FRP creep deformations have to be taken into consideration. A similar problem occurs when dealing with steel-concrete composite structures. In fact, in this case, creep phenomena concerns the concrete component, while the steel component does not flow.

The viscous behaviour of FRP materials depends on many factors, like the matrix properties, type of fibre, fibre volume fraction, fibre orientation, load history, environmental conditions (temperature and humidity).

From a theoretical point of view FRP laminates can be classified as orthotropic viscous materials. Consequently, the long term behaviour analysis should require the characterization of all mechanical properties over time.

In particular, with reference to the retrofitting of RC members, the constitutive laws to be investigated is essentially one-dimensional (along the natural direction lying on the longitudinal axis). This allows us to simplify the experimental investigation by the recourse to simple creep tests: a sample is subjected to a constant tensile force and its elongation is monitored over time (Fig. 1). In the first part of the experiment the well known primary creep is dominant. The initial elastic elongation is followed by fast growing deformations. During the next phase the elongation continues on with a constant rate over a longer time period (secondary creep).

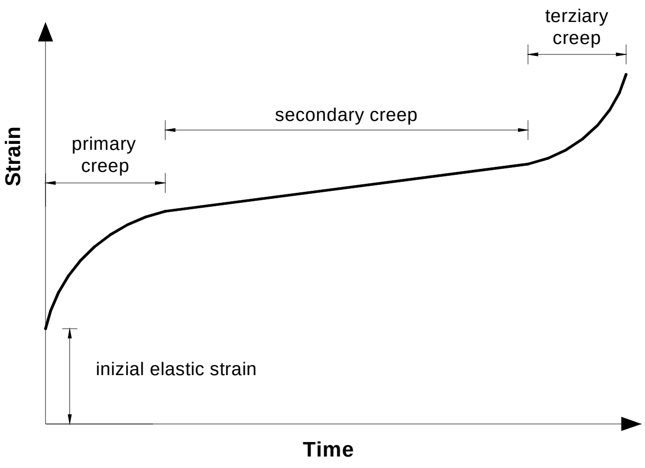

Figure 1. Creep deformations over time.

A third phase (terziary creep) can also occur, under very high stress or temperature levels: strains grow at an increasing rate until the sample breaks.

The long-term prediction of such effects is usually performed by introducing linear viscoelastic one-dimensional models. Such 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).

Until now, no viscous constitutive law has a widespread validity for composite materials, except in restricted applications of aeronautical, naval or mechanical fields. To characterise the viscous properties of FRPs within the context of civil interventions further experimental investigations are required.

3 EXPERIMENTAL SET-UP

As mentioned above, in order to study the creep behaviour of CFRP laminates, a long-term (two year) experimental programme is being carried out by the authors.

The test involves a system composed of a thin CFRP plate bonded to the top flange of a simply supported titanium beam (Ti-6Al-4V). More details are shown in Fig.2. By this way the actual mechanical conditions, occurring in retrofitting concrete structures, have been simulated. In fact, the behaviour of the titanium alloy beam is not time-dependent, as is the case of aged concrete structures. Moreover, like FRP, the titanium alloy here considered exhibits a linear elastic response up to very large normal strains. As a consequence, it is possible to evaluate the instantaneous stresses inside the materials by measuring corresponding strains.

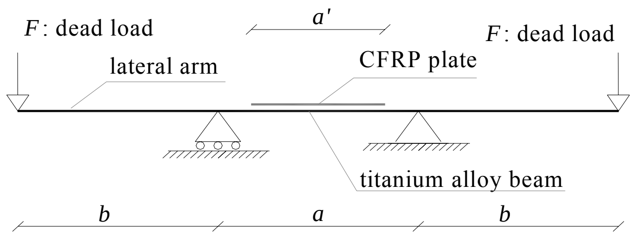

Figure 2. Experimental scheme.

The static scheme adopted by the authors is represented in Fig. 2. Its total length is equal to 7300mm = $a + 2 \cdot b$, where a is the length of the titanium alloy beam (3500mm), and b (=1900mm) denotes the length of the two steel lateral arms. Such arms are connected to the titanium alloy beam by bolted joints (Fig. 3). The bond CFRP/beam has been made by using the adhesive (trade name: Loctite Multibond 330). Finally, a' = 2900 mm, is the length of the FRP reinforcement: a *CarboDur H514* plate, manufactured by Sika Group. The plate is characterised by a fibre volume fraction higher than 70%, along the longitudinal axis.

Dead loads have been applied at the free ends of the two lateral arms, symmetrically, according to the scheme in Fig.2.
In particular, 1000mm×200mm×10mm steel sheets, each one about 0,20 kN (Fig.4), were used.

It is easy to verify that (Fig. 2):

i) a constant bending moment (M = - F · b) occurs within the supports;

ii) no shear stresses arise.

Figure 3. Bolted joints.

Figure 4. Dead loads applied by using steel sheets

The cross-section of the reinforced beam (titanium + CFRP) is shown in Fig. 5 (length unit: mm). The main mechanical properties of the titanium alloy, CFRP and adhesive are described below (Table1).

Table 1. Certified mechanical properties (stresses unit: N/mm^2).

	Ti-6Al-4V	CFRP	Glue layer
Normal elastic modulus	110000	≥300000	-
Yield normal stress	790 (20°C)	-	-
Ultimate normal stress	895 (20°C)	1450	-
Ultimate shear stress	-	-	≥16,5
Ultimate normal strain	0,1000	≥0,0045	-

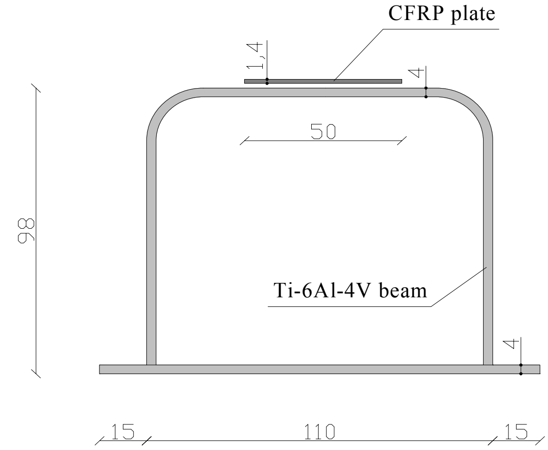

Figure 5. Cross-section (length unit: mm)

The experimental programme has been divided into two phases, each one performed under controlled temperature (20°C ± 1°C) and humidity (50% ± 5%):

- 1st phase: generation of a low stress level in the plate (20% of CFRP tensile strength). Until now this phase, 6-month long, has been completed, and the results obtained by the authors have been recently presented (Ascione & Mancusi, 2006).
- 2nd phase: generation of a higher stress level (70% of CFRP tensile strength). This phase, 18-month long, is still underway, and the results already obtained by the authors, relative to the first six months, are here presented for the first time.

The strain state evolution is monitored by continuous data acquiring hardware/software system equipped with 35 strain-gauges. They are applied both to the titanium beam as well as to the CFRP plate within the cross-section (Fig. 6: positions *a*, *e*, *f* for Ti-6Al-4V; positions *b*, *c*, *d* for CFRP) and along the longitudinal axis. Due to the linear elastic response of both materials, stresses can be easily related to strains. Furthermore, an optometric system, OptoNCDT 1401 by *με Micro Epsilon*, is used in order to measure the mid-span deflection over time (in the same position *f* above mentioned).

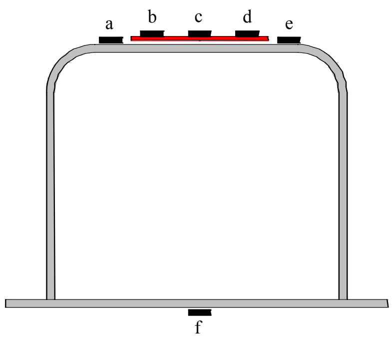

Figure 6. Strain gauges position (mid-span cross-section).

Once the normal stresses corresponding to the measured strains (positions *a*, *e* and *f*) have been calculated, it is possible to evaluate the resultant axial force, N_{Ti}, attained within Ti-6Al-4V alloy.

Assuming the supports are frictionless, by equilibrium along the longitudinal axis, the instantaneous axial force within the CFRP plate, N_{CFRP}, is equal to $-N_{Ti}$.

As a consequence of the above hypothesis, the average instantaneous normal stress in the CFRP plate, σ_{CFRP} , can be related to the measured average normal strain $\varepsilon_{CFRP} = (\varepsilon_b + \varepsilon_c + \varepsilon_d)/3$, being ε_i the normal strain at position i (i=b, c, d).

4 EXPERIMENTAL RESULTS

As referred above, in this section we discuss some experimental results obtained during the first six months of the 2nd phase, which is still underway at Material and Structures Testing Laboratoty of the Salerno University. Such a phase is characterised by an initial stress level in the CFRP plate equal to about 70% of the CFRP tensile strength. When the 2nd phase was going to start, viscous effects previously provoked in the 1st phase had already affected the plate. Such effects, however, were very negligible as shown below, in Table 2, where some of the data acquired during the 1st phase are summarized (strain unit: $\mu\varepsilon$). They refer to the mid-span cross-section.

Table 2. Data acquired during the 1st phase

Elapsed time	Strain gauges position a	b	c	d	e	f
[days]			$[\varepsilon \times 10^6]$			
t_0= 0	848	876	886	872	849	-959
t_1= 180	858	848	867	849	857	-962

In particular, data concerning a, e and f strain-gauges (Fig. 6 - Table 2) allow us to evaluate the internal axial force, N_{Ti}, within the titanium alloy component. The above assumption of linear-elastic behaviour is utilized.

On the other hand, data concerning b, c and d strain-gauges allow us to evaluate the average value, ε_{CFRP}, of the instantaneous normal strain in the CFRP plate. The internal axial force acting on the CFRP plate can be assumed equal to $N_{CFRP} = - N_{Ti}$.

Consequently, the average stress value in the CFRP plate can be evaluated as follows:

$$\sigma_{CFRP} = N_{CFRP} / A \qquad (1)$$

where symbol A denotes the FRP cross-section area.

In Table 3 the last column presents the instantaneous values of the following ratio:

$$E_{CFRP} = \sigma_{CFRP} / \varepsilon_{CFRP} . \qquad (2)$$

As can be seen, during the whole 1st phase, the viscous effects were very negligible.

Table 3. Stress-strain analysis – 1st phase.

Elapsed time	N_{Ti}	N_{CFRP}	σ_{CFRP}	ε_{CFRP}	E_{CFRP}
[days]	[N]	[N]	[N/mm^2]	$[\varepsilon \times 10^6]$	[N/mm^2]
t_0= 0	-23746	23746	339	878	386105
t_1= 180	-23256	23256	332	855	388304*

*this value results a bit higher than that one at time t_0 only due to experimental error.

After six months the 1st phase had begun, dead loads were increased, and held constant until today. In Table 4 data acquired during the 2nd phase at three different times are summarized: when 2nd phase started (t_2), 15 days after (t_3), 180 days after (t_4). Likewise in the case of Table 2, they refer to the mid-span cross-section.

Table 4. Data acquired during the 2st phase (still underway)

Elapsed time	Strain gauges position a	b	c	d	e	f
[days]			$[\varepsilon \times 10^6]$			
t_2= 0	2582	2685	2691	2674	2613	-2933
t_3= 15	3903	1057	1149	1019	3982	-3651
t_4= 180	3939	1011	1077	955	4015	-3638

Table 5 summarises the correspondent stress-strain analysis. In this case, the viscous effects are more relevant, due to the rheological behaviour of the glue layer at FRP to metal interface. In fact, making reference to the creep of the glue layer, it is possible to understand the detected behaviour: after a certain time elapsed, the experiment shows normal strains in the CFRP plate (measurements made at b, c and d positions in Fig. 6) decreased below the values attained in titanium alloy (measurements made at a, e and f positions in Fig. 6).

Table 5. Stress-strain analysis – 2st phase (still underway).

Elapsed time	N_{Ti}	N_{CFRP}	σ_{CFRP}	ε_{CFRP}	E_{CFRP}
[days]	[N]	[N]	[N/mm^2]	$[\varepsilon \times 10^6]$	[N/mm^2]
t_2= 0	-72406	72406	1034	2683	385389
t_3= 15	-27104	27104	387	1075	360000
t_4= 180	-22693	22693	324	1014	319527

The following Figs. 7a, b show the response of the system over the time range $[t_2, t_3]$.

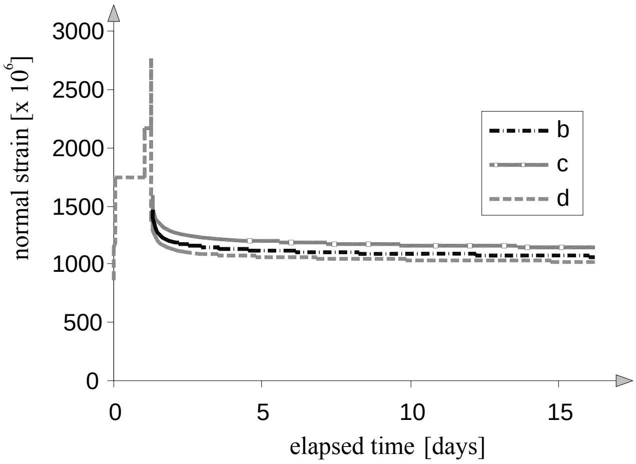

Figure 7a. Strain analysis within CFRP - range $[t_2, t_3]$.

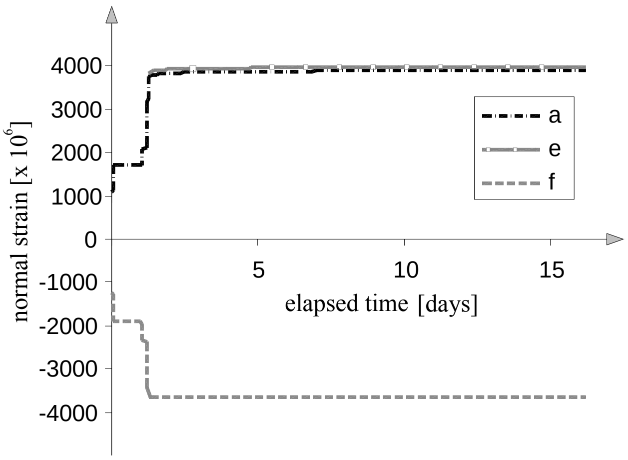

Figure 7b. Strain analysis within Ti-6Al-4V - range $[t_2, t_3]$.

Moreover, in the previous Figs.7a,b close to the time origin, the plots present many discontinuities, corresponding to load steps. In fact, the loading of the retrofitting system was realized by the authors in successive steps, using the above mentioned steel sheets, and took about 24 hours to complete.

Finally, changes in term of the vertical deflection of the system at mid-span cross-section were also measured by the optometric sensor, above mentioned and placed at *f* position (Fig. 6).

Table 6. Changes in term of vertical deflection at mid-span (%)

time	%
t_3	39,4
t_4	43,0

The results of Table 6 confirm the main importance of the first period, $[t_2, t_3]$, on the long-term behaviour, when very high initial internal stresses are present in the CFRP plate.

5 CONCLUSIONS

The experimental results described in the previous section show the investigated CFRP plating exhibits small viscous effects, if the initial stresses are less than 20-25% of the FRP tensile strength.

On the contrary, fast changes in term of system mechanical response (beam + CFRP plate) can be highlighted, if the CFRP internal stresses increase up to 70-75% of the corresponding tensile strength, as it happened during the experiment (2nd phase).

The whole viscous phenomenon, observed in such a phase, occurred within the first 15 days. During this period, a fast decrease of the stresses and strains in the CFRP was observed, while in the subsequent time interval, $[t_3, t_4]$, only negligible changes in term of stresses and strains occurred.

In other words, the viscous effects, detected during the 2nd phase, were relevant and expired within a few days.

The results obtained, suggested to the authors to stop the 2nd phase which was still underway, although it was initially planned over an 18-month period.

Within the next 12 months, similar investigations, under stress levels in the CFRP equal to about 30-50% of the tensile strength will be performed. Such percentage values correspond to the maximum stress levels suggested in the new guide-lines CNR-DT 200/2004, recently edited by Italian National Research Council. An English translation of the guide-lines is available (2006).

The results of the investigation will contribute to assess the safety of the design rules given in such guide-lines.

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