Long-term properties of bond between concrete and FRP

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ABSTRACT: Results of an experimental campaign concerning long-term behavior of bond of FRP plates bonded to concrete are presented. CFRP plates with three different bonded lengths (from 100 mm to 400 mm) have been subject to long term loads by using a mechanical system able to apply a constant traction force. Tests have been carried out in a climatic room with a constant temperature T=20°C and humidity RH=60%. Strain profile evolution with time along the bonded length have been recorded by using a number of strain gages placed along the plates. An appreciable stress redistribution with time along the plate has been observed. A simplified visco-elastic analytical model has been finally used to reproduce experimental findings. Good matching between experimental and numerical data has been found.

1 INTRODUCTION

Durability with time of FRP strengthening interventions on reinforced concrete structures strongly depends on interface behaviour between concrete and FRP.

Effectiveness of strengthening can be remarkably reduced due to rheological properties of materials involved (concrete, adhesive, FRP). An important role is also played by the temperature variation. In this framework, only few information can be found in literature concerning the time behaviour of strengthened civil structures (Plevris & Triantafillou 1994; Savoia et al. 2005, Diab & Wu 2006).

In the present paper, results of an experimental campaign concerning long-term behaviour of bond between concrete prisms and FRP plates are presented. Three different bonded lengths (from 100 mm to 400 mm) have been adopted. Seven to eleven strain gauges (depending on bonded lengths) along FRP plates have been used to measure longitudinal strains. A mechanical system able to apply a traction force constant in time to the extremity of plates has been designed. In order to eliminate strain thermal drift, long-term tests have been carried out in climatic room with standard ambient conditions. Strains have been measured during time by using an automatic control system. Strain profile evolutions with time along the bonded length have been recorded. At the moment, time duration of tests is about 650 days.

It is shown that a significant redistribution of shear stresses along the anchorage occurs due to creep deformations at the interface level.

A simplified model has been finally presented, able to describe evolution with time of strain and shear stress distribution along the plate. It is based upon a linear interface model properly modified by introduction of effective longitudinal and shear moduli. Numerical results are in good agreement with experimental data, especially in the initial part of bonded plates, where shear slips are higher.

2 GEOMETRY AND MECHANICAL PROPERTIES OF SPECIMENS

2.1 *Specimen preparation*

Long-term behaviour of CFRP plates bonded to concrete surfaces has been investigated by considering three different bonded lengths (100, 200 and 400 mm) and two concrete specimens (two anchorages for each specimen).

Concrete specimen dimensions were 150×200×600 mm. They were fabricated using normal strength concrete. Concrete was poured into wooden forms, externally vibrated. The top was steel – troweled. Five 15 cm – diameter by 30 cm – height standard cylinders were also poured and used to evaluate mechanical properties of concrete, according to Italian standards. Specimens were demoulded after 24 hours and covered with saturated clothes for 28 days; subsequently, they were stored at room temperature and uncontrolled humidity inside the laboratory.

Mean compressive strength f_{cm} = 52.6 MPa from compression tests and mean tensile strength f_{ctm} = 3.81 MPa from indirect traction tests have been obtained. Mean value of elastic modulus E_{cm} = 30700 MPa and Poisson ratio ν = 0.227 have been obtained from preliminary tests. Concrete specimens were sufficiently old before tests (two years) so that shrinkage strains can be neglected.

As for composite plates, CFRP Sika CarboDur S plates, 80 mm wide and 1.2 mm thick, have been used. According to technical data provided by the producer, plates have carbon fiber volumetric content equal to 70 percent and epoxy matrix. Minimum tensile strength is 2200 MPa and mean elastic modulus is E_p = 165000 MPa.

Two opposite surfaces of each concrete block have been grinded with a stone wheel to remove the top layer of mortar, until the aggregates were visible (approximately 1 mm). Plates have been bonded to surfaces by using a 1.5 mm thick layer of two – components Sikadur – 30 epoxy adhesive, having mean compressive strength of 95 MPa and mean elastic modulus E_a = 12800 MPa, according to producer data. No primer before bonding has been used. Two CFRP plates have been bonded to opposite faces of each specimen, with different bonded lengths (concrete *Block P1*: B.L. = 100, 200 mm; *Block P2*: B.L. = 200, 400 mm), see layout reported in Figure 1a. Curing periods of anchorages of blocks *P1* and *P2* were, respectively, 15 and 20 days prior to testing.

2.2 *The bond surface*

Two different positions of bond surface on the concrete specimen were considered in previous experimental tests and FE numerical investigations (Mazzotti et al. 2004), i.e., starting from the loaded end of the specimen or at a given distance from it. These studies showed that if bonding of CFRP plate starts close to the front side of concrete specimen, very high tensile stresses are present in this concrete portion and, typically, an early failure occurs in delamination tests due to concrete cracking of a prism with triangular section. On the contrary, when plate bonded length starts far from the front side, tensile stresses are much smaller and FRP – concrete interface is subject to prevailingly shearing stresses up to delamination failure. Behaviour of the interface is not affected by boundary effects and this test set-up is than more appropriate to obtain data for calibration of interface laws.

In the present experimental investigation, plate bonded length starts 100 mm far from the loaded end of specimen (Fig. 1a).

3 EXPERIMENTAL SETUP AND INSTRUMENTATION

Experimental setup is depicted in Figure 1a. Concrete block was positioned on a rigid frame with a front side reaction element (60 mm height) in order to prevent longitudinal displacements. Free ends of plates were mechanically clamped within a two steel plate systems. A double hinge system allowed for rotations around transverse axis. Traction force was applied to steel plates by using a mechanical frame allowing for magnification of applied force at the opposite side of horizontal arm. Force was given as weight of a number of steel plates (Fig. 1b). Amplification factor of mechanical system is about 4. Tests were performed by prescribing constant values of applied force.

Along CFRP plates bonded to concrete, series of

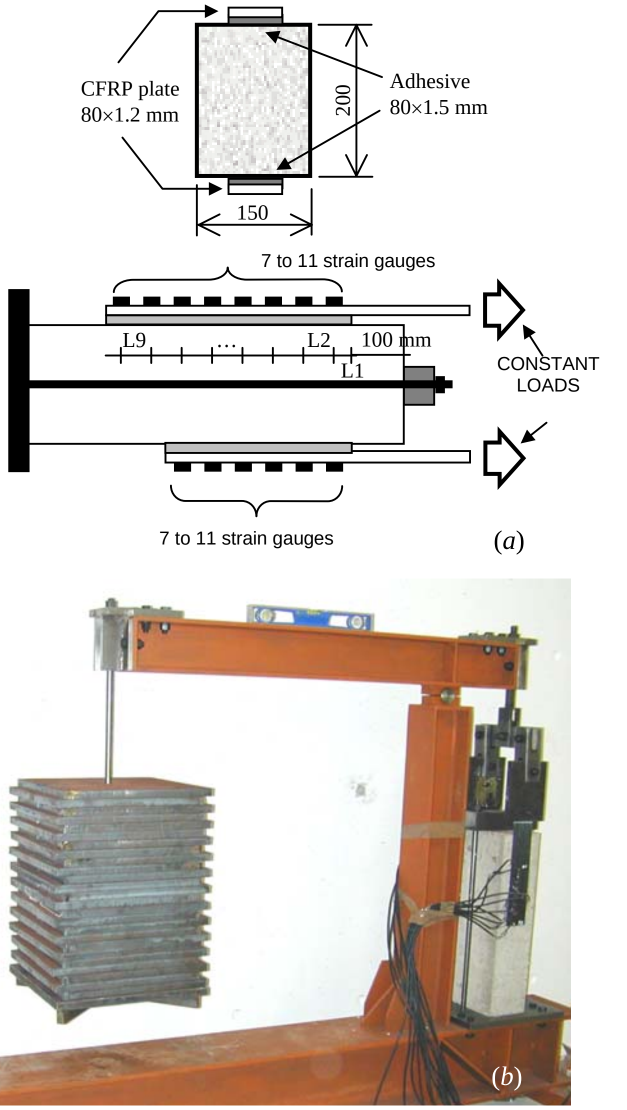


Figure 1. (*a*) Geometry of specimens and (*b*) experimental setup for long – term tests.

Table 1. Distances (mm) between strain gauges along the FRP plate, for different bonded lengths (B.L.).

B.L.	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11
100	10	10	10	15	15	15	15				
200	10	10	10	20	20	20	30	30	40		
400	10	10	20	20	40	40	50	50	50	50	50

seven – to – eleven strain gauges (depending on the plate length) were placed, along the centerline. For each bonded length, spacing between strain gauges is reported in Table 1.

4 RESULTS OF EXPERIMENTAL TESTS

4.1 *Loading program*

Two different loading conditions have been considered: plates of specimen *P1* have been subject to a traction force of 12.30 kN (about 50 percent of maximum transmissible load, according to delamination tests on analogous specimens, see Mazzotti et al. 2004, 2005b), followed by 690 days at constant loading. Plates bonded to specimen *P2* have been subject to the same sustained load (12.30 kN) for 510 days; after that, a second load step of 3.80 kN has been applied and maintained for further 160 days. Longitudinal strains along the plate at different loading levels and different time intervals have been recorded by an automatic computer system.

Reliability of symmetric double plate system (Fig. 1a), adopted in this experimental campaign, has been verified by comparing strain distribution measured along the plates during loading phase with analogous results obtained from similar specimens, tested according to conventional set-up (Mazzotti & Savoia 2005).

4.2 *Long term behaviour*

Figures 2a – d show time evolution of longitudinal strains along the plates for 100 – 200 mm (specimen *P1*) and 200 – 400 mm (*P2*) bonded lengths, respectively. For each strain gauge, distance from the initial section of the ancorage is reported in parenthesis. Time is reported adopting a logarithmic scale for plates bonded to specimen *P1*: behaviour after small time intervals can then be observed. On the contrary, for plates bonded to specimen *P2*, linear time scale has been adopted (Figs 2c, d); in this way, behaviour after second load increment (at 510 days) can be observed. It is worth noting that, due to stability of climatic condition and having adopted an automatic data acquisition system during the whole test, smooth curves have been obtained, even for those strain gauges whose strain variation is small.

Reliability of long-term loading system and repeatability of experimental results have been already verified in (Mazzotti & Savoia 2005), where strains evolution with time of two plates with same bonded length of 200 mm (one bonded to specimen *P1* and one to specimen *P2*) have been compared. Very good agreement has been obtained.

From Figures 2a – d, it can be observed that at low stress levels, plates with different bonded length exhibit a similar behaviour: rate of strain starts decreasing immediately after load application (as in classical creep tests on concrete specimens). Adopting time log scale, stabilization of delayed strain rate is typically considered when a linear increase of

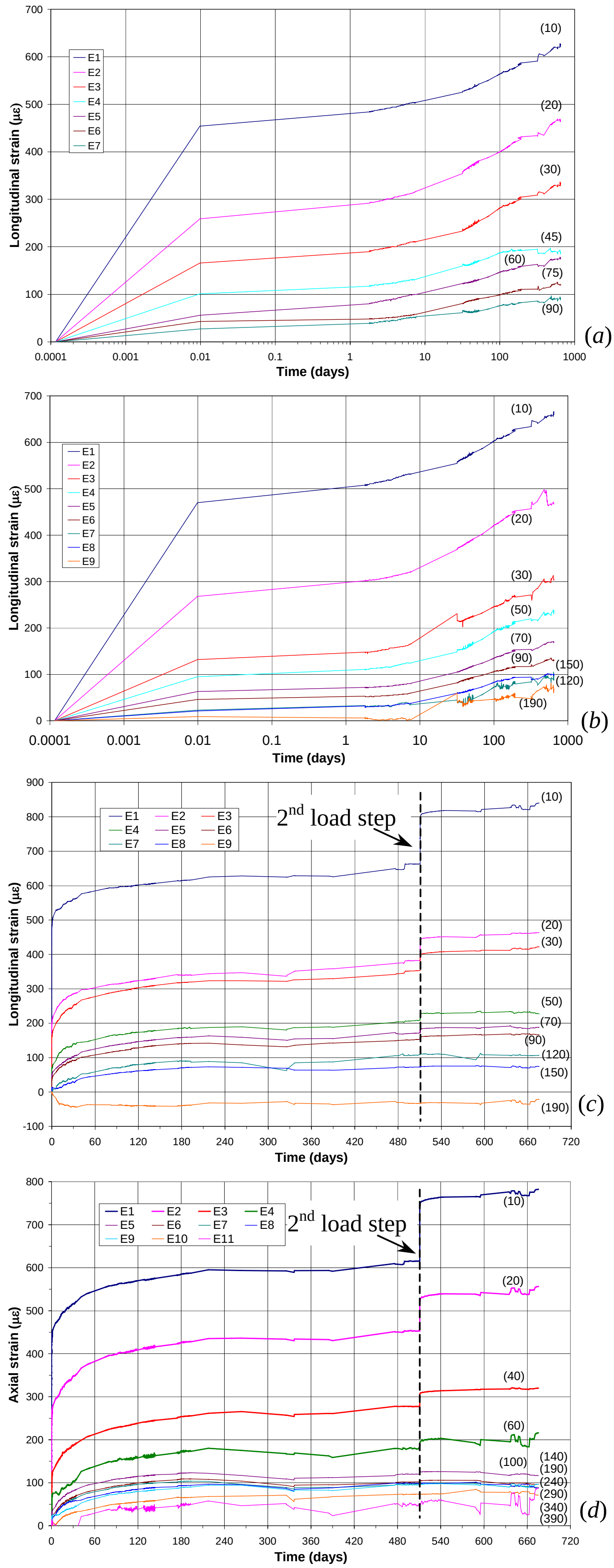


Figure 2. Time evolution of strains in FRP plates at different positions along the anchorage: specimen *P1* – (*a*) B.L.=100 mm, (*b*) B.L.=200 mm; specimen *P2* – (*c*) B.L.=200 mm, (*d*) B.L.=400 mm. Number in parenthesis indicates the distance from the initial section of the anchorage.

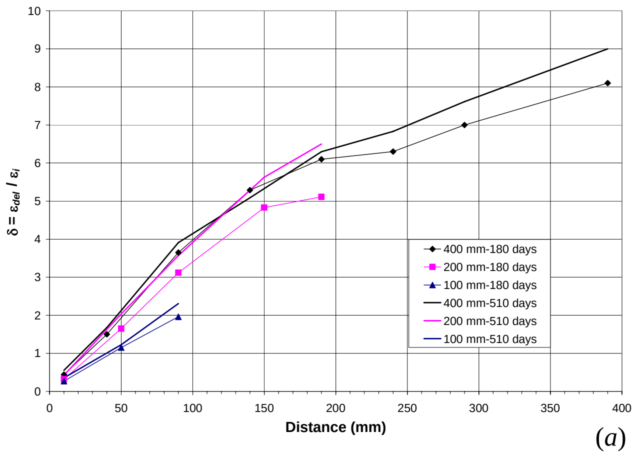
strain is attained. This behaviour has been obtained after about three months of constant loading and can be considered as the beginning of steady-state increase of delayed strain. After 670 days of loading, no remarkable changes in curve slope (with time in log scale) have been observed.

A delayed strain coefficient has been defined as the ratio between delayed strain and instantaneous strain:

$$\delta(t) = \frac{\varepsilon_{del}(t)}{\varepsilon_i}. \qquad (1)$$

Delayed strain can be due to both creep compliance and stress variation in the plate, caused by stress redistribution. Of course, if stress distribution was constant in the anchorage during time (no redistribution), and considering linear creep behaviour for both adhesive and concrete cover, delayed strain coefficient at a given time should be equal for all strain gauge positions.

Figure 3a shows, for three bonded lengths, variation of delayed strain coefficient with the distance from the traction side after 180 and 510 days of loading. Delayed strain coefficient increases significantly far from loaded plate side: delayed deformation is up to 9 times greater than instantaneous deformation. Two types of behaviour can be observed for each bonded length: close to loaded end, delayed



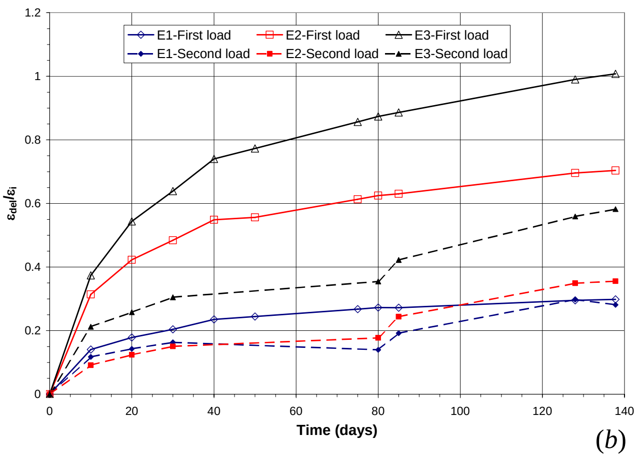


Figure 3. Ratio between delayed and instantaneous strains: (*a*) along the plate at 180 and 510 days of loading; (*b*) evolution with time for first three strain gauges (B.L.=200 mm).

strain coefficient increases almost linearly with distance, and slope increases with increasing of bonded length (from 200 to 400 mm). At a distance from loaded end of about 150 – 200 mm, curves reach a second linear branch with smaller slope up to the end of plates (for 200 mm and 400 mm cases).

Delayed strain coefficients obtained after 510 days of loading are only slightly higher than correspondent values after 180 days, suggesting that both stress redistribution phenomena and creep deformation change only slightly after six months from initial loading.

For specimen *P2*, delayed strain coefficient from Equation 1 has been obtained for two distinct loading steps the specimen was subject to. With reference to bonded plate with B.L.=200 mm, evolution with time of coefficient $\delta(t)$ has been reported for first three strain gauges in Figure 3b, both after initial (solid lines) and second load step (dashed lines). Time evolution of delayed strain coefficient δ obtained for first strain gauge is very similar between two loading steps; this is due to position of instrument, at the very beginning of bonding length, where influence of viscous properties of plate-concrete interface is very low, creep behaviour of CFRP plate being also very small. On the contrary, for strain gauges far from initial section, a remarkable reduction of coefficient $\delta(t)$ after 2nd load step can be observed. As a confirmation, Figure 4 shows superposition of strain evolution with time of strain gauges belonging to two plates with B.L.=200 mm; solid lines refer to specimen *P2* subject to second load step Δp^2 after 510 days from first loading Δp^1 (Δp^2=0.35Δp^1), whereas thin lines refer to specimen *P1* subject to the initial load step only.

Finally, Figures 5a – d show strain profile along plates at different times, for four different specimens. Strain profiles are quite similar, showing decreasing values of delayed strains with time moving away from the traction side; on the contrary, after a distance of 150 – 180 mm (realistic value of transfer length), delayed strains increase with time is almost constant.

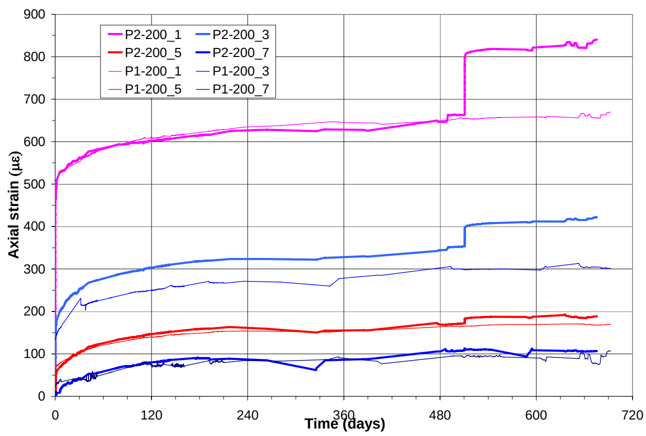


Figure 4. Superposition of strain evolution with time of strain gauges 1,3,5,7 from B.L.=200 mm of specimens *P1* and *P2*.

5 DISCUSSION OF RESULTS

Variation of delayed strain coefficient along the FRP plates is the result of different phenomena.

First of all, CFRP plates exhibit creep deformation when subject to long – term loading. Nevertheless, according to experimental results reported in the literature (Ascione et al. 2005), CFRP plates adopted in the present experimental study is practically insensitive to creep strains, being less than 2 per cent even for medium stress levels.

Secondly, adhesive and concrete cover constituting the interface where load is transferred from plate to concrete are subject to creep strains, increasing compliance of the interface. Increasing with time, plate – concrete slip provides for a shear stress redistribution along the interface: high shear stresses close to loaded end decrease and a longer length of interface is subject to shear stress transfer.

Third, due to very high shear stresses at the adhesive and concrete cover level, close to the loaded end creep phenomenon may be highly non linear. Hence, compliance increase at the beginning of the anchorage is much higher than far from it.

Evolution with time of shear stress redistribution and creep deformation at the interface level (which is variable along the anchorage) may explain the experimental results described in the previous section. In fact, far from the loaded section of the plate, normal stresses in the plate increase and, consequently, the same behaviour is exhibited by axial strains.

Moreover, shear stress redistribution is more evident in the case of long bonded lengths, i.e. longer than transmission length (about 150 – 180 mm). For this reason, the rate of increase of axial strains in FRP plate is higher for the longest length (400 mm), see Figure 3a. At distance from loaded end greater than 200 mm, shear stresses are small also after long term loading application, and, consequently, the second branch in Figure 3a has smaller slope.

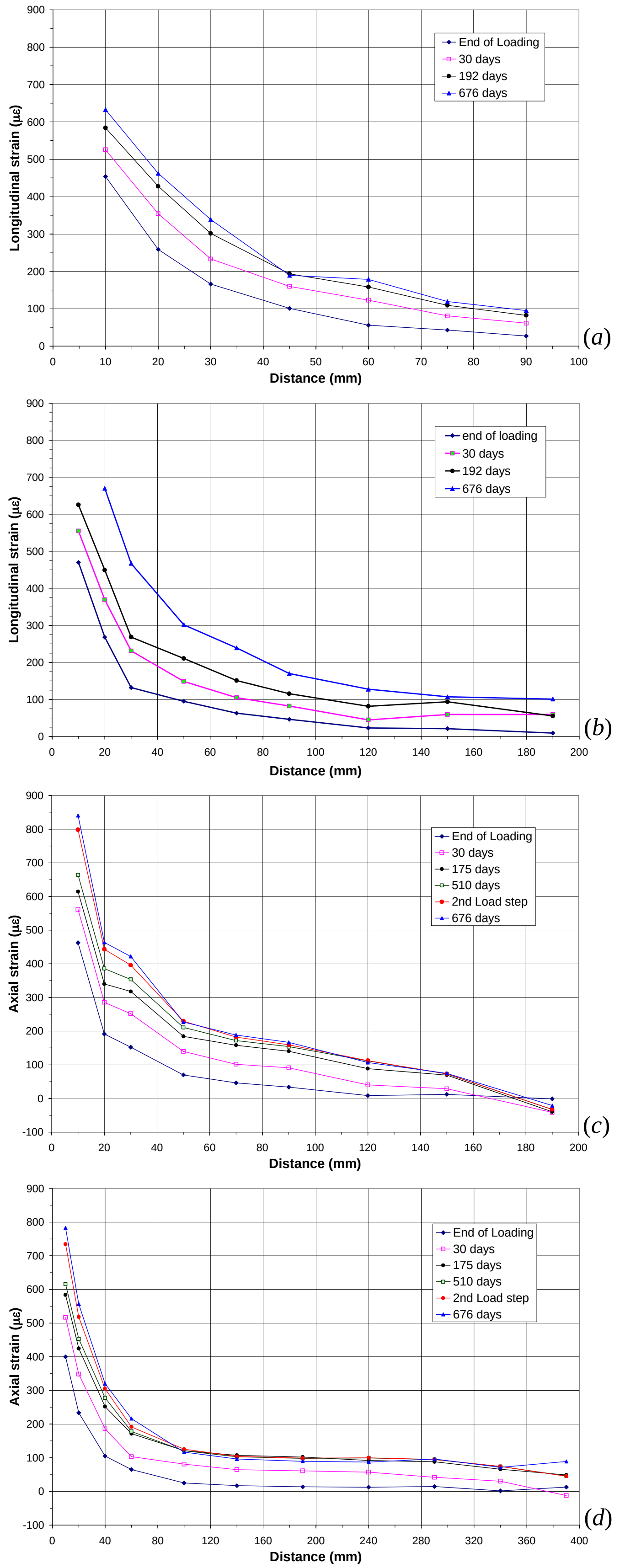


Figure 5. Evolution with time of strains along the bonded length, at different times. Specimen P1: (*a*) B.L.=100 mm, (*b*) B.L.=200 mm. Specimen P2: (*c*) B.L.=200 mm, (*d*) B.L.=400 mm.

6 SIMPLIFIED CREEP MODEL

In order to describe complex phenomena reported in previous paragraph, visco-elastic constitutive behavior for both interface and CFRP plate must be considered.

Due to shear stress redistribution with time, a convolution equation should be solved (Bazant, 1988). The simplest way to solve approximately the convolution integral is the Effective Modulus (EM) method. According to this theory, long term behavior of a visco-elastic material with a moderate time variation of stress can be described by using pseudo-elastic relations. For the problem at hand, neglecting deformation of concrete specimen, constitutive equations can be written as:

$$\tau = K_p(t)\, s_p, \quad \sigma_p = E_p(t)\,\varepsilon_p, \qquad (2)$$

where τ and s_p are interface shear stress and slip, respectively, while σ_p and ε_p are plate axial stress and strain. Moreover, $K_p(t)$ and $E_p(t)$ are interface shear effective stiffness and plate longitudinal effective modulus which can be expressed as:

$$K_p(t)=\frac{K_p(t_0)}{1+\phi_K(t,t_0)} \qquad E_p(t)=\frac{E_p(t_0)}{1+\phi_E(t)}, \tag{3}$$

where $K_p(t_0)$, $E_p(t_0)$ are elastic moduli at the time of loading t_0 and $\phi_K(t, t_0)$, $\phi_E(t)$ are coefficients of viscosity of FRP-concrete interface and CFRP plate, respectively.

The main advantage of EM method is that it is based on linear pseudo-elastic constitutive relations, which can be easily introduced in a bond-slip model.

To this purpose, a linear bond – slip model is adopted. Notation adopted for displacements and stress resultants is reported in Figure 6. Plate is subject to axial deformation only, i.e., bending of FRP reinforcement is neglected. This assumption is valid in the present case, due to negligible bending stiffness of FRP reinforcement with respect to concrete specimen counterpart. Since concrete specimen dimensions are much greater than FRP-reinforcement, strain in concrete can be neglected (ε_c=0), being very small compared to plate strains. Hence, FRP-concrete slip coincides with FRP axial displacement, i.e. $s_p \cong u_p$.

Governing equations are equilibrium, constitutive and compatibility conditions, which can be written in the form:

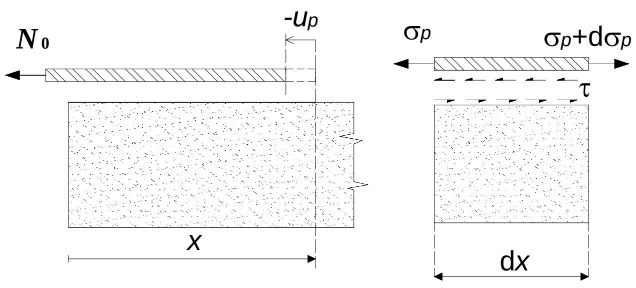
$$\frac{\mathrm{d}u_p}{\mathrm{d}x}=\frac{\sigma_p}{E_p(t)}, \qquad \frac{\mathrm{d}\sigma_p}{\mathrm{d}x}=\frac{\tau}{t_p}, \tag{4}$$

where t_p is plate thickness. Derivation of Equation 2b yelds:

$$\frac{\mathrm{d}^2 s_p}{\mathrm{d}x^2}=\frac{\mathrm{d}\varepsilon_p}{\mathrm{d}x}=\frac{1}{E_p(t)}\frac{\mathrm{d}\sigma_p}{\mathrm{d}x}. \tag{5}$$

Substituting Equation 2a in 5, governing differential equation and boundary conditions can be written as (see Fig. 6a):

$$\begin{cases} \dfrac{\mathrm{d}^2 s_p}{\mathrm{d}x^2} - \dfrac{1}{E_p(t)t_f}K_p(t)s(x)=0 \\ N(0)=N_0 \\ s_p(+\infty)=0 \end{cases} \tag{6}$$



(*a*) (*b*)

Figure 6. Bond – slip model for FRP-concrete interface.

As for bonding conditions, load application at the initial section (x=0) and null slip at $x\to+\infty$ have been considered. Linear differential Equation 6 can be given a closed form solution, so obtaining plate strain and shear stress, respectively:

$$\varepsilon_p(x,t)=\frac{N_0}{E_p(t)A_p}e^{-\alpha(t)x}$$
$$\tau(x,t)=\alpha(t)\frac{N_0}{b_p}e^{-\alpha(t)x} \tag{7}$$

where

$$\alpha(t)=\left(\frac{1}{E_p(t)t_p}\right)^{1/2}K_p(t)^{1/2}. \tag{8}$$

In order to compare experimental results with numerical predictions, initial tangent modulus has been evaluated from stiffness of interface in the linear range, so obtaining $K_p(t_0)$=450 N/mm^3. As for the interface creep coefficient ϕ_K, different values have been obtained at different time intervals from loading to match with experimental results. An exponential type law has been then calibrated by mean square fitting, so obtaining the expression:

$$\phi_K(t,t_0)=1.6\cdot(1-e^{-\frac{\Delta t}{155}}). \tag{9}$$

For time evolution of CFRP plate creep coefficient $\phi_E(t)$, the following simplified expression has been adopted:

$$\phi_E(t)=0.05\cdot(1-e^{-\frac{\Delta t}{130}}), \tag{10}$$

where asymptotic value 0.05 has been considered from creep tests on CFRP plates (Ascione et al. 2005).

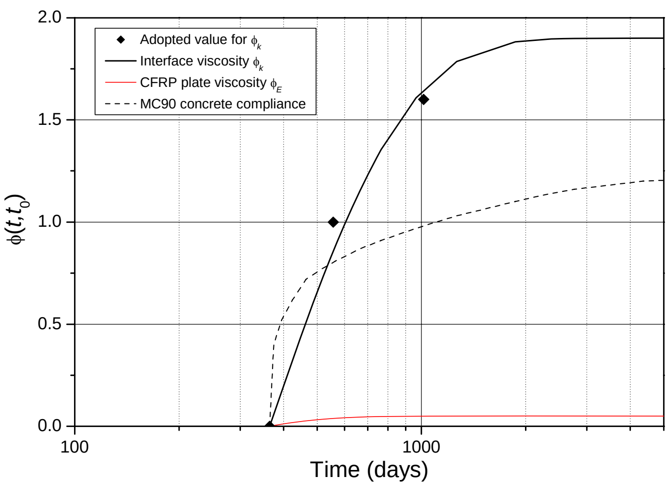


Figure 7. Creep functions adopted for interface (shear) and CFRP plate (axial strain), compared with MC90 creep function.

Figure 7 shows both simplified empirical laws for creep coefficients, together with creep coefficient $\phi(t,t_0)$ defined according to Model Code 90 for the considered concrete. It can be noted that interface compliance is higher than concrete creep, due to additional contribution related with viscosity of adhesive.

Figure 8 shows strain distribution along bonded plate for B.L.=100, 200 mm of specimen *P1* at different times from initial loading. In both cases very good correlation between experimental data and numerical predictions have been obtained.

Under constant load, the model properly describes strain distribution along the shortest bonded plate (B.L.=100 mm), which is smaller than transfer length (100÷150 mm), and is characterised by a stress redistribution with time throughout all its entire length. In spite of a very small strain variation with time at the beginning of bonded part (dashed line at x=0), due to creep deformation of FRP plate only, an appreciable strain increase can be observed at the opposite end of the plate.

In the second case (B.L.=200 mm), correlation is good in first part of bonded plate (60÷90 mm), where stress redistribution occurs. On the contrary, simplified model provides for a poor prediction in the final part of plate, being unable to describe the strain increase recorded by strain gauge with time.

Finally, comparison between experimental shear stress distribution along plates and numerical predictions (Fig. 9) is always very good for both bonded lengths. Experimental shear stresses have been evaluated starting from strain distribution through equilibrium relations (e.g. Mazzotti et al. 2005a) and considering an effective CFRP plate elastic modulus $E_p(t)$, reduced according to expression:

$$E_p(t) = \frac{E_p}{1+\phi_E}. \tag{11}$$

Stress redistribution with time gives smaller shear stresses close to loaded end and elongation of bonded length subject to shear (effective length).

Effective length is in fact proportional to $\alpha(t)N_0/b_p$, with $\alpha(t)$ defined in Equation 8. This coefficient increases with time because, as shown in Figure 7, creep compliance increase with time of interface K_p is greater than creep compliance of FRP plate itself ($E_p(t)$).

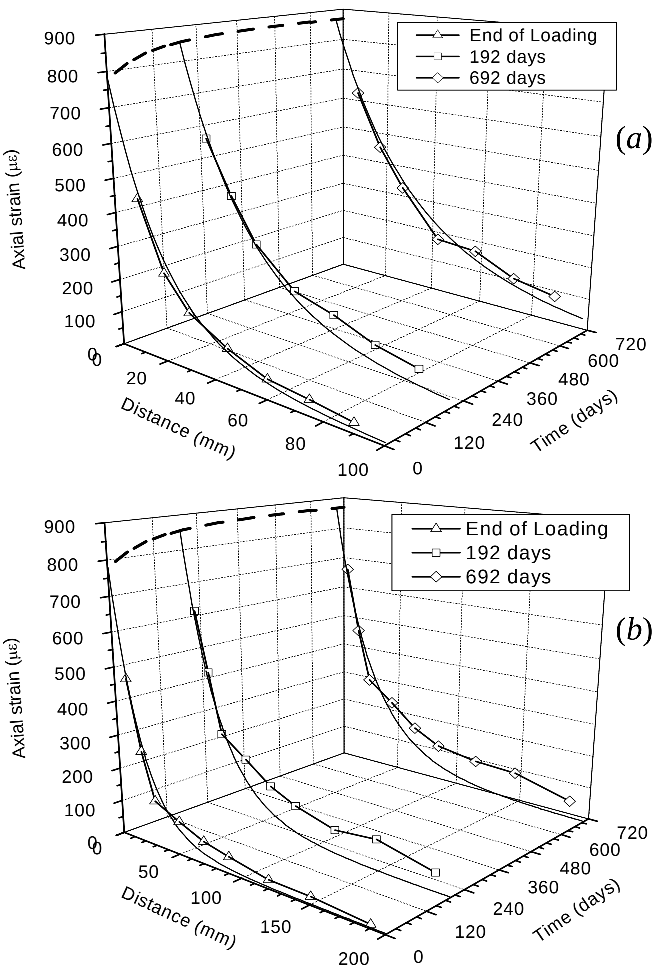


Figure 8. Evolution with time of strains along the bonded length, at different times. Comparison with numerical prediction for specimen *P1* – (*a*) B.L.=100 mm, (*b*) B.L.=200 mm.

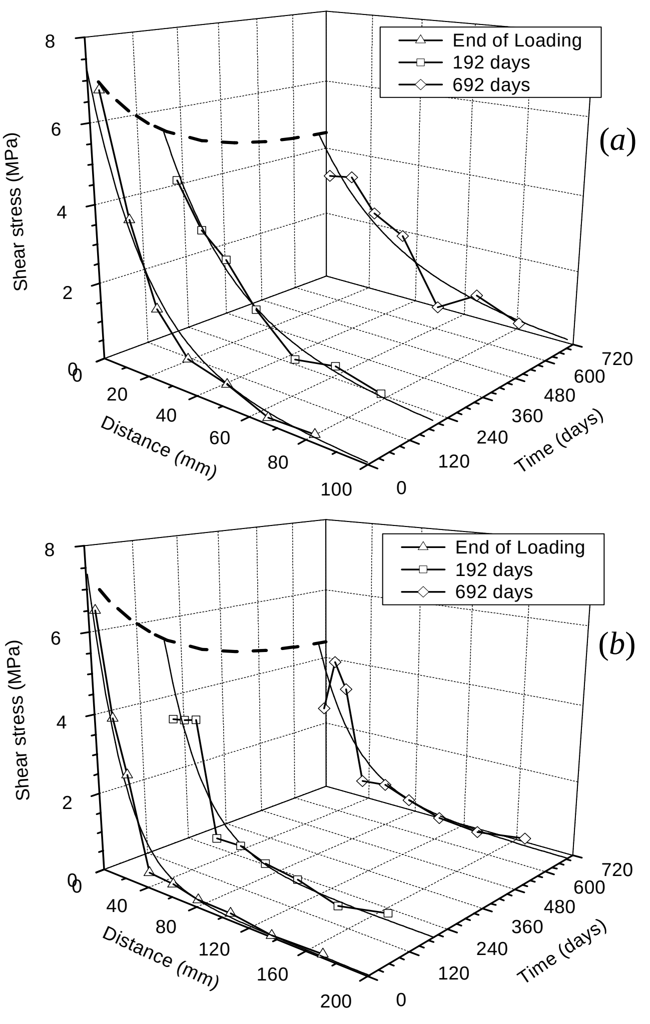


Figure 9. Evolution with time of shear stress along the bonded length, at different times. Comparison with numerical prediction for specimen *P1* – (*a*) B.L.=100 mm, (*b*) B.L.=200 mm.

7 AKNOWLEDGEMENT

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