A New Set-Up for FRP-Concrete Stable Delamination Test

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Synopsis: Results of an experimental campaign on FRP – concrete delamination are presented. Two specimens have been tested by using a particular experimental set-up where a CFRP plate has been bonded to concrete and its back side fixed to an external restraining system. The adopted set-up allows a stable delamination process and transition between two limit states (perfect bonding and fully delaminated plate) to be observed. Both strain gages along the FRP plate and LVDT transducers have been used. Starting from experimental data, shear stress – slips data have been computed. A non linear interface law has been calibrated and compared with analogous results obtained by a more conventional experimental set-up. A numerical bond – slip model has been used, adopting the above mentioned law for the FRP – concrete interface to simulate experimental tests. Numerical results are found to be in good agreement with experimental results.

Keywords: concrete; delamination; experimental study; FRP; interface

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INTRODUCTION

When using FRP (Fibre Reinforced Polymer) – plates or sheets to strengthen reinforced concrete beams, FRP – concrete bonding is very important. Since delamination is a very brittle failure mechanism, it must be avoided in practical applications. Bonding depends on mechanical and physical properties of concrete, composites and adhesive. Definition of a correct interface law is then important to predict ultimate failure load due to delamination. It is required to estimate the effectiveness of FRP-strengthening of RC (reinforced concrete) elements also under service loadings, due to significant stress concentrations close to transverse cracks in concrete [1].

Very few experimental studies can be found in literature which can be useful to calibrate a FRP – concrete interface law; both global data (applied force) and local data (e.g. strain measurements along the plate) are necessary [2, 3, 4, 5]. Furthermore, delamination is an instable process due to sudden elastic energy release and its experimental observation is very difficult in tests under displacement control due to the occurrence of snap-back behaviors[6]).

In the present paper, an experimental set-up is presented allowing for a stable delamination process. The specimen back-side is fixed to an external retaining system, i.e. concrete and CFRP (Carbon Fiber Reinforced Polymer) plate in that section has null displacement. The delamination process was developed with constant value of applied force, which was used to define fracture energy of interface law. Two specimens have been prepared with a number of closely spaced strain gages to measure strains along the FRP plate. Moreover, LVDTs (Linear Voltage Differential Transducers) have been used to measure plate elongation. Starting from experimental data, average shear stresses between two subsequent strain gages and corresponding shear slips have been computed. These data have been used to calibrate a non linear interface law, according to a procedure described in Mazzotti et al. (2003)[7]. Comparison between present interface law and the same law calibrated with adopting conventional delamination set-ups is presented.

Finally, a bond – slip model, originally presented in Savoia et al. (2003)[6] has been used. Concrete and plates are considered elastic materials and the proposed non linear interface law is adopted between two materials. Numerical results are found to be in good agreement with experimental results.

GEOMETRY AND MECHANICAL PROPERTIES OF SPECIMENS

Plate – concrete bonding has been investigated by testing two specimens (SP1 and SP2) with a CFRP plate bonded to a concrete block. Load is applied at one end of the plate, whereas the opposite extremity of both plate and concrete specimen is clamped to an external retaining system. For both specimens, the plate is 80 mm wide and a 500 mm long , representing the bonded length (Figure 1*a*).

Concrete block dimensions were 150×200×600 mm. They were fabricated using normal strength concrete. Concrete was poured into wooden forms and externally vibrated. The top was steel-troweled. Five 15 cm-diameter by 30 cm-high 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; after that, they were stored at room temperature with variable humidity inside the laboratory until tests occur.

Mean compressive strength f_{cm} = 52.7 MPa from compression tests and mean tensile strength f_{ctm} = 3.81 MPa from Brasilian tests have been obtained on cylinders at an age of 20 months. Mean value of elastic modulus has been found E_{cm}=30700 MPa and Poisson ratio ν=0.227.

For the composites plates, CFRP Sika CarboDur S plates, 80 mm wide (b_p) and 1.2 mm thick (h_p) have been used (Figure 1*a*). According to technical data provided by the manufacturer, the plates have a fiber volumetric content equal to 70 percent, and the epoxy matrix, minimum tensile strength of 2200 MPa and a mean elastic modulus E_p = 165,000 MPa.

Top surfaces of concrete blocks were grinded with a stone wheel to remove the top layer of mortar, just until the aggregate was visible (approximately 1 mm). The plates were bonded to the top surface of blocks using a 1.5 mm thickness of two – component Sikadur-30 epoxy adhesive, which does not require primer before bonding. The adhesive has a mean compressive strength of 95 MPa and a mean elastic modulus E_a = 12,800 MPa, according to the manufacturer datasheet. Curing period of all specimens was at least 1 day prior to testing.

In the present experimental investigation, the plate bonded length starts 100 mm from the front side of specimen and has a total bonded length of 500 mm (i.e. plate covers the whole concrete block (Figure 1*b*). Previous experimental investigations [8, 9] showed that adoption of this particular bonding system provides for a bond stress-slip behaviour and is less affected by boundary conditions and more representative of the material behaviour from cracked sections (i.e. as in the case of plate end debonding).

THE EXPERIMENTAL SETUP

Each concrete block was positioned on a rigid frame with a front side steel reaction element 60 mm high, to prevent global horizontal translation. Moreover a steel apparatus was clamped to the back side of the specimen in order to prevent, in that section, the displacements of both concrete and plate (Figure 2). Bonded length L_{tot} from initial to clamped section was 350 and 360 mm, respectively for SP1 and SP2. The opposite side of the plate was mechanically clamped with a two steel plates system that was free to rotate around the vertical axis. Traction force was then applied to the steel plates system by using a mechanical actuator (Figure 1*b*). Tests were performed under displacement control of the plate free end.

Instrumentation

A load cell has been used to evaluate the applied traction force. Along the CFRP plate, a series of thirteen strain gauges were placed on the centerline. In Figure 1*c*, spacing between strain gauges is reported, starting from the traction side of bonded part of CFRP plate. Two LVDTs were placed at the opposite sides of free bonded length in order to measure CFRP plate elongation and to verify the effectiveness of the clamping system (Figure 1*b*).

RESULTS OF DELAMINATION TESTS

The experimental results

Tests were carried out by performing a first load cycle up to 10 kN of traction force, followed by a monotonic loading at a rate of about 0.2 kN/s. During delamination a plate free end displacement rate of about 50 μm/s was adopted and tests conducted under displacement control.

In Figure 3, force-plate elongation curves of both specimens are reported; the curves are very similar and three main parts can be identified: the first branch is almost linear up to 70-80 % of maximum transmissible force. Beyond that value, stiffness degradation can be observed up to the onset of delamination, when the shear strength is attained at the beginning of bonding length. Subsequent delamination occurred at an almost constant value of applied force (F≈34 kN for both specimens). The delamination process lasted for about 15 seconds. Finally, when complete delamination occurred, the only resisting element was the CFRP plate, properly fixed at the extremity, and its behavior was linear elastic. Specimens were unloaded and reloaded again up to 50 kN. The unloading and reloading branches, as expected, are perfectly linear elastic and characterized by a tangent stiffness of about 42 kN/mm, and very close to the theoretical value of:

$$K_{tg} = \frac{E_p \cdot b_p \cdot h_p}{L_{tot}} = \frac{165 \cdot 80 \cdot 1.2}{355} = 44.6\,\text{kN/mm}\,. \tag{1}$$

Some analogies with the tension-stiffening effect can be drawn. Prior to delamination, a specimen can be considered in an uncraked state (usually defined as st*ate I*, where both concrete and reinforcement contribute to specimen stiffness). After complete delamination, only the CFRP plate carries the applied load (*state II*). The delamination process links these two limit states.

Effectiveness of the clamping system was verified by measurement of absolute displacement of the plate close to restrained section. The maximum displacement recorded by LVDT 2 was about 0.15 mm.

Longitudinal strains along the plate at different loading levels are reported in Figures 4*a-b*, both for SP1 and SP2 specimens. Corresponding values of applied force are reported in Figure 4*c*. Strains at $x = 0$ are obtained from values of applied force as $\varepsilon_0 = F / E_p A_p$.

For low-to-medium load levels of applied force, the effect of clamping is not significant and the classical distribution of strains along the FRP plate, already found in other experimental tests [2, 7, 9], can be observed. FRP strains are very regular showing an exponential decay starting from the loaded section ($x = 0$). This strain profile corresponds to a linear behavior of the interface. For high force levels, strains tend to be almost constant along the CFRP plate close to loaded end, due to onset of delamination phenomenon along the bonded length. Close to clamped section where delamination did not yet occur, an exponential decay behavior can be observed again.

With classical set-up [2, 7], complete delamination occurs during a snap-back branch [6] and it is not possible to conduct stable measures during the delamination process because it becomes a dynamic event, due to instantaneous releasing of elastic energy of the plate. On the contrary, the set-up adopted in this study provides a stable delamination process which can be fully observed. Experimental data measured during delamination are indicated by square marker in Figures 4*a-b*, whereas black dots are used for pre- and post-delamination data. The same distinction will be used in the next figures. After complete delamination, strains along the plate are constant and proportional to the applied force.

A further advantage of the proposed set-up is the possibility of obtaining a value of maximum force at delamination which can be considered equal to the asymptotic value of transmissible force by an anchorage of infinite length. Making use of the relation[10] between maximum transmissible force $F_{\max}$ and fracture energy G_f of a general non linear interface law:

$$F_{\max} = b_p \sqrt{2 E_p h_p G_f} \;, \qquad (2)$$

where E_p, h_p, b_p are elastic modulus, thickness and width of the plate, respectively, the value $G_{f,80} = 0.46$ N/mm was obtained. Subscript “80” indicates plate width.

Eqn (2) was previously derived by Wu et al. (2002)[11] for a bilinear interface law and by Brosens (2001)[12] in the case of a power law.

POST-PROCESSING OF EXPERIMENTAL DATA

Strains along the FRP plate at different loading levels were used to calculate shear stress – slip data. The origin of the x-axis is taken at the origin of the bonded plate. Considering an elastic behavior for the composite, the average value of shear stress between two subsequent strain gages can be written as:

$$\bar{\tau}_{i+1/2} = \frac{E_p A_p (\varepsilon_{i+1} - \varepsilon_i)}{b(x_{i+1} - x_i)}, \tag{3}$$

with A_p, E_p being cross section and elastic modulus of the composite.

Moreover, assuming that perfect bonding (no slip) occurs at the end of bonded plate and concrete strain is negligible with respect to FRP counterpart, integration of the strain profile gives the following expression for the slip at x, with $x_i \le x \le x_{i+1}$:

$$s(x) = s(x_i) + \int_{x_i}^{x} \varepsilon(x)\mathrm{d}x = s(x_i) + \frac{(\varepsilon_{i+1} - \varepsilon_i)}{(x_{i+1} - x_i)}\frac{x^2}{2} + \varepsilon_i x, \tag{4}$$

where the initial condition $s(0) = 0$ is assumed.

Average value $\bar{s}_{i+1/2}$ of slip between x_i and x_{i+1} is then computed. The obtained shear stress-slip couples ($\bar{\tau}_{i+1/2}$, $\bar{s}_{i+1/2}$) are reported in Figures 5*a, b* for SP1 and SP2 specimens, respectively. Curves related to delamination phase are reported with square markers. Adoption of this set-up allows complete delamination to be observed and also the softening branch, usually identified with a limited number of very scattered points, is properly described. Note that some small negative values of shear stress can be found in the softening branch; these values are obtained from the initial portion of the plate where complete delamination has already occurred and strains should be perfectly constant according to theory. In experimental tests, small strain variations have been recorded. According to eqn. (3), these small changes can affect the shear stress sign, providing negative values when theoretically they should be null values. For this reason all experimental data were considered in the calibration procedure described in the next paragraph.

CALIBRATION OF A NON LINEAR INTERFACE LAW

According to the procedure described in Mazzotti et al.[7], shear stress – slip data are used to calibrate a non linear FRP – concrete interface law. All the data related to both experiments are grouped together (Figure 6) and an interface law recently proposed by the authors in terms of fractional law:

$$\tau = \tau_{\max}\frac{s}{\bar{s}}\frac{n}{(n-1) + (s/\bar{s})^n} \tag{5}$$

is adopted, where τ_{max} is the peak shear stress, $\bar{s}$ the corresponding slip, and n is a parameter mainly governing the softening branch. Values of $n > 2$ are required in order to obtain positive and finite values of fracture energy.

Both shear stress – strain data ($\bar{\tau}_{i+1/2}$, $\bar{s}_{i+1/2}$) and fracture energy G_f are used to evaluate the three unknown parameters of interface law in eqn (5), i.e., τ_{max}, $\bar{s}$, n. A least square minimization between theoretical and experimental shear stress – strain data is performed, adopting as a constraint in the minimization procedure the value of fracture energy obtained from eqn (2). Further details on numerical procedure can be found in Mazzotti et al. [7].

The values $\tau_{max} = 6.43$ MPa, $\bar{s} = 0.044$ mm, $n = 4.437$ have been obtained. In Figure 6 the proposed interface law is reported, together with all shear stress – slip experimental data. It is worth noting that the proposed law is in good agreement with experimental data both for slips smaller than $\bar{s}$ and in the softening branch where experimental results are more scattered.

Comparison with other tests

The results presented here can be compared with results reported in Mazzotti et al. [7, 9], adopting the same concrete and specimen dimensions and the same CFRP plates. In this study, classical delamination set-up was adopted, with free back side of the plate. Different bonded lengths were considered and further details can be found in Mazzotti et al.[7, 9]. From these tests, the maximum transmissible force (considered as an asymptotic value) was evaluated by a numerical interpolation of values of applied forces at failure for different bonded lengths and a value F_{max}=36.2 kN was obtained. The actual maximum force value, corresponding to plateau of Figure 3, is about 34 kN with a 6% difference. According to eqn. (2), fracture energy is slightly smaller than in previous tests, where $G_{f,80}$ = 0.517 N/mm was obtained.

In Figure 7, a comparison between interface laws calibrated by using present and previous experimental data is reported. The curves are very similar and only in the softening branch the present curve is more sharply descending due to better experimental description of this region. Hence, methodology of interface law identification proves to be very reliable because both variations in test method do not remarkably affect the final results.

NUMERICAL SIMULATIONS OF TESTS

Experimental tests have been numerically simulated, in order to verify the accuracy of the proposed plate – concrete interface law. A bond-slip kinematic model was adopted and originally presented in Savoia et al. (2003)[10]. The model is based on the assumption of pure extension for two different materials, concrete and FRP plate (no bending). Linear elasticity is adopted for concrete and plate, whereas the non linear law (5) is used for the interface between two materials. Then, a finite difference discretization is used for the unknown variables (axial displacements and stress resultants of concrete and plate).

In the numerical model, both concrete and FRP plate are restrained at the end section and bond length is L = 355 mm. Comparison between experimental and numerical results are reported in Figures 3, 8 and 9.

In Figure 3, plate elongation-force curve is compared with experimental curves. As previously described, the behaviour of the specimen is a transition between *State I* condition for low level loads (both stiffness contributions of concrete and FRP plates) and *State II* condition after FRP delamination (FRP plates only contribute to specimen stiffness). Hence, the post-delamination branch is now stable and has followed up to complete delamination in the experimental tests. The results confirm that the proposed interface law provides for a good prediction of delamination load.

Strain distributions in the FRP plate along the bonded length are reported in Figure 8. Experimental data from the SP1 specimen are considered. Numerical results are generally in very good agreement with the experimental data (considering the unavoidable scattering of experimental results at higher load level). The behavior for low load levels is well predicted. There is very good agreement between numerical and experimental results for very high loads, i.e., during plate delamination (square markers). The numerical model was able to correctly follow progressive plate delamination, as it occurred in experimental tests. Comparison between shear stress distribution along the plate, obtained by post-processing experimental data and by numerical simulation is also reported, both for low force levels (Figure 9*a*) and during the delamination phase (Figure 9*b*). Good agreement is found with results obtained by experimental data, although the last ones are sometimes scattered; in any case, maximum value of shear stress and also its position and the gradient of shear stress distribution along the bonded length are well predicted.

CONCLUSIONS

Results from a set of experimental delamination tests have been presented. A particular set-up was designed, providing for stable delamination. Applied force, displacements and strains along FRP plate were measured. Complete progressive delamination was observed and the corresponding value of applied force was used to estimate the fracture energy of interface law.

Force-elongation curve can be divided into three main branches: the first one is almost linear up to the onset of delamination; the second one represents delamination process and has a constant value of applied force; in the third one, complete delamination occurred and the load is then directly transferred to the clamped end of CFRP plate.

An interface shear stress – slip law has then been calibrated starting from experimental data, and adopting the value of fracture energy as a constraint in the minimization procedure between experimental and predicted values. Finally, numerical simulations were performed and results are found to be in good agreement with experimental results.

Experimental tests on FRP – concrete delamination are fundamental to obtain data to establish the maximum value of strain in FRP reinforcement prior to end or intermediate debonding from concrete substrate, see for instance Refs. [13], [14], [15]. In the last two references, maximum admissible strain in FRP reinforcement has been defined as a function of mechanical/geometrical properties of reinforcement and of fracture energy of FRP – concrete interface, where the latter has been estimated from a statistical analysis of results of delamination tests. Moreover, values of maximum shear stress before delamination have been adopted in Ref. [14] as the basis for verification of FRP – strengthened structures under service loadings.

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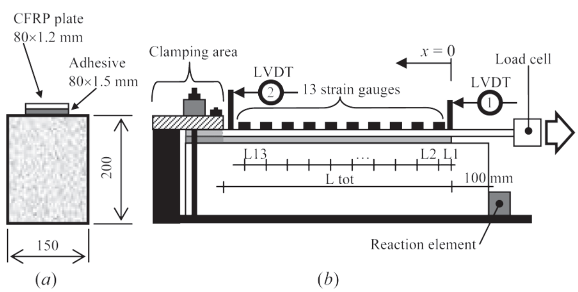


L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13
10	20	20	20	30	30	30	30	30	30	30	30	30

(*c*)

Figure 1—Experimental set-up: (*a*) Specimen transverse section, (*b*) side view with instrument positions and CFRP plate clamping system, (*c*) spacing between strain gauges (mm) along the CFRP plate.

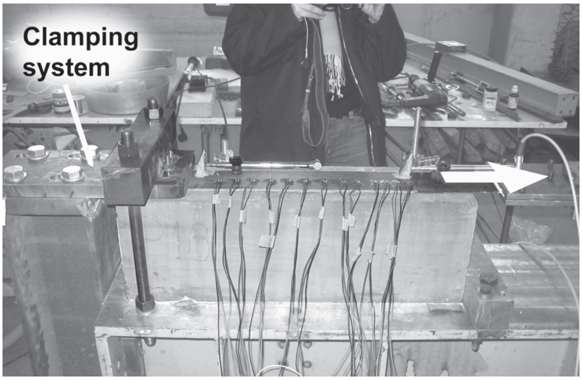


Figure 2—Experimental set-up: view of the clamping system for concrete and plate at the opposite sides of the specimen.

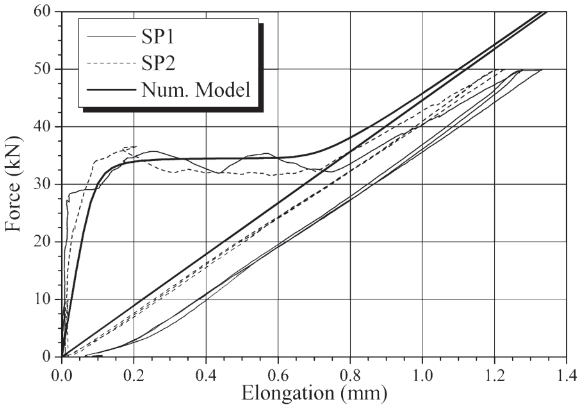
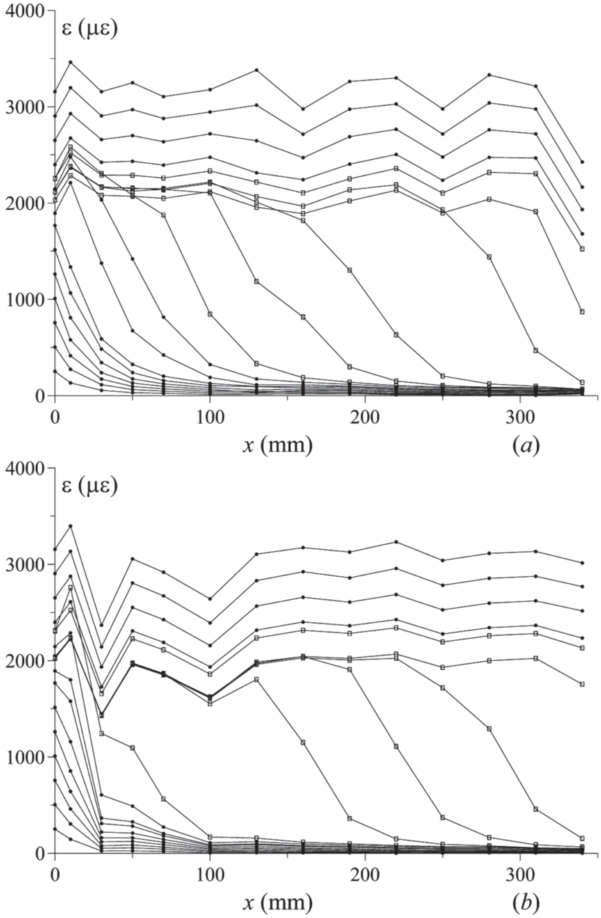


Figure 3—Force-plate elongation curves from experimental tests (specimens SP1, SP2) and numerical simulations.



L_{tot}	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13
355	4	8	12	16	20	24	28	30	34	40	42	46	50

(c)

Figure 4—Profiles of experiemntal strains in CFRP plates along the bonded lengths of (*a*) SP1 and (*b*) SP2 speciments. (*c*) Loading levels; —⊟— measures taken during the delamination phase (load level equal to 34 kN).

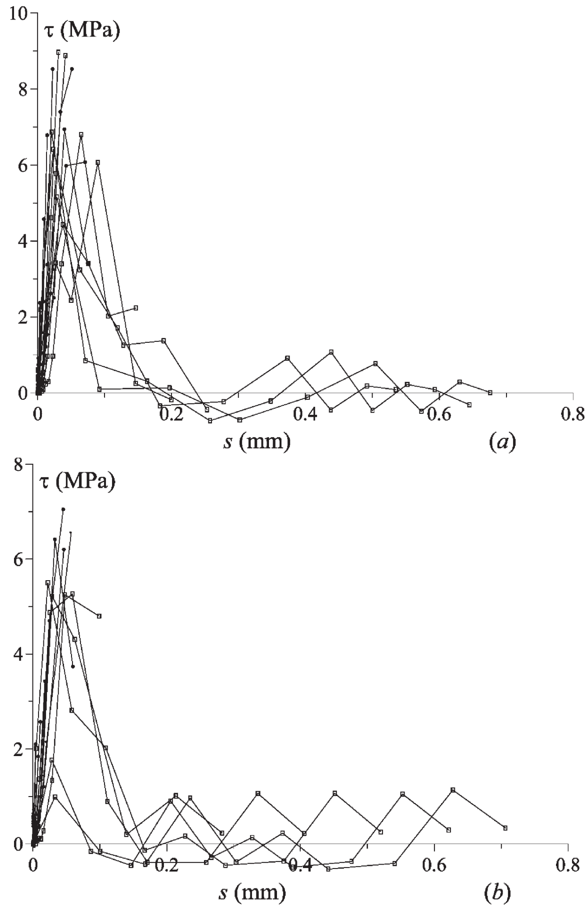


Figure 5—Shear stress—slip data obtained from post-processing experimental results from (*a*) SP1 and (*b*) SP2 specimens; —□— measures taken during delamination phase.

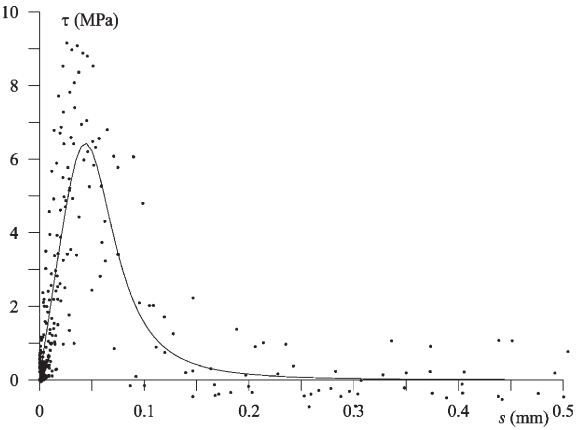


Figure 6—Shear stress-slip data obtained by post-processing experimental results from SP1 and SP2 specimens and proposed interface law.

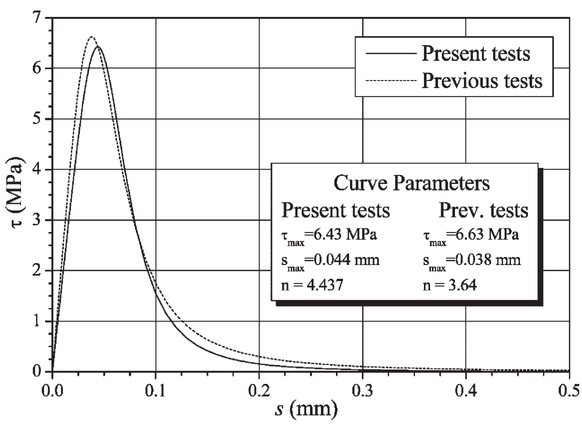


Figure 7—Comparision between interface laws calibrated with present experimental results and previous results by Mazzotti et al. [9]

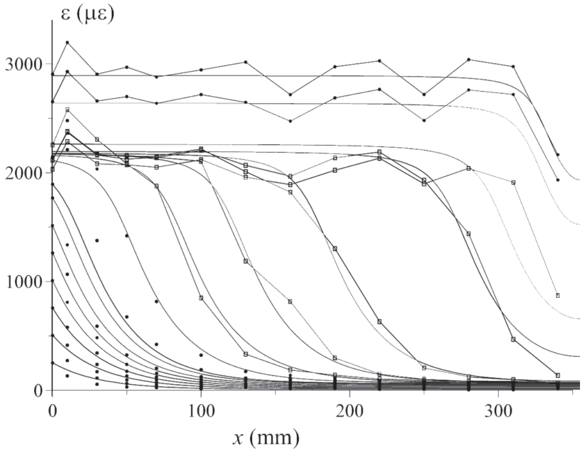
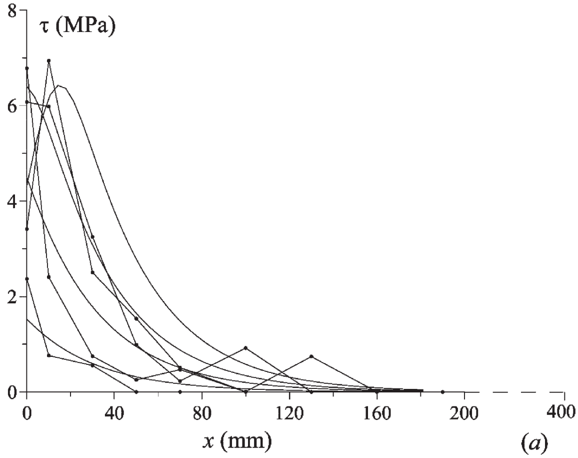


Figure 8—Profiles of strains along FRP plate: comparison between numerical and experimental results from specimen SP1; —⊟— measures taken during delamination phase.



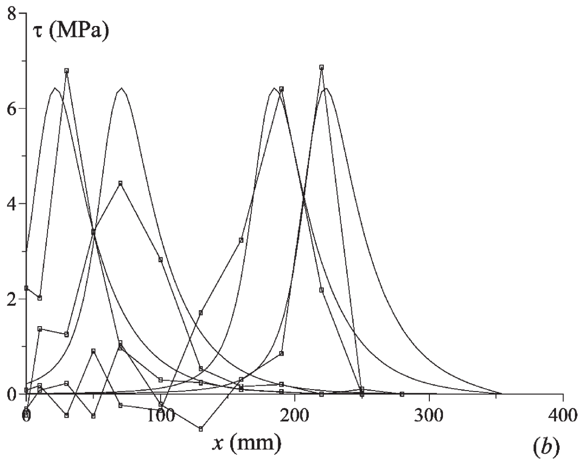


Figure 9—Profiles of shear stressed along FRP plate for specimen SP1. Comparison between numerical and experimental results for: (*a*) low and (*b*) high loading levels; —⊟— measures taken during delamination phase.