Concrete interface relationships under monotonic and cyclic actions

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ABSTRACT: External bonding of fibre reinforced polymer (FRP) composites has become a popular technique used worldwide for strengthening existing reinforced concrete (RC) structures. Interaction phenomena having place at the FRP-to-concrete interface deeply affect the overall behaviour of RC beams externally strengthened by FRP. Consequently, several proposals have been carried out for describing the relationship between FRP-to-concrete relative displacements and interface shear stress. The present paper is mainly devoted to comparing the effectiveness of different identification methods for shear-stress-relative-slips law throughout the FRP-to-concrete interface. Several experimental results (pull-out tests under monotonic and cyclic actions), both available in the scientific literature and carried out directly by the authors, are utilised with this aim. The first cyclic delamination tests, carried out by the authors, allow a preliminary investigation on the influence of cyclic external actions on the bond of FRP reinforcement to the concrete substrate.

1 INTRODUCTION

Peeling phenomena resulting in premature failures are quite frequent in reinforced concrete (RC) beams externally strengthened by FRP sheets or laminates. Several scientific contributions have been proposed by researchers in the last years concerning both interface stress evaluation and FRP-to-concrete interface behaviour.

The shear-stress-relative-slip relationship, describing the FRP-to-concrete interface law, can be identified starting from the experimental results of pull-out tests; the distribution of shear stresses could be, in fact, obtained by the variation of axial stress and strain throughout the FRP and the corresponding slips values by integrating the axial strains measured during the test. In this way a direct identification method (DirIM) is put in place since the interface law is calibrated directly with respect to experimental values of shear stresses and relative slips.

Although plenty of alternative models are available in the literature (i.e. Savoia et al., 2003) to describe FRP-to-concrete interface interaction, a simplified bi-linear relationship can reproduce the key aspects of the interface behaviour as pointed out by the comparative study carried out by Lu et al. (2005).

Such a way it was followed by Faella et al. (2003) to calibrate an interface relationship based on the experimental results presented by Chajes et al. (1999). Although such direct identification method is very easy under the analytical standpoint, the drawback of the method is that the distribution of shear stresses cannot be directly compared with data provided by the pull out tests, because both interface shear stresses and local displacements cannot be directly measured during the usual pull-out tests.

In order to overcome such problem, the indirect identification procedure (IndIM) can be pursued to calibrate an interface relationship starting from the availability of axial strain evolution in FRP plate at different load levels up to debonding failure: once a bi-linear interface relationship has been assigned, the corresponding theoretical strain distributions can be evaluated and
compared with experimental data; the procedure is iterative and ends when the difference between theoretical and experimental strains is less than a prefixed tolerance (Faella et al., 2003).

The present paper is aimed at evaluating and comparing the results obtained by using both DirIM and IndIM to identify FRP-to-concrete interface law by using experimental results of pull-out tests under monotonic and cyclic actions, either available in the scientific literature (Chajes et al., 1999) or carried out directly by the authors (Nigro et al, 2008).

2 EXPERIMENTAL DATA

The following mechanical parameter have been used to perform the theoretical analyses:
- Pull-out tests under monotonic actions carried out by Chajes et. al. (1999) on CFRP plates (Young’s modulus $E_f = 108380$ MPa, width $b_f = 25.4$ mm, thickness $t_f = 1.020$ mm) applied on concrete prisms (cylinder mean strength $f_{cm} = 36.40$ MPa, width $b_c = 228.6$ mm).
- Pull-out tests under monotonic and cyclic actions carried out by the authors on CFRP sheets (Young’s modulus $E_f = 230000$ MPa, width $b_f = 100$ mm, thickness $t_f = 0.166$ mm) applied on concrete prisms with cylinder mean strength $f_{cm} = 23.82$ MPa, width $b_c=150$ mm.

FRP bond length, $L_b$, and test failure load, $P_{test}$, are given on the left hand of Table 1 for experimental tests carried out by Chajes et al. (1999) and the right hand for tests provided by the authors.

Each test has been identified by a label “XY_n”; X indicates the type of reinforcement (L=Laminate; S=Sheet), Y indicates the type of action (M=Monotone; C=Cyclic), n is the progressive test number.

Table 1. FRP bond length $L_b$ and test failure load $P_{test}$

<table>
<thead>
<tr>
<th>Label</th>
<th>$L_b$ [mm]</th>
<th>$P_{test}$ [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LM_1$^a$</td>
<td>50.8</td>
<td>8.10</td>
</tr>
<tr>
<td>LM_2$^a$</td>
<td>101.6</td>
<td>12.81</td>
</tr>
<tr>
<td>LM_3$^a$</td>
<td>152.4</td>
<td>11.92</td>
</tr>
<tr>
<td>LM_4$^a$</td>
<td>203.2</td>
<td>11.57</td>
</tr>
<tr>
<td>SM_1$^b$</td>
<td>400</td>
<td>21.41</td>
</tr>
<tr>
<td>SM_2$^b$</td>
<td>400</td>
<td>21.81</td>
</tr>
<tr>
<td>SM_3$^b$</td>
<td>400</td>
<td>21.24</td>
</tr>
<tr>
<td>SC_4$^b$</td>
<td>400</td>
<td>20.95</td>
</tr>
<tr>
<td>SC_5$^b$</td>
<td>400</td>
<td>20.47</td>
</tr>
</tbody>
</table>

$^a$ Chajes et al.,1999 [1] $^b$ Present paper

The Single Shear Test (SST) setup layout used for the tests performed by the authors is depicted in Figure 1. Tests were carried out under a servo-hydraulic MTS testing machine at the laboratory of the Department of Structural Engineering (DIST) of the University of Naples Federico II. Monotonic tests were performed in a displacement control way, while cyclic tests were developed in two main phases:
- force control cyclic actions: four series characterized by ten cycles of load-unload (without load reversal) up to different load values; the maximum value achieved was equal to 90% of the average delamination load recorded during the monotonic tests;
- displacement control monotonic action: once the last load cycle was applied, monotonic actions were assigned up to the specimen failure.

![Figure 1. Test setup layout.](image-url)
3 IDENTIFICATION METHODS

According to the study made by Taljsten (1996), derived by linear fracture mechanics, the maximum value $F_{\text{max}}$ of the force applied to the FRP-to-concrete joint can be expressed as follows:

$$ F_{\text{max}} = \sqrt{2G_F E_f t_f b_f} \quad (1a) $$

$$ F_{\text{max}} = \sqrt{2G_F E_f t_f b_f} \left[ \frac{L_b}{L_{\text{eff}}} \left( 2 - \frac{L_b}{L_{\text{eff}}} \right) \right] \quad (1b) $$

$G_F$ and $L_{\text{eff}}$, depending both on the mechanical properties of the adhesive FRP-to-concrete interface, are respectively the specific fracture energy of the interface and the effective transfer length. Equation (1a) can be applied only if $L_b > L_{\text{eff}}$. If $L_b \leq L_{\text{eff}}$ a smaller value of the ultimate force has to be expected according to the (1b) relationship.

Elasto-softening bilinear relationship is one of the most widely accepted expressions for the interface relationship and fracture energy; three mechanical parameters completely identify such relationship (maximum shear stress $\tau_{\text{max}}$, ultimate slip $s_u$, and elastic stiffness $k_e$), but obviously knowledge of $G_F$, derived by solving equations (1a) and (1b), is not sufficient for determining such parameters.

As a matter of principle, two approaches are possible to calibrate an interface relationship; they are briefly outlined in the following sections.

3.1 Direct Identification Method (DirIM)

The first approach starts from the experimental strains measured during the test: the distribution of shear stresses can be roughly evaluated through equilibrium of the axial stresses depending on the axial strain; the corresponding slip values can be obtained by integrating throughout the FRP the axial strains. In such way, a couple of values $(\tau, s)$ that can be “directly” used to calibrate the $\tau$-$s$ relationship, can be determined: a possible theoretical law relating $\tau$ and $s(x)$ can be obtained by some parameters collected in the unknown vector $q$ (i.e. $q = (s_e, \tau_{\text{max}}, s_u)$ in the case of bi-linear law)

$$ \tau = \tau(s(x), q) \quad , $$

(2)

through a numerical regression, such as the least square method. This law can be (directly) calibrated with the aim of obtaining the value $\bar{q}$ that determine the law best fitting the couples $(\bar{\tau}, \bar{s})$:

$$ \bar{q} = \arg \min_q \left\{ \sum_{i=1}^{m} \sum_{j=1}^{m} \left[ \tau_{(i)}(x, q, \tau_{(i)}, q)^2 \right] \right\} \quad \text{with } j=1...m \text{ and } i=1...n \quad (3) $$

$m$ is the number of strain gauges available for the experimental test and $n$ the number of registered load levels up to failure.

3.2 Indirect Identification Method (IndIM)

An alternative procedure using the experimental measures in terms of axial strain values $\varepsilon_{j, f(1)}$ recorded at distance $x_j$ under the force $F^{(1)}$ can be conceived for “indirectly” calibrate the $\tau$-$s$ interface relationship definite by vector of parameters $q$. In particular, for each set of parameters collected in $q$ a given interface law is defined and the corresponding theoretical value $\varepsilon_{j, f(1)}$ of the axial strain developed in the FRP plate at a distance $x_j$ under the force $F^{(1)}$ can be evaluated. Numerical procedures, such as finite differences, can be generally utilized to determine $\varepsilon_{j, f(1)} = \varepsilon_{f(1)}(x_j, F^{(1)}, q)$; however, closed-form solutions are currently available for
some shape for the interface law, such as the bi-linear one reported in Faella et al. (2003). Once the theoretical values of the axial strains have been evaluated for every available load step and measure station, the optimal value of the vector of parameters can be evaluated through a numerical regression on the measured values $\varepsilon_{f,j}^{(i)}$ of the axial strains developed in FRP.

$$\bar{q} = \arg \min_q \sum_{i=1}^{n_1} \sum_{j=1}^{n_2} \left[ \varepsilon_{f,j}^{(i)} - \varepsilon_f \left( f_j, F^{(i)} ; q \right) \right]^2.$$ (4)

4 SHEAR STRESSES AND RELATIVE SLIPS

With reference to experimental data reported in Table 1 both DirIM and IndIM have been applied in order to plot the $\tau$-$s$ relationship and derive the corresponding specific fracture energy $G_F$, computed by totaling up the area under the bi-linear curve.

Table 2. Specific fracture energy $G_F$: (DirIM) Vs (IndIM)

<table>
<thead>
<tr>
<th>Label</th>
<th>LM_1</th>
<th>LM_2</th>
<th>LM_3</th>
<th>LM_4</th>
<th>SM_1</th>
<th>SM_2</th>
<th>SM_3</th>
<th>SC_4</th>
<th>SC_5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_F$ (DirIM)</td>
<td>0.45</td>
<td>1.20</td>
<td>0.86</td>
<td>0.78</td>
<td>0.66</td>
<td>0.86</td>
<td>0.48</td>
<td>0.67</td>
<td>0.67</td>
</tr>
<tr>
<td>$G_F$ (IndIM)</td>
<td>0.73</td>
<td>1.75</td>
<td>1.03</td>
<td>0.98</td>
<td>0.66</td>
<td>0.67</td>
<td>0.72</td>
<td>0.72</td>
<td>0.65</td>
</tr>
<tr>
<td>$G_F$, (IndIM)/$G_F$, (DirIM)</td>
<td>1.61</td>
<td>1.46</td>
<td>1.20</td>
<td>1.26</td>
<td>0.99</td>
<td>0.78</td>
<td>1.50</td>
<td>1.07</td>
<td>0.98</td>
</tr>
</tbody>
</table>

Table 2 shows that IndIM leads to specific fracture energy $G_F$ larger than those computed by DirIM in almost all analyzed cases. Moreover, in the case of experimental tests carried out by the authors, values of $G_F$ obtained with IndIM are as stable as the measured failure loads $P_{\text{test}}$, confirming the superior accuracy of IndIM with respect to DirIM.

Some of the most representative bi-linear interface relationships obtained by applying both DirIM and IndIM (LM_3, LM_4 and SM_1, SM_2) are reported in Figure 2 and Figure 3.

Figure 2. Bi-linear interface relationship: (DirIM) Vs (IndIM).

Figure 3. Bi-linear interface relationship: (DirIM) Vs (IndIM).
The two methods lead to results that could be even significantly different, especially in terms of ultimate slips. Furthermore, the ascending branches of DirIM curves are characterized by a lower slope with respect to IndIM. Comparisons between the theoretical and experimental values of the axial strains throughout the FRP plate are reported, for different values of load test, in Figure 4. The results are referred to test SM_3. The theoretical strain values have been obtained by closed-form solutions reported in Faella et al. (2003)

![Figure 4. Theoretical and experimental strains: (DirIM) Vs (IndIM)](image)

The theoretical values of strains obtained assuming the interface relationship identified though IndIM are much closer to the observed ones than the values which can be derived assuming the $\tau$-s relationship calibrated by means of DirIM.

In Figure 5 experimental strains recorded throughout the FRP plate at different values of force values (expressed as a percentage of $P_{test}$) are reported with reference to both monotone test (SM_3) and cyclic test (SC_4).

![Figure 5. Comparison of experimental strains: monotone Vs cyclic.](image)

![Figure 6. Comparison of shear interface stresses: monotone Vs cyclic](image)

The figure shows that during the cyclic test, at the same values of external load, the recorded strains are generally larger than those recorded during the monotonic test. This is a result of a migration of the interface shear stresses due to the cyclic nature of the imposed action, as clearly shown by the shear stress profiles depicted in Figure 6.

It is noted that the specific fracture energy mean values related to monotone tests are very close to those obtained with reference to cyclic ones; such result is clearly shown in Table 3 where average $G_F$ values, obtained by both DirIM and IndIM for monotone (SM_1, SM_2 and SM_3) and cyclic tests (SC_4 and SC_5), are reported; such result is in agreement with the corresponding experimental mean failure load (see Table 3).

| Table 3. Fracture energy mean values: Monotone Vs Cyclic |
|---------------------------------|------------|-------------|
| IndIM $G_F$ | monotone | cyclic | cicl/mon |
| DirIM $G_F$ | 0.666 | 0.670 | 1.006 |
| $P_{test}$ (mean value) | 21.48 | 20.71 | 0.964 |

Bi-linear interface relationships obtained by using IndIM are reported in Figure 7 starting
from both monotonic and cyclic tests outcomes. The comparison between the interface relationships shows that the ascending branches of curves referred to cyclic tests are characterized by a lower slope; however they are reasonably close one another for all the four tests, regardless of the monotonic or cyclic nature to the applied actions. Finally, the theoretical strain profile along the specimen, obtained by using the IndIM, and the experimental strains recorded during test SC_4 are reported in Figure 8; such figure shows that IndIM allows obtaining shear stress-slips relationship based on strains very close to the experimental ones confirming the remarkable accuracy of IndIM even for cyclic tests.

5 CONCLUSIONS

The present paper discuss the aspect of how utilizing experimental data obtained through pull-out tests for calibrating the \( \tau - s \) relationship at the FRP-to-concrete interface under both monotonic and cyclic actions. Referring to two possible identification methods (DirIM and IndIM), the following conclusions are drawn: a) the two approaches for calibrating the interface law usually lead to results that could be even significantly diverse, in particular regard to ultimate slips. Moreover ascending branch of DirIM curves are characterized by a lower slope with respect to IndIM; b) IndIM leads to theoretical strain curves more consistent to the experimental strains. The first cyclic pull-out tests have allowed a preliminary investigation on the influence of cyclic external actions on the bond FRP reinforcement to the concrete substrate. First results show that they have significantly influenced the strain profile during the test inducing a migration of shear stress distribution at interface, but they have not influenced the failure load.

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REFERENCES