SENSITIVITY OF FRP-CONCRETE BOND BEHAVIOR TO MODIFICATION OF THE EXPERIMENTAL SET-UP

Claudio MAZZOTTI  
Associate Professor, Claudio.mazzotti@unibo.it  
DICAM – Structural Engineering, University of Bologna, Italy

Barbara FERRACUTI  
PhD, barbara.ferracuti@unibo.it  
DICAM – Structural Engineering, University of Bologna, Italy

Antonio BILOTTA  
PhD, antonio.bilotta@unina.it  
DIST – Structural Engineering, University of Naples Federico II, Italy

Francesca CERONI  
Assistant professor, ceroni@unisannio.it  
DING - Structural Engineering, University of Sannio, Italy

Emidio NIGRO  
Associate Professor, emidio.nigro@unina.it  
DIST – Structural Engineering, University of Naples Federico II, Italy

Marisa PECCE  
Full Professor, pecce@unisannio.it  
DING - Structural Engineering, University of Sannio, Italy

Abstract

The paper deals with the results of an experimental program aimed at investigating the bond behavior of different types of Externally Bonded Carbon (EBR) plates. The activity falls within an international Round Robin Test organized by the fib TG 9.3. The same experimental program has been carried out simultaneously by the Laboratory of Structural Testing of the University of Bologna and the Laboratory of Structural Engineering of the University of Naples Federico II and consisted in 18 bond tests on concrete prisms strengthened with EBR carbon plates. Each lab performed the bond tests according to two different set-ups for the Monotonic Single Shear Tests (SST). The comparisons of the results of tests carried out by the two laboratories according to the same loading scheme, but realized with different experimental set-ups are aimed to investigate the influence of the testing procedure on the bond strength. The results are analyzed in terms of debonding load, failure modes and strain distribution.

Keywords: Bond test, Debonding, EBR plates, Experimental set-up, FRP.

1. Introduction

It is well known that the high performance of Fiber Reinforced Polymers (FRP) materials, used as external strengthening of existing Reinforced Concrete (RC) elements, often cannot be properly exploited since this strengthening system typically fails due to the loss of bond at the concrete/FRP interface (debonding failure). Therefore, the evaluation of the bond strength at the interface is a key issue in the design procedure.

Several formulations are now available in the technical literature and in national and international codes to evaluate the maximum tensile stress in the external reinforcement at
debonding as a function of concrete and FRP mechanical properties [1-5]. Moreover, the numerical parameters included in most formulations have been usually calibrated by using experimental results of bond tests. Therefore, many bond tests have been carried out in the past [5-9] to measure the debonding load and to investigate the failure conditions of concrete elements externally bonded with FRP plates and sheets.

Several experimental set-ups have been proposed so far in literature to investigate the bond strength, but a standard procedure hasn’t been identified yet. The following classification of test set-up is commonly accepted [5], [10], [11]: (a) double-shear pull-pull tests; (b) double-shear push-pull tests; (c) single-shear pull-pull tests; (d) single-shear push-pull tests; (e) beam (or bending) tests. These arrangements are based on the definition of the loading condition of the element and on the possible symmetry of the system.

In order to extend the results of bond tests to various types of strengthening (flexural, shear, torsion), the pull-pull test set-up provides the load condition more similar to the actual one in RC elements. However, it is also the most difficult to realize with a reliable set-up and it could underestimate the bond strength due to the influence of detailing [12-14].

Asymmetrical schemes are in general preferable to the symmetrical ones because the latter are more influenced by the alignment detailing of the two strengthened sides. Moreover the specimen symmetry is lost when the debonding starts on one side of the specimen and prevents from following correctly the post-peak behavior.

Within the activity of fib Task Group 9.3, a Round Robin Test concerning the bond strength of the FRP-concrete interface has been promoted and recently concluded; several international partners were involved in the experimental activity, characterized by the adoption of the double shear pull-pull set-up. Between them, the Laboratory of Structural Testing of the University of Bologna and the Laboratory of Structural Engineering of the University of Naples Federico II decided to adopt the single shear pull-pull set-up and to share all the materials (concrete, adhesive and FRP reinforcement). In the present paper, first comparison of experimental results obtained by the two labs will be presented and discussed.

2. Experimental program

2.1 Description of set-up adopted by Research Units

The experimental program of each Research Unit consisted in 18 bond tests on concrete specimens strengthened with EBR systems; the two labs shared the same concrete (mix design and mechanical properties are described in section 2.2) strengthened with six different types of CFRP plates (described in section 2.3).

The general test set-up has been defined according to the indications provided by the fib Task Group 9.3 - FRP Reinforcement for Concrete Structures - Externally bonded reinforcement that has organized a Round Robin Test (RRT) involving several laboratories. In particular, the Authors of the present paper decided to adopt an asymmetrical version of the pull-pull set-up in order to reduce the effects of detailing and imperfections of the specimens on the experimental bond strength values.

A previous Italian RRT, whose bond tests have been performed according to a push-pull asymmetrical set-up, evidenced a good effectiveness and a rather low scattering of results of this testing procedure [15].

The Research Unit (RU) of Naples (NL in the following) and the RU of Bologna (BL in the following) tested exactly the same number and types of strengthened specimens, changing only some detailing of the experimental set-up; for this reason, both set-ups are described separately in the following.
The RU of Naples carried out all bond tests by using a universal servo-hydraulic testing machine. In particular, the specimen is clamped to the lower part of the testing machine by a couple of steel bars embedded in the concrete prism and bolted to a system of steel plates fixed in the grips. The test set-up is depicted in Figure 1a. Several strain gauges were applied along the reinforcement in order to measure axial strains during bond test. All tests were performed under displacement control [16].

The RU of Bologna designed a specific test machine in order to perform the bond tests. The system is composed of a steel beam which acts as contrast, a mechanical actuator on one side of the beam and a steel plate able to assure the concrete block restraint on the opposite side of the beam. The specimen is placed on the steel beam and its internal bars are connected to the rear steel contrast; the unbonded free end of the FRP reinforcement is glued to two steel plates, bolted to the mechanical actuator (Figure 1b). Several strain gauges were applied along the reinforcement in order to measure axial strains during bond test and two LVDTs were also applied at the beginning and at the end of the FRP bonded part in order to measure its axial elongation. The tests were performed under displacement control.

2.2 Properties of Concrete

Concrete specimens were cast in the same batch and made up with the same nominal dimensions: width $b_c = 160$ mm, height $h_c = 200$ mm and length $l_c = 400$ mm. Concrete mix was specifically designed to obtain low compressive concrete strength to simulate the FRP application on existing concrete elements.

For 1 m$^3$ of concrete, the following components were used: 1250 kg of gravel 4/14, 965 kg of coarse sand, 350 kg of Cem I 42,5 and 230 lt of water.

Compressive tests were performed on three cylindrical specimens at 35 days after the casting: the mean compressive cylindrical strength was $f_{cm} = 19$ MPa and the mean Young's' modulus was 18.6 GPa. Further compressive tests, realized on concrete cubes (side 150 mm) after 200 days from casting (at about the same time of bond tests) gave a mean cubic strength $R_{cm}=23$ MPa. Bending tests were also performed at the same time, providing for a tensile mean strength $f_{ctm} = 2.5$ MPa.

2.3 Geometrical and mechanical properties of EBR

The bond tests on EBR systems consisted in 18 tests for each RU on six different types of CFRP plates (3 tests for each plate typology). All the reinforcements were bonded to the
concrete specimen for a length \( l_b = 300 \text{ mm} \), starting 50 mm from the end of the concrete specimen where the tensile force was applied, to avoid edge effect. Before the application of the FRP reinforcement, the concrete surface was preliminarily treated by bush hammering, in order to eliminate the mortar till having the aggregate clear. Note that the concrete surface has been consolidated with primer only for the Sto Scandinavian materials, that explicitly suggested to use it.

The main test variables of the experimental program were the Young’s modulus (109-221 GPa) and the thickness (1.25-1.7 mm) of the FRP reinforcement. The width of the FRP plate is \( b_f = 100 \text{ mm} \) for all specimens except for the type S613 (\( b_f = 60 \text{ mm} \)); these values correspond to have a shape ratio \( b_f/b_c = 0.63 \) and 0.38, respectively.

The main geometrical and mechanical parameters are summarized in Table 1: the Young’s modulus \( E_f \), the thickness \( t_f \), the axial stiffness \( E_f\cdot A_f \), and the experimental tensile strength of each plate \( f_{fu} \). The mechanical properties are the average values obtained by experimental tensile tests on at least five samples; the Coefficients of Variation (CoV) of these experimental tests are also reported in Table 1 inside parenthesis.

Table 1 – FRP geometrical and mechanical properties (EBR)

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Label</th>
<th>( E_f ) (CoV) GPa</th>
<th>( t_f ) [mm]</th>
<th>( E_f\cdot A_f ) [kN]</th>
<th>( f_{fu} ) (CoV) MPa</th>
<th>Adhesive</th>
</tr>
</thead>
<tbody>
<tr>
<td>SikaCarbodur</td>
<td>C-1.25x100</td>
<td>171 (2%)</td>
<td>1.25</td>
<td>21375</td>
<td>2856 (10%)</td>
<td>Sika dur 30</td>
</tr>
<tr>
<td>SikaCarbodur</td>
<td>C-1.40x100</td>
<td>221 (4%)</td>
<td>1.40</td>
<td>30940</td>
<td>2955 (8%)</td>
<td>Sika dur 30</td>
</tr>
<tr>
<td>SikaCarbodur</td>
<td>C-1.30x60</td>
<td>175 (4%)</td>
<td>1.30</td>
<td>13650</td>
<td>3194 (3%)</td>
<td>Sika dur 30</td>
</tr>
<tr>
<td>ECC PC Carbocomp</td>
<td>C-1.60x100</td>
<td>109 (15%)</td>
<td>1.60</td>
<td>17440</td>
<td>1453 (9%)</td>
<td>PC 5800/BL</td>
</tr>
<tr>
<td>S&amp;P CFK</td>
<td>C-1.20x100</td>
<td>160 (4%)</td>
<td>1.20</td>
<td>19920</td>
<td>3011 (2%)</td>
<td>S&amp;P Resin 220</td>
</tr>
<tr>
<td>Sto Scandinavian</td>
<td>C-1.70x100</td>
<td>141 (1%)</td>
<td>1.70</td>
<td>23970</td>
<td>2637 (3%)</td>
<td>Stopox 452 EP + stopox SK 41</td>
</tr>
</tbody>
</table>

2.4 Failure modes and loads

The experimental maximum loads, \( P_{max} \), recorded from each test from both RUs, are reported in Table 2 along with the mean maximum load value, \( P_{max} \), the CoV of each specimen group and the failure type.

Most specimens failed due to debonding with detachment of a thin layer of concrete (DB-C, Figure 2a). In few cases only, the adhesive debonding (DB-A, Figure 2b) or a mix mode FRP-concrete debonding and splitting (DB-C/SP, Figure 2c) occurred. The other failure mode observed was the concrete splitting along the internal steel reinforcing bars (SP, Figure 2d); this type of failure is not characteristic of the bond test but is due to the specific shape of the specimen and to the concrete strength. For this reason, the corresponding values of ultimate force has not been regarded as bond strength and they have not been considered for the calculation of the mean values reported in Table 2.

Figure 3 shows, for each type of FRP reinforcement, the comparison between the mean maximum load \( P_{max} \) obtained by the two labs; RU of Bologna provided maximum load higher than those provided by RU of Naples. The difference is not completely stable but ranges between 8% and 15% of the values obtained by BL; only in one case the difference is much higher (about 25%). A possible explanation of this systematic difference can be found considering that in the set-up adopted by BL the concrete face opposite to the FRP bonded one is prevented from transverse displacement because it is placed on the contrast beam (Figure 4a); on the contrary, the same surface in the other set-up is completely free from restraints (Figure 4b). For this reason, when the tensile load is applied to the FRP
reinforcement a bending moment occurs due to the misalignment of the two forces (action and reaction), eventually producing a deformation of the concrete prism generating peeling stresses in the FRP reinforcement. It is very well known that the shear bond stress is very sensitive to peeling components, thus reducing the bond strength.

Figure 3 shows also the theoretical bond strength given by the *fib* model [3], Italian CNR DT200 model [4] and the Chen and Teng model [1]. The safety factors have been assumed

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Failure mode</th>
<th>Naples</th>
<th>CoV [%]</th>
<th>Failure mode</th>
<th>Bologna</th>
<th>CoV [%]</th>
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<tbody>
<tr>
<td>C-1.25x100_1</td>
<td>DB-C</td>
<td>41.25</td>
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<td>DB-C</td>
<td>54.56</td>
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<tr>
<td>C-1.25x100_2</td>
<td>DB-C</td>
<td>38.14</td>
<td>39.70</td>
<td>5.5</td>
<td>SP</td>
<td>52.91*</td>
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<tr>
<td>C-1.25x100_3</td>
<td>SP</td>
<td>32.68*</td>
<td></td>
<td>DB-C</td>
<td>52.22</td>
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<tr>
<td>C-1.40x100_1</td>
<td>DB-C</td>
<td>48.40</td>
<td></td>
<td>DB-A</td>
<td>40.73*</td>
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<tr>
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<td>45.98</td>
<td>19.8</td>
<td>DB-C</td>
<td>56.58</td>
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<tr>
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<td></td>
<td>DB-C</td>
<td>46.87</td>
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<tr>
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<td>DB-C</td>
<td>33.18</td>
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<td>DB-C</td>
<td>35.19</td>
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<tr>
<td>C-1.30x60_2</td>
<td>DB-C/A</td>
<td>29.86</td>
<td>31.64</td>
<td>5.3</td>
<td>DB-C</td>
<td>38.00</td>
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<td>DB-C</td>
<td>34.17</td>
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<tr>
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<td></td>
<td>DB-C</td>
<td>50.44</td>
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<tr>
<td>C-1.60x100_2</td>
<td>DB-C/A</td>
<td>39.87</td>
<td>44.64</td>
<td>15.1</td>
<td>DB-C</td>
<td>54.62</td>
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<td>C-1.60x100_3</td>
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<td>DB-C</td>
<td>54.02</td>
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<td>C-1.20x100_1</td>
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<td>53.69</td>
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<tr>
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<td>DB-C</td>
<td>48.05</td>
<td>50.17</td>
<td>4.6</td>
<td>DB-C</td>
<td>55.20</td>
</tr>
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<td>DB-C/SP</td>
<td>52.60</td>
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<tr>
<td>C-1.70x100_1</td>
<td>DB-C</td>
<td>54.79</td>
<td></td>
<td>SP</td>
<td>60.85*</td>
<td></td>
</tr>
<tr>
<td>C-1.70x100_2</td>
<td>SP</td>
<td>51.41*</td>
<td>54.68</td>
<td>0.3</td>
<td>DB-C</td>
<td>56.76</td>
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<tr>
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<td>54.57</td>
<td></td>
<td>DB-C</td>
<td>55.89</td>
<td></td>
</tr>
</tbody>
</table>

*not considered in the mean value. DB-C = debonding in concrete, DB-A = debonding at laminate adhesive interface, SP = splitting of concrete

Figure 2. Debonding mode of EBR specimens: a) debonding in concrete (DB/C); b) debonding at laminate adhesive interface (DB-A); c) splitting of concrete (SP); d) debonding in concrete + splitting of concrete (DB-C/SP).
equal to 1 and the mean predictions have been considered for the models of CNR and Chen and Teng. It can be observed that the theoretical values provided by the three models are quite similar. Moreover, the comparison between theoretical predictions and experimental results shows that the experimental failure loads are in most cases larger than the theoretical ones.

![Figure 3. Comparison of experimental maximum loads obtained from both labs with the theoretical predictions provided by fib, CNR and Chen & Teng models.](image)

Figure 4. Schematic description of the possible mechanism of deformation of the concrete specimen according to the set-up adopted by (a) the BL or the (b) NL.

2.5 Comparisons of strain distributions

In order to verify if the two versions of the pull-pull set-up adopted by the two labs provided for some differences also in term of strain pattern, in Figure 5a-b the strain distributions obtained by NL and BL with two types of FRP have been superimposed. Only the strain distribution corresponding to a selected number of levels of applied force has been reported for reasons of clarity. The comparison shows that in all the cases considered the two corresponding strain distributions are very similar when low levels of applied force are considered. By contrast, close to debonding strains from NL become generally higher than strains from BL. This difference, again, can be explained by considering the additional flexural deformation which is probably subject the concrete specimen without a contrast in the transverse direction (section 2.4 and Figure 4).

3. Conclusions

The same experimental program has been carried out simultaneously by two labs by adopting similar test set-ups, namely Single Shear Test (SST), with a pull-pull scheme realized with some slightly different constructive details; the obtained results allowed, at first, the influence of the testing procedure on the bond strength to be investigated. In particular, a difference of
about 10% was observed in terms of debonding loads probably due to a different lateral restraint condition of the specimens in the two set-ups.

Generally, for each single type of FRP reinforcement the coefficient of variation is quite low and comparable between the two Labs. In few cases, concrete splitting along the internal steel reinforcing bars was observed by both labs, mainly due to the pull-pull test scheme adopted and, thus, to the tension condition induced in the concrete block.

The comparison between experimental and theoretical debonding loads showed that the theoretical values are generally on the safe side respect to experimental ones for both test set-ups.

Finally, the axial strains recorded by means of several strain gauges glued along the FRP reinforcement showed that they could be influenced by the tension condition in the concrete that is typical of the pull-pull set-up.

In order to confirm the outcomes of this experimental program and clarify the differences between the results obtained by the two Labs, further developments will be carried out. In particular, these results will be compared with the results obtained by using Push-Pull Single Shear tests on very similar types of FRP plates in order to investigate the effect of the loading condition of the concrete block on the both global and local behavior. This aspect should be investigated also by performing numerical analysis by FE models simulating the different test set-ups.

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