Experimental investigation of the static bond of GFRP rebar and concrete

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ABSTRACT: This paper presents an experimental investigation dealing with the quasi-static behavior of the bond between GFRP (glass fibre reinforced polymer) rebars and concrete. The pull-out set-up with eccentrically GFRP bar was adopted to measure the effect of three parameters: (1) thickness of the concrete cover, (2) diameter and surface of the bar and (3) concrete mechanical properties. GFRP unidirectional E-glass rebars were considered of two diameters (6 and 8 mm) and two external surfaces (external ribbed surface cut into the bar after curing and surface deformed and coated with coarse sand). The rebars were embedded in cubic concrete specimens with three concrete covers: 10, 15 and 20 mm. Two concrete classes were used C25/30 and C50/60. The experimental results showed similar shear strength of GFRP and steel bars of diameter 8 mm, and an increasing shear strength increasing the concrete cover.

1 INTRODUCTION

The replacing of steel rebars with GFRP (Glass Fibre Reinforced Polymer) rebars in reinforced concrete was extensively investigated in the last decades (Bisby et al. 2007). The main advantages in using GFRP (glass fibre reinforced polymer) reinforcement are: their lightweight nature for weight sensitive structures, their non-corrosive and non-conductive characteristics, as well as their high strength-to-weight ratio (GangaRao et al. 2007).

One of the main aspects in design of reinforced concrete structures is to ensure an adequate adhesion of rebar to concrete to prevent bond failure (EN 1992-1-1 2005). This requirement justifies the effort spent in researcher and manufacturing to increase the adhesion strength of FRP (fibre reinforced polymer) rebar to concrete.

Many studies were performed using standard pull-out test setup (EN 10080 2005). One advantage of the FRP bars is its softer surface than steel bars leading to avoid high local stress concentrations in bond contact points to concrete, which often results in delays of cover splitting cracks along the bars. The stress distribution necessary for developing the ultimate splitting crack pattern is very dependent on the type of bar surface. Higher concrete mechanical performance exhibited tendency for earlier cover cracking (Tepfers et al. 2003). The pullout tests conducted on GFRP bars embedded in concrete showed that cracking caused by splitting forces is delayed in specimens reinforced with GFRP rebar than in ones with classical steel rebar (Weber 2005). Moreover, experiments showed that increasing the concrete cover causes increase of the confinement pressure, which results in better bond strength (Alves at al. 2011).
FRP rebar can be used in combination with thin concrete cover, bearing in mind its high resistibility against aggressive environments, but still having particular care of ensuring proper bond condition to concrete. In Horak et al. (2013), authors observed that the optimal concrete cover should be at least one diameter of the anchored FRP rebar for concrete of grade C25/30 and better. The concrete cover has relevant impact on the failure mechanism. Cover of one bar diameter generates failure for splitting, while for higher covers, two or more diameters, pullout or fracture of bars occurs (Ehsani et al. 1996).

The above mentioned and other important works available in the literature underline the main parameter affecting the adhesion of FRP rebar to concrete: external surface of the bar; concrete cover; concrete mechanical properties. The influence of those parameters on the adhesion of GFRP bar and concrete are experimentally investigated in the present paper. The pull-out set-up with eccentrically GFRP bar was adopted to measure the effect of three parameters: (1) thickness of the concrete cover, (2) diameter and surface of the bar and (3) concrete mechanical properties. Unidirectional E-glass FRP rebars were considered of two diameters (6 and 8 mm) and different external surfaces. The rebars were embedded in cubic concrete specimens with three concrete covers: 10, 15 and 20 mm. Two concrete classes were used C25/30 and C50/60.

2 MATERIALS AND EXPERIMENTAL FEATURES

2.1 Materials

Unidirectional E-glass FRP rebars, named ComBAR® (Schöck 2015), were adopted with diameter 8 mm, as well as ASLAN 100 rebars with diameter 6 mm (Hughes Brothers 2015). The GFRP rebars are produced by pultrusion technique with vinyl-ester resin. Those of diameter 8 mm have external ribbed surface cut into the bar after curing, while 6 mm rebars have surface deformed with helical wrap and coated with coarse sand (Figure 1). According to the data sheet of the producers, the mechanical properties of the rebars are in the direction of the bar axis: tensile strength 1000 MPa and 825 MPa; elastic modulus 60 GPa and 41 GPa for ComBAR and ASLAN, respectively.

For the sake of comparison, tests with conventional steel ribbed bars (grade B500B) of the same diameters (6 and 8 mm) were carried out.

![Figure 1. Surface of the GFRP rebars: (a) ASLAN 100; (b) ComBAR.](image)

Two concrete classes were used C25/30 and C50/60. 54 cubic concrete samples were tested, during the experimental campaign, to measure the concrete mechanical properties at room conditions. The compressive tests provided average cubic strength with the standard deviation listed in Table 1, for the two concrete qualities.
Table 1. Cubic strength of the two concrete qualities.

<table>
<thead>
<tr>
<th>Cubic strength (MPa)</th>
<th>average</th>
<th>standard deviation</th>
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<tbody>
<tr>
<td>C25/30</td>
<td>31.6</td>
<td>4.0</td>
</tr>
<tr>
<td>C50/60</td>
<td>62.3</td>
<td>4.2</td>
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2.2 Experimental setup

The pull-out setup with eccentrically GFRP bar was adopted assuming the suggestions in fib bulletin 40 (2007) and in EN 10080 (2005). The experimental set-up was installed in a hydraulic loading device equipped with a load cell of 100 kN.

The rebars were embedded in cubic concrete specimens (side of 200 mm) to provide three concrete covers: 10, 15 and 20 mm. The geometry of the specimen is shown in Figure 2, where $\ell$ is the bar free length from the adhesion zone to the grip tabs, $\varnothing$ is the bar nominal diameter and $c$ is the concrete cover. The length of adhesion surface between bar and concrete was selected as $5\varnothing$, inserting an aluminum pipe on the bar. Three specimens were tested for each combination of: two concrete qualities (C25/30 and C50/60), three concrete covers (10, 15 and 20 mm) and two diameters of GFRP bar (6 and 8 mm). Moreover, for comparison, specimens were casted containing steel ribbed bars, three for each combination of: the two concrete qualities, two diameters (6 and 8 mm) and two concrete covers (10 and 20 mm). The total number of specimens tested was: 36 with GFRP bars and 24 with steel bars.

The adopted pull-out test setup produces a compressive transfer of the load to the concrete block with a steel plate (see Figure 3). To allow dilatation of the concrete in the direction perpendicular to the bar, a PTFE sheet was positioned between the steel plate and the concrete specimen. The bars were gripped with a cylindrical sleeve.

Two displacement transducers (LVDT) were placed one on the top cross section of the bar and one on the concrete cube (Figure 3). The difference of the two relative displacements provides the slip between the bar and the concrete.
Some tests were assisted with two digital cameras acquiring frames at a frequency of 1 Hz with a resolution of 2448 x 2050. The images post-processing allowed the measurement of the 3D full field strain on one side of the specimen, closest to the bar, during loading by the 3D digital image correlation technique using the ARAMIS software (Gom 2015). For this purpose one side of the specimen was speckled with white and black acrylic paints (Figure 3).

The quasi-static pullout tests were performed setting a cross-head displacement rate of 1 mm/min.

![Pull-out experimental setup.](image)

**Figure 3.** Pull-out experimental setup.

3 RESULTS AND COMPARISONS

The results of the experimental pullout tests show similar bond behavior of the GFRP and steel rebars. Assuming the average shear stress ($\tau$) on the contact surface between bar and concrete, estimated as $\tau = F/(\pi d^2)$, the complete $\tau$ vs. slip curves are compared in Figure 4. They demonstrate a typical bonding behavior with almost no slip up to the maximum shear stress (shear strength) and a very similar non-linear post peak branch of the GFRP (Figure 4a,b,c,d) and steel (Figure 4e,f) bars. Moreover, the observed behavior does not change varying the concrete quality, the concrete cover and the bar diameter.

![Shear strengths.](image)

**Figure 5.** Details of the average shear strengths and shows the influence of the considered parameters. Increasing the concrete cover, the shear strength increases for both GFRP and steel bars, as observed in literature (see e.g. Alves et al. (2011)). The shear resistance of the adhesion of ComBAR GFRP bar diameter 8 mm are quite similar to the one of steel bar, value are in the same experimental scatter (Figure 5c,d), for both concrete qualities. Some discrepancies were recorded for the lower concrete cover with concrete C50/60 (see Figure 5d). The ASLAN GFRP bar of diameter 6 mm had lower shear strength comparing to steel (Figure 5a,b). One of the main motivations of the different behavior of the two GFRP bars is clear observing their external surface after pull-out. The ASLAN 100 had external layer, including the helical wrap and coarse sand, completely detached (Figure 6a) and still in contact with concrete. On the other hand, the ComBAR shows undamaged ribs and some concrete still attached to the bar.
Figure 4. Shear stress vs. slip for the considered concrete covers: (a, c, e) concrete C25/30; (b, d, f) concrete C50/60; (a, b) GFRP ComBAR diameter 8 mm; (c, d) GFRP ASLAN diameter 6 mm; (e, f) steel bar diameter 8 mm.
Figure 5. Comparison of the average shear strength for the considered concrete covers: (a, c) concrete C25/30; (b, d) concrete C50/60; (a, b) ASLAN rebars diameter 6 mm; (c, d) ComBAR rebars diameter 8 mm. Bars indicate standard deviation of three tests.

Figure 6. External surface of the GFRP rebars after pull-out: (a) ASLAN 100 with concrete cover 20 mm; (b) ComBAR with concrete cover 15 mm.
As observed in literature (Tepfers et al. 2003), the thickness of concrete cover can modify the failure modes during pull-out. The three typical failure modes were observed with the considered GFRP bars measuring the strain map by 3D DIC on the external surface of the concrete cube in a zone of 5x5cm centered on the bar bonded to concrete (Figure 7). Pictures in Figure 7 show the map of the strain resultant at the maximum load recorded during testing of specimen with ComBAR, concrete C25/30 and the three different concrete covers. With concrete cover 10 mm, the strain map highlights several cracks leading to splitting off of the surrounding concrete (Figure 7a). Diffuse small cracks were observed on the specimen with cover of 15 mm inducing the cover failure (Figure 7b). The shear-bond failure in concrete or at the FRP bar surface was observed in specimens with concrete cover 20 mm (Figure 7c), with almost constant strain distribution on the concrete surface.

![Figure 7](image)

**Figure 7.** DIC map of the strain resultant at the maximum load on a surface of 5x5cm centered on bond length, for specimen with ComBAR 8 mm, concrete C25/30 and concrete cover: (a) 10 mm; (b) 15 mm; (c) 20 mm.

4 CONCLUSIONS

The experimental campaign aimed to investigate the quasi-static adhesion behavior of GFRP bars and concrete. The effects of some parameter affecting the adhesion were considered: diameter and external surface of the GFRP bar; concrete cover; concrete mechanical properties. The main results of pull-out tests are:

- The shear strength of ComBAR GFRP bar diameter 8 mm are quite similar to the one of steel bar, while ASLAN bar of diameter 6 mm have lower shear strength comparing to steel.
- The different external surface of the GFRP bars lead to different damage modes: the ASLAN 100 had complete delamination of the external layer; the ComBAR showed undamaged ribs.
- The DIC measurement of the strain distribution on the external surface of the concrete cube highlighted the influence of the concrete cover on the failure mode. The lower cover (10 mm) generated the splitting of the concrete; with the cover of 15 mm, diffuse cracks were observed inducing the cover failure; the shear-bond failure in concrete or at the FRP bar surface was observed in specimens with concrete cover 20 mm.

The obtained results demonstrate the comparable bond behavior of GFRP and steel bars, as already known, and highlighted some peculiarities of the adhesion between GFRP bars and concrete. The experimental results will be adopted as reference for the future investigation of GFRP and concrete bond under cyclic loadings.
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References