EXPERIMENTAL INVESTIGATION OF BOND BEHAVIOR OF ROUGHENED CFRP BARS IN HIGH STRENGTH CONCRETE

T. Tibet AKBAS¹, Oguz C. CELIK², Cem YALCIN³

ABSTRACT

Composite reinforcing bars (rebars) used in concrete members featuring high performance properties, such as strength and durability, could have beneficial effects on the behavior of these members. This would be especially important when a building is designed/constructed in an aggressive environment. Although tension capacity/weight (or volume) ratios in composite rebars are considerably high when compared to steel rebars, major weaknesses in fiber reinforced polymers (FRP) reinforced concrete members (beams, columns, or slabs) is mainly due to the poor bond behavior. This is essential when the member is subjected to cyclic loadings during an earthquake. Although monotonic bond tests are available in the literature, limited experimental studies exist for cyclic testing.

In order to address this problem and possibly reach some design recommendations, twelve specimens of 7.5mm-diameter roughened (sand coated) carbon fiber reinforced polymers (CFRP) bars embedded in high strength concrete ($f_c \geq 50$MPa) specimens that were designed for pull-out tests with monotonically (6 specimens) and cyclically (6 specimens) applied axial displacements. No confinement was provided in the specimens. A 21.25mm concrete cover was chosen. Development lengths of $10d_b$, $15d_b$, $20d_b$, $25d_b$, $30d_b$, and $40d_b$, development lengths were taken as the main parameters in this work. Both tension load (or bond strength) versus slip, monotonic and cyclic curves, and rebar strain measurements were determined and compared. Bond slip (i.e. debonding) and concrete splitting types of failure modes were observed. Developed bond stresses corresponding to the obtained experimental load values were obtained in a range between 13.0MPa and 6.5MPa for monotonic loading and 11.0MPa and 6.6MPa for cyclic loading.

Keywords: Bond Strength; CFRP; Embedment Length; High Strength Concrete; Cyclic Loading.

1. INTRODUCTION

Carbon fiber members are used as retrofitting materials to increase the capacity of existing buildings (Chen and Teng, 2001). Recent studies have shown the usage of carbon fiber reinforcing rebars in concrete members as an alternative material to steel rebars. Since these materials could be produced in any desired shapes. Recent works have shown that carbon reinforcement rebars could be used in reinforced concrete (RC) members that were designed for steel rebars. Thus, FRP reinforced concrete members such as beams, columns, and slabs could be designed and constructed. Carbon rebars are preferable in various fields due to their high chemical resistances. High strength and light weight are other remarkable features of composite rebars (carbon fiber reinforced polymer-CFRP, glass fiber reinforced polymer-GFRP, etc.). Some construction applications of carbon rebars could be found in marine structures, bridge concrete slabs and concrete pavements. Some experimental studies have supported the suitability of composite rebars for structural use (ACI440, 2006). Experimental studies showed similar behavioral properties of carbon rebars in RC sections when compared to steel rebars. These studies also revealed that required embedment lengths of these rebars should be taken into account correctly and carefully. Unlike steel rebars, not enough information is

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available for better understanding the behavior of carbon rebars in normal and especially in high strength concrete members.

Many researchers conducted comprehensive studies on obtaining accurate values of embedment and anchorage lengths of steel rebars. Goto (1971) experimentally showed that deformed reinforcing bars could develop bond stresses via bearing mechanism of ribs and produce non uniform bond stress behavior. Alsiwat and Saatcioglu (1992) analytically expressed this phenomenon based on past experimental studies and existing empirical models. They developed a bond-slip model to obtain stress or force distribution along the anchorage length of rebar. Other researchers worked on the impact of RC detailing on bond-slip relationships. They evaluated bond behavior with the different conditions of concrete cover and confinement (Harajli, 2009). According to detailed experimental studies using direct tension pullout tests, it was observed that composite rebars, like steel rebars, do not uniformly transfer forces to concrete (Tastani&Pantazopoulou, 2010).

Steel rebar surface properties are standardized as a result of ongoing experiments for years. However, composite rebars could be produced with various new materials and could also have different surface conditions like ribbed or roughened by different ways such as sand coating. On the other hand, plane bars, steel or fiber composites, have poor bond resistance, even in high strength concrete. ACI 440 recommends basic formulations for calculation of required embedment length of rebars. Harajli&Abouniaj (2010) stated that these formulations are not conservative and realistic.

This experimental study mainly focuses on comparing the bond behavior of roughened CFRP rebars in high strength concrete under monotonic and cyclic loading conditions. In addition to loading procedure, various embedment lengths are taken as a primary test parameter in this work. Obtained results showed that sequence of loading has a significant impact on the behavior of CFRP reinforced concrete members.

2. SPECIMEN PREPARATION

This is an extension of work done initially by the authors (Akbas et al. 2016). Although similar specimens and test setup are used, different rebar surface conditions are considered as another parameter. Note that the selected U-shaped concrete block specimen configurations were also proposed and used by (De Lorenzis et al. 2002). These blocks have side dimensions of 35cmx35cmx30cm as shown in Fig.1a, providing a sufficient embedment length for the rebars to be tested. CFRP rebars were embedded into those blocks with a constant cover and varying embedment depths. To ensure the desired concrete cover a polystyrene foam element has been placed inside the mold with 15x15x30cm sizes (Fig.1b).

![Figure 1. (a) Concrete block dimensions (Unconfined), (b) Polystyrene foam placing](image)

In order to provide full fixity of the concrete block specimen at the base of the experimental setup, four steel pipes were placed at each corner of the specimen’s mold. The specimens were then fixed to the base via four 20mm-diameter threaded steel tie bars with. No confinement was provided in the concrete blocks. All rebars had 7.5mm of diameter. Surfaces are roughened by using sand coating. For observing load transfer mechanism between rebar and concrete along the bonding region, six different embedment lengths were considered as multiples of rebar diameters (10db, 15db, 20db, 25db, 30db and 40db). Rebars
have been wrapped with soft plastic pipe at the two ends of embedded parts for obtaining the desired embedment lengths in the specimens. Although loading setup had capability to test specimens concentrically or eccentrically, roughened CFRP rebars were tested concentrically in this experimental work.

3. MATERIAL PROPERTIES

Selected concrete cover was kept constant and no confinement was provided in concrete blocks. Due to higher tension, and thus required bond strength capacities of CFRP bars, it was considered that, the carbon rebars would be more compatible with high strength concrete. Therefore, it was decided to use high strength concrete in the experiments. An appropriate mix design was developed by targeting C50 (cylindrical strength of 50 MPa) or higher class of concrete. Specimens were poured with concrete mixture twice on different dates. A %10 difference is observed between the tested compression capacities of produced concretes. According to the concrete strength test results, 28 days compression capacities (cylindrical) of the produced concretes were 54.2 and 59.8 MPa.

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Water/ cement (kg/m³)</th>
<th>Water (kg/m³)</th>
<th>Cement (kg/m³)</th>
<th>Coarse aggregate, 12-25mm (kg/m³)</th>
<th>Coarse aggregate, 6-12mm (kg/m³)</th>
<th>Fine aggregate, 0-6mm (kg/m³)</th>
<th>Silica fume (kg/m³)</th>
<th>Plasticizer (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSC</td>
<td>0.30</td>
<td>135</td>
<td>300</td>
<td>522</td>
<td>468</td>
<td>787</td>
<td>150</td>
<td>5.85</td>
</tr>
</tbody>
</table>

Figure 2. Mixture design

Selected carbon rebars were BASF Mbar Galileo HS7.5. An improvement on bond characteristics was provided by using sand coating on surface and a photo of the rebars is shown in Fig. 3. These carbon rebars with d₀=7.5 mm diameter and 44 mm² of cross sectional area, according to manufacturer’s data, could resist up to 100.0kN tension force under 1.8% elongation.
Table 2. Mechanical properties of CFRP rebars (BASF, 2000).

<table>
<thead>
<tr>
<th>Property</th>
<th>Values in the longitudinal direction of the fibres</th>
<th>Average value</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-Modulus</td>
<td></td>
<td>130,000 N/mm²</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td></td>
<td>2,300 N/mm²</td>
</tr>
<tr>
<td>Strain at break</td>
<td></td>
<td>&gt; 1.80 %</td>
</tr>
</tbody>
</table>

4. TEST SETUP AND EXPERIMENTAL PROCEDURE

A special test setup that was designed initially to test steel rebars was further modified to accommodate carbon fiber rebars with test parameters. Prepared specimens were tested at the Structures Laboratory of Bogazici University. A special anchorage device (Fig. 4a) was designed and manufactured to provide a reliable connection between the CFRP rebar and actuator (200kN with ±100 mm of stroke). A conical jaw was placed into the designed connection part. Up to 25mm diameter rebars could be tested with this modified setup (Fig. 4b).
To obtain the load transfer behavior and distribution of forces along the embedment length, strain gauges were attached on CFRP bar surface to various locations. Selected strain gauge type was compatible with FRP materials. Because of their orthotropic material properties, carbon rebars exhibit high tensile strength in the longitudinal direction and they are weak in transverse direction. For this reason, tested rebars were surrounded with a 250mm long steel pipe for preventing material crushing around this region. Load transfer between steel sleeve and rebar was provided by filling high strength epoxy which had more than 5MPa bond capacity. As seen on schematic arrangement of test setup in Fig.5, the actuator was positioned on top of the loading frame and actuated downward direction. Specimens were seated on a steel plate having a thickness of 25mm, which was welded to a concrete filled steel foundation beam. Two steel plates with 25 mm thickness were used to connect the edge rods and to compress the specimen from top. In common pullout tests, fixing plates of concrete surfaces were very close to the rebars used. These plates may create confinement effect around the rebars and may change the real behavior. In this experimental work, this effect has been eliminated by proposing an improved test setup. It was expected that the obtained results could exhibit the real behavior more precisely.
5. INSTRUMENTATION

For monitoring the strain distribution inside the concrete block on rebar surfaces, three strain gauges (SG1, SG2 and SG3) were attached on each rebar (Fig.6). These strain gauges are illustrated schematically in Fig. 7. Strain gauge measurements were taken at the beginning of the bonded area (SG1), in the middle of bonded area (SG2) and at the end of bonded area (SG3). The specimens were displacement-controlled tested with 0.01 mm displacement increments.

Figure 6. Strain gauges location

One LVDT was connected to the rebar with a manacle to trace the relative slip (Fig. 8). Another LVDT was connected on the concrete block surface and also to the hydraulic jack with the help of a wire.

Figure 7. Strain gauges locations

Figure 8. LVDT locations

6. TEST RESULTS

Experimentally obtained values are summarized in Table 3. Specimen labels, embedment lengths, loading types, concrete strengths, bond strengths, average bond stresses obtained, and the observed failure modes are given in this table.

Under monotonic testing, maximum axial loads of 19.5kN and 51.8kN were obtained for 10d₀ and 40d₀.
specimens, respectively. As for cyclic (not reversed) loading, 11.7kN and 46.8kN load values were reached for 10dₜ and 40dₜ specimens, respectively. Developed bond stresses corresponding to these load values were 11.03MPa and 6.51MPa for monotonic loading and 6.62MPa for cyclic loadings. These revealed that experimental bond stresses could be significantly reduced when cyclic loads were applied. This results in reduced capacities for the specimens under cyclic loading. Experimental results showed that the attained minimum and maximum loads of 11.7kN and 51.8kN, were far below the maximum capacity (100kN) of the sand coated CFRP bars used. Both pullout and splitting failure modes are detected. No fractures were obtained in the CFRP bars during these tests.

Bond stress (MPa) versus slip (mm) graphs were plotted and illustrated in Fig.9. Accordingly, it was observed that the initial stiffness of the specimens changed depending on the cycles of loading procedure. In monotonically loaded specimens, measured bond stresses for shorter embedment lengths (for example for the 10dₜ specimen) had higher stresses than that of the specimens with longer embedment lengths.

Specimens S31 and S32 were failed from splitting mode while other specimens exhibited pullout failure mode. For the splitting failure, loud sounds were heard whereas the pullout (or slip) failure mode was quiet. Since the concrete blocks were not confined, the splitting failures in some tests were quite brittle and caused complete and sudden cracks on the concrete blocks.

Table 3. Test results

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Iₑ² (mm)</th>
<th>Loading Type</th>
<th>fₑ³ (MPa)</th>
<th>ACI440</th>
<th>Test</th>
<th>Failure Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>u⁴</td>
<td>f⁵</td>
<td>u</td>
</tr>
<tr>
<td>S31-40D-M-U</td>
<td>300</td>
<td>M</td>
<td>54.2</td>
<td>4.52</td>
<td>31.9</td>
<td>6.51</td>
</tr>
<tr>
<td>S32-40D-T-U</td>
<td>300</td>
<td>C ⁷</td>
<td>54.2</td>
<td></td>
<td></td>
<td>6.62</td>
</tr>
<tr>
<td>S33-30D-M-U</td>
<td>225</td>
<td>M</td>
<td>54.2</td>
<td>5.03</td>
<td>26.7</td>
<td>9.77</td>
</tr>
<tr>
<td>S34-30D-T-U</td>
<td>225</td>
<td>C</td>
<td>54.2</td>
<td></td>
<td></td>
<td>8.28</td>
</tr>
<tr>
<td>S35-25D-M-U</td>
<td>187.5</td>
<td>M</td>
<td>54.2</td>
<td>5.44</td>
<td>24.0</td>
<td>10.30</td>
</tr>
<tr>
<td>S36-25D-T-U</td>
<td>187.5</td>
<td>C</td>
<td>54.2</td>
<td></td>
<td></td>
<td>8.06</td>
</tr>
<tr>
<td>S37-20D-M-U</td>
<td>150</td>
<td>M</td>
<td>59.8</td>
<td>6.35</td>
<td>22.4</td>
<td>11.37</td>
</tr>
<tr>
<td>S38-20D-T-U</td>
<td>150</td>
<td>C</td>
<td>59.8</td>
<td></td>
<td></td>
<td>7.05</td>
</tr>
<tr>
<td>S39-15D-M-U</td>
<td>112.5</td>
<td>M</td>
<td>59.8</td>
<td>7.42</td>
<td>19.7</td>
<td>12.98</td>
</tr>
<tr>
<td>S40-15D-T-U</td>
<td>112.5</td>
<td>C</td>
<td>59.8</td>
<td></td>
<td></td>
<td>11.05</td>
</tr>
<tr>
<td>S41-10D-M-U</td>
<td>75</td>
<td>M</td>
<td>59.8</td>
<td>9.56</td>
<td>16.9</td>
<td>11.03</td>
</tr>
<tr>
<td>S42-10D-T-U</td>
<td>75</td>
<td>C</td>
<td>59.8</td>
<td></td>
<td></td>
<td>6.62</td>
</tr>
</tbody>
</table>

¹ roughened d₀=7.5mm rebar, ² embedment length, ³ concrete compressive strength (cylinder 28. days), ⁴ average bond stress, ⁵ bond strength, ⁶ monotonic loading, ⁷ cyclic (not reversed) loading.
General shape of the behavioral curves obtained from this study are similar to the curves given in the existing literature. Typical mode shapes for pullout and splitting failures are given in Fig. 10(a) and (b), respectively.
According to the experimental results obtained, developed bond stresses varied between 6.5~13 MPa. To obtain the influence of embedment length on bond development, the experimental results obtained from this study has been plotted and given in Fig. 11. As expected, a decreasing in bond strength/stress with increasing embedment length is observed (Akbas et al. 2015). Also, it is seen that, by increasing the embedment length, monotonic loading bond stresses are getting close to the cyclic loading results.

Figure 11. Variations in bond stress with embedment length and loading procedure applied
7. CONCLUSIONS

Experimental bond behavior of roughened CFRP bars in high strength (f’_c ≥ 50MPa) concrete was investigated under monotonic and cyclic loading conditions. Various embedment lengths were taken as experimental parameters. All 12 specimens had a constant concrete cover of 21.25mm. A displacement-controlled testing procedure was applied. The following major conclusions could be drawn from this work:

- Bond behavior of CFRP rebars in high strength concrete is affected by the embedment length, as expected.
- In general, rebars having 10d_b, 15d_b, 20d_b, 25d_b and 30d_b embedment lengths had pullout failure, while rebars having 40d_b embedment lengths failed from splitting. No damage or cracks were observed prior to failure.
- Comparing the behavior of the specimens with different embedment lengths showed that average bond stress decreased with increasing embedment length.
- A nonlinear strain distribution was obtained on the rebars in the concrete block. A gradual increase and redistribution in strains were measured until failure. Before failure, the last strain gauge started to show some strain values.
- Initial bond stiffness of specimens decreased as number of load cycles increased. Cyclic loading reduced the bond capacity of the specimens. Reduction in short and long development length specimens were within the range of 40% and 15%, respectively.
- Comparing the monotonic and cyclic loading for different embedment lengths showed that the bond stresses were getting closer by increasing the embedment length.

8. REFERENCES

Harajli M.H. (2009), Bond Stress-Slip Model for Steel Bars in Unconfined or Steel, FRC, or FRP Confined Concrete under Cyclic Loading, Journal of Structural Engineering, May, pp. 509-518.