CONTRIBUTION TO STRENGTHENED REINFORCED CONCRETE STRUCTURES BY EXTERNALLY BONDED CARBON FIBRES FABRICS

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ABSTRACT

The present paper reports results from an experimental investigation of the mechanical behavior of reinforced concrete structures externally strengthened by bonded carbon fibers fabrics (Carbon Fiber Reinforced Polymer or CFRP). The focus is on the local and global strain distribution, the load-carrying capacity and the mode of failure. The effect of fibers fabrics configuration and some geometrical parameters are presented. The CFRP reinforced concrete beams are subjected to four points bending. The extensometer technique based on electrical strain gauge is used to study the local behavior of the structure. This technique allows measuring the strain of steel, carbon fabrics and concrete. The effect of the same parameters on the strengthening structure local behavior is examined. The tests show better results in case of unidirectional fibers and wrapped strengthening use. The ultimate load and strain of the specimens are compared to the reference specimen. The structures cracking and the different failure modes are studied. The cracking mechanisms and the mode of failure under static loading are presented and analyzed. The results show not only an increase of more than 82 % of the load carrying capacity of the corbels and 210 % of that of the reinforced concrete beam but also improvement of their rigidity. The theoretical analysis based on the classical theory of beams and deformation compatibility relationship enables meaningful comparisons between the theoretical and the experimental results.

Keywords: strengthening, short corbel, reinforced concrete, mechanical behavior, composite materials, beam.

INTRODUCTION

The use of composite carbon fiber plates, although recent in civil engineering, is an interesting alternative in the field of repairing of structures or strengthening new designs. Carbon Fiber Reinforced Polymer (CFRP) reinforced concrete structures are obtained by bonding composite sheets to the tensile strength sides of the structures [1-6]. Thus a significant increase of old structures bending and shear strength is achieved.

Of course, this technique provides structures conforming to the criteria of safety and fitness especially in case the changing environment requires the structure durability improvement. The advantages of this technique, among others, refer to the better distribution of stresses in the adhesive layer compared with that of the tightening or brazing technique. Furthermore, the work can be carried out while the structure is still in use. The technique discussed is also easy to implement and provides quick installation.

Composite materials offer the designer an outstanding combination of properties not available by other ma-
Fiber materials such as glass, carbon and aramid can be introduced at a certain position, a volume and a direction in the matrices (e.g. epoxy) to obtain maximum efficiency. The lightness, the corrosion resistance, the electromagnetic neutrality and the greater efficiency in construction compared with those of the more conventional materials are another advantages offered by CFRP. The latter are used to confine new concrete beams and columns, to strengthen the columns, the corbels and the beams in seismic areas, or to strengthen the tension faces of the reinforced concrete beams [7 - 9].

This paper deals briefly with the results of tests carried out on different beams and corbels strengthened with CFRP and an analysis of the mechanical behavior of these assembled structures. The effect of CFRP and adhesives thickness on the structure mechanical behaviors is also examined. The evaluation of the stress distribution in the structure is done on the ground of the optimal anchor length of the composite material laps. The mechanism of cracking and different collapses is considered.

**EXPERIMENTAL**

**Materials**
Identical mixed concrete was used for all beams. The volume cement:sand:gravel ratio in the concrete mix was 1 : 1.7 : 2.9. The water/cement ratio was 0.5, while cement type II Portland was used. The maximum size of the aggregate was 16 mm. Four 160 mm x 320 mm concrete cylinders were cast and tested to determine the mechanical proprieties of the concrete.

**Methods**

Figs. 1a, 1b and 1c show the sizes of the beams and corbel specimens tested in this study.

The carbon fiber fabrics were adhered to the lower surface of the reinforced concrete structures using an epoxy resin. This technique was increasingly used in the field of civil engineering for old structures rehabilitation providing resistance increase to bending and shearing stress in the structures. This approach contributed also to the structures durability by strengthening them.

A single type of CFRP sheet was used during the test: a unidirectional CFRP with fibers oriented only in the longitudinal direction. The fiber composite material consisted of carbon bonded together with an epoxy matrix.

The extensometer technique based on electrical strain gauges was used to study the local behavior of the structures. This technique allowed evaluating the strain of steel, carbon fabrics and concrete. So, the load versus the strain at the cross section between the column and the corbel was plotted. The beams were instrumented with electrical gauges as shown in Fig. 2a. All the beams were tested under a four-point load. The center deflection, the concrete strain distribution, the strains in the CFRP and the state of cracking were followed in the course of each test.

The instrumentation illustrated in Fig. 2a provided the understanding of the mechanical phenomenon when cracks occurred. A few strain gauges positions at the cross section of the member mid-span are shown here referring to CFRP (J1, J2, J3), and on steel (J4, J5, J6).

The strain gauges (G1, G2 and G3) of 120 Ω and
the gauge factor of 2.09 % referring to corbel (Fig. 2b) had a length of 5 mm to measure the strain of the main reinforcement as well as the horizontal strengthening. In this case the steel tie rod was placed between the corbel and the column along the tensile and compression strut.

RESULTS AND DISCUSSION

The properties of the materials studied are listed in Table 1. The average compression strength of concrete is 33 MPa, while the flexural tensile strength was 4.5 MPa.

The concrete has an average elastic modulus of compression of 30 GPa. The carbon composite sheets show a linear elastic behavior up to the failure. The elastic modulus and ultimate strength are 121 GPa and 1035 MPa, respectively. The elongation at failure is 0.8 % for the unidirectional carbon fiber sheet, while 0.5 % for the bidirectional carbon fiber sheet. Steel (S500) bars a diameter of 6 mm and 8 mm are used. The failure tensile strength $f_u$ is 610 MPa, while the modulus of elasticity $E_s$ is 200,000 MPa. The Poisson’s ratio is equal to 0.30.

Series 1

The results of the first series (Fig. 1a, all the details of series 1 and 2 are reported in ref. [7]; those referring to series 3 pointed out in ref. [8] are not presented in this paper) show that the ultimate loads of the beams are almost identical. But it is worth noting the effect observed with the beam with Sikadur adhesive in the course of first cracks occurrence. The Sikadur adhesive is a two-component mixture used to bond the composite plates and the concrete. In addition, the deflection is significantly reduced compared with that of the reference beam. The failure rupture of the concrete layer is located between the reinforced steel and CFRP.

Table 1. Properties of the used materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s modulus $E$ (GPa)</th>
<th>Ultimate stress $f_u$ (MPa)</th>
<th>Poisson ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>30±2</td>
<td>33±2 ($f_c$)</td>
<td>0.25</td>
</tr>
<tr>
<td>Steel bar</td>
<td>200±1</td>
<td>610±10 ($f_u$)</td>
<td>0.29</td>
</tr>
<tr>
<td>Adhesive</td>
<td>4.1±0.1</td>
<td>36±1 ($f_a$)</td>
<td>0.41</td>
</tr>
<tr>
<td>UCFRP</td>
<td>121±2</td>
<td>1035±63 ($f_u$)</td>
<td>0.45</td>
</tr>
<tr>
<td>BCFRP</td>
<td>87±3</td>
<td>720±50 ($f_u$)</td>
<td>0.35</td>
</tr>
</tbody>
</table>

(UCFRP) - Unidirectional Carbon Fiber Reinforced Polymer
(BCFRP) - Bidirectional Carbon Fiber Reinforced Polymer
The results of the second series show that the application of CFRP sheet causes an increase of the ultimate load from 40 kN to 90 kN. The deflection is reduced to two-thirds (Table 2 and Fig. 3). The results show also that the strain distribution remains approximately linear in the compression zone throughout the loading range. The strain distribution in the tensile zone is approximately linear at low loads, while it becomes increasingly nonlinear at higher loads. The latter effect is caused by the concrete cracking.

The experimental results confirm the assumption that the plane sections are also preserved for strengthened beam. The strain distributions show a movement of the neutral axis towards the compression zone as the loading approaches a failure [7].

### Table 2. Beam test results.

<table>
<thead>
<tr>
<th>Designation</th>
<th>Design</th>
<th>$\frac{F_R}{F_0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCB</td>
<td>Reinforced concrete beam</td>
<td>1</td>
</tr>
<tr>
<td>SRCB</td>
<td>Strengthened Reinforced concrete beam</td>
<td>2.25</td>
</tr>
<tr>
<td>SCB</td>
<td>Strengthened Concrete beam</td>
<td>1.35</td>
</tr>
</tbody>
</table>

**Series 2**

The results of the second series show that the application of CFRP sheet causes an increase of the ultimate load from 40 kN to 90 kN.

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![Fig. 3. Strengthening effect on the beams mechanical behavior.](image-url)
Analytical model of beams

The investigations have shown that premature failures may occur because of shear and normal stress concentration at the sheet ends ([7], Fig. 4) resulting in debonding off the concrete cover along the level of conventional internal reinforcement. The interface shear at a distance x from the origin is evaluated using Eq. 1. Further, the normal stress in CFRP and the characteristic slip $d^*$ are described by Eq. 3. Triantafillou [3] advances the same analytical model to describe the maximum achievable prestress near the two ends upon releasing the pre-stressing strength.

The interface shear at failure is schematically illustrated in Fig. 4. The descending portion of the interface shear in the nonlinear region ($l'/2 < x < l/2$) is due to the concrete softening behavior. The softening branch in Fig. 4 is determined by the peak strength $t$ and the characteristic slip $d^*$. Then the shear strength levels down almost to zero. Kaiser suggests the following average values: $t^* = 8 \text{ MPa}$ and $d^* = 30 \mu\text{m}$.

\[
\tau(x) = \frac{t^* \sinh(wx)}{\sinh(wl')} \quad 0 \leq x \leq l'
\]

\[
\tau = t^*(1 - \frac{x^*}{(1 - l')/2}) \quad 0 \leq x^* \leq (1 - l')/2
\]

\[
\delta^* = \frac{t^*(1 - l')^2}{24E_c t_2}
\]

where $w^2 = \frac{G}{t_1 \left(\frac{1}{t_2 E_f h E_c}\right)}$, $t_1$ and $t_2$ are the adhesive and CFRP thickness, respectively, $h$ is the concrete depth, $E_c$ is the concrete elastic modulus, while $E_f$ is CFRP elastic modulus. An optimum value of $l'$ equal to 153.6 mm is obtained (consider Eq. 2). This result is in an agreement with the experimental observations.

Series 3

From the large amount of data obtained in testing corbel specimens, only typical data are reported here in Table 3. They refer to the type of strengthening on bending and shear in case of carbon fiber fabrics bonded directly to either surfaces or full wrapping of short reinforced concrete corbel. Four concrete corbels are tested. Three of them are strengthened CFRP, while the fourth has no strengthening. The results show that there is a very significant increase (from 41 % to 82 %) of the capacity loading of the three reinforced specimen.

The ultimate strength, $F_0$, of the reference corbel is equal to 357 kN. The results show the load $F/R/F_0$ increase to 1.41 % for CI2b and 1.82 % for CB3u. In the former case, the 45 plates are bonded to the sewing degrees’ oblique fissure. The bonded fabric of the carbon fibers area represents 32.5 % of the corbel total area. In case of strengthening it becomes equal to 51.6 %, while this area is 60.0 % when the complete tire of the console is concerned. The results show that strengthening is more effective in wrapping through the combined effect of the concrete and the carbon fiber fabric. The tensile strength is increased by 14 % when the bonding surface is doubled. Of course, in the case of the containment, are double ultimate load. The test results show also that the load capacity is increased on composite plates.

Influence of the type of strengthening

The CI2b is reinforced by gluing carbon composite plate perpendicularly to the diagonal crack appearance. Higher mechanical strength of the short CI2b corbel is observed. The composite plates placed perpendicular delay effectively the cracks onset and propagation. But the application of rigid carbon composite plates causes a premature failure of the specimen. This is accompanied by detachment of the plate at each point of direct gluing to the face.
Table 3. Design and test results of the strengthened corbels testing specimen.

<table>
<thead>
<tr>
<th>Designation</th>
<th>Design</th>
<th>( \frac{F_R}{F_0} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CI2b</td>
<td>Strengthened corbel by bonded Inclined bidirectional carbon fiber fabrics on both sides</td>
<td>1.41</td>
</tr>
<tr>
<td>CP3u</td>
<td>Strengthened corbel by bonded unidirectional carbon fiber fabrics on both sides</td>
<td>1.55</td>
</tr>
<tr>
<td>CB3u</td>
<td>Wrapping strengthened corbel by bonded composite plates on both sides</td>
<td>1.82</td>
</tr>
</tbody>
</table>

\( F_R \): ultimate load of strengthened reinforcement concrete corbel
\( F_0 \): ultimate load of un-strengthened reinforcement concrete corbel

The curves in Fig. 5 show the comparison of the local steel strain at the cross section of the strengthened reinforced concrete corbels CB3u, CP3u, CI2b and C0. A containment effect is evidenced by the strain reduction and the significant decrease of ultimate load – more than two times when those of CB3u and C0 are considered. In view of strengthening, CI2b configuration appears effective, insofar as crack is sewn by bonded carbon fiber fabrics to 45°. The confinement effect disappears as in the other two cases. Strains are more important (~7000 µm/m). The recovery strengths in the tie rod steel cause a local yielding leading to high deformations. In fact, strengthened concrete corbel reinforced by bonded carbon fiber fabrics trips to 45° has a ductile mechanical behavior. However, CP3u shows a behavior similar to that of CB3u. Plate detachment is prevented.

CRACKING AND COLLAPSE

Many modes of failure are observed for beams of series 1 and 2: a failure of CFRP, a failure of the concrete in the compression area, a rupture of the concrete layer situated between the reinforced steel and CFRP, a cohesive failure in the adhesive joint (due to the poor preparation of the mixture or unfavorable temperature conditions), an adhesive failure at the plate-glue and glue-concrete interfaces (the wrong choice of materials and poor surface preparation can facilitate this type of collapse). However, unlike other studies [8], the following failures are mainly observed in case of twenty short strengthened concrete corbels: tensile-bending which often causes a tearing of CFRP or rupture failure of the composite material, failure by compression, flexion, failure bending strength shear.

CONCLUSIONS

The flexural strengthening of a concrete beam reinforced by gluing carbon fiber composite sheets increases the flexural ultimate strength by 220 % compared with the nominal ultimate strength. The flexural strength and the stiffness are enhanced by the application of carbon fiber composite sheets. Three important char-
Characteristic domains are found: a global elastic domain, a microcracking and crack propagation domain, and an unstable domain. The study referring to different adhesives shows that these glues have a little effect on the ultimate strength. One mode of failure is observed: a rupture of the concrete layer situated between the reinforced steel and CFC sheet. The analytical study allows the description of the shear stresses distribution and the peeling mechanism in the adhesive, the plate and the concrete layers. The results show a concentration of shear stresses at the ends of the join adhesive layer. The same is observed in case of concrete. But the shear strength increase changes the stresses state and leads to development of a peeling stress. Thus, a stress of the concrete should be attained, which causes a failure of RC beam strengthened by peeling of the composite plate. The results show an optimum value of the maximum tensile strength at the third layer, which is then followed by a slight decrease. The thick composite 3mm sheet (tree layers of fabrics) provides ultimate optimal loads of strengthening of short reinforced concrete corbels. The contribution of strengthening, as shown in Fig. 5, is very significant and interesting. An increase in failure tensile strength by more than 82 % is observed by bonding carbon fiber fabric. The short CI2B console has a higher mechanical strength.

REFERENCES