Use of carbon fiber laminates for strengthening reinforced concrete beams in bending
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ABSTRACT
The use of Fiber Reinforced Polymer (FRP) is becoming a widely accepted solution for repairing and strengthening ageing in the field of civil engineering around the world. In the present paper, experimental study designed to investigate the flexural behavior of reinforced concrete beams strengthened with CFRP laminates attached to the bottom of the beams by epoxy adhesive subjected to transverse loading. A total of five beams having different CFRP laminates configurations were tested to failure in four-point bending over a clear span 1900mm. Four beams were strengthened by changing the levels of CFRP laminates whereas the last one was not strengthened with FRP and considered as a control beam. Test results showed that the addition of CFRP sheets to the tension surface of the beams demonstrated significantly improvement in stiffness and ultimate capacity of beams. The response of control and strengthened beams were compared and efficiency and effectiveness of different CFRP configurations were evaluated. It was observed that tension side bonding of CFRP sheets with U-shaped end anchorages is very efficient in flexural strengthening. The paper also highlighted the beams failure modes due to the different level of strengthening scheme.

Keywords: RC Beams, Anchorage length, Stiffness, Deflection, Flexural performance.

1. Introduction
The external bonding of high-strength Fiber Reinforced Plastics (FRP) to structural concrete members has widely gained popularity in recent years, particularly in rehabilitation works and newly builds structure. Comprehensive experimental investigations conducted in the past have shown that this strengthening method has several advantages over the traditional ones, especially due to its corrosion resistance, high stiffness-to-weight ratio, improved durability and flexibility in its use over steel plates. Moreover, these materials are less affected by corrosive environmental conditions, known to provide longer life and require less maintenance. The need for rehabilitation or strengthening of bridges, building and other structural elements may arise due to one or a combination of several factors including construction or design defects, increased load carrying demands, change in use of structure, structural elements damage, seismic upgrade, or meeting new code requirements. These factors may cause the infrastructure structurally inefficient and sometimes responsible for making the structures functionally obsolete. Before the introduce of fiber reinforced polymer (FRP) strengthening
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Technologies, one popular technique for upgrading reinforced concrete beams was the use of external epoxy-bonded steel plates (Swamy et al., 1987; Hamoush and Ahmed, 1990). In recent years, FRP sheets have shown great promise as an alternative to steel plates for concrete structures repair or strengthening. Swiss researchers pioneered work on the use of FRP as a replacement for steel in plate bonding applications (Meier and Kaiser, 1991) and numerous researchers have shown that the concrete rehabilitation using FRP is very successful application at retrofit or increasing the strength of reinforced concrete members (El-Badry, 1996; Tamuzs and Tepfers, 2004). The basic concepts in the use of FRPs for strengthening of concrete structures are covered in a review article (Triantafillou, 1998). Some of researches (Meier and Kaiser, 1991; Saadatmanesh and Ehsani, 1991) have shown that Fiber Reinforced Polymer (FRP) composites in strengthening RC members, in the form of sheets, have emerged as a viable, cost-effective alternative to steel plates.

In FRP-strengthened beams failure may occur due to beam shear, flexural compression, FRP rupture, FRP de-bonding or concrete cover ripping as presented by (Ascione and Feo, 2000), and (Bonacci and Maalej, 2000; Bonacci and Maalej, 2001). Based on experimental results conducted by (Teng et al., 2003), the most common failure mode is due to de-bonding of FRP plate or ripping of the concrete cover. These failure modes are undesirable because the FRP plate cannot be fully utilized. Premature failure modes are caused by interfacial shear and normal stress concentration at FRP cut-off points and at flexural cracks along the beam. The end peel mode starts at the ends of the plates and propagates inwards along the beam. Inclined and horizontal cracks form in the concrete causing it to break away from the beam while remaining firmly attached to the plate. This mode has been investigated experimentally and analytically by many researchers (Jones et al., 1988; Saadatmanesh and Malek, 1997; Rabinovich and Frostig, 2000). The peeling of CFRP composite may cause a sudden and catastrophic failure of the structure. One way to prevent the premature peeling of CFRP laminates from the concrete substrate is by using end anchorage. In fact, proper anchoring systems may help CFRP laminates develop higher stresses throughout their length (Rabinovich and Frostig, 2000; Zumaat and Alam, 2007; Barnes and Mays, 1999). Based on the research (Eshwar et al., 2003), the use of end anchorage increased the flexural capacity of strengthened beams by as much as 35% when compared to strengthened beams without anchorage. This study indicated that the anchors decreased stress concentrations and increased bond strength. A number of researchers (Jones et al., 1988; Garden and Hollaway, 1998; Spadea et al., 1998) have claimed a need to provide mechanical anchorage at the ends of the FRP strip to prevent catastrophic brittle failure of the strengthened beam by strip detachment. End anchorage is usually provided in the form of anchor bolts or cover plates. Similar mechanical anchorages have been recommended for use with epoxy-bonded steel plates (Hussain et al., 1995).

Much of recent works (Meier and Kaiser, 1991; Alam and Zumaat, 2009; Siddiqui, 2009; Alsayed et al., 2002; Ziraba et al., 1994; Sobuz and Ahmed, 2011) have shown that external bonded of FRP to structural concrete members is an effective and simple method to increase their structural capacity, for example as in reinforced concrete columns or reinforced concrete beams retrofitted by FRP laminates. Despite this research effort, studies on the multi-layered and lateral faces side strips of CFRP strengthened RC beams...
are relatively few, especially with regard to its flexural strengthening aspect. Significant structural improvement was observed from these studies in terms of ultimate capacity and stiffness, although de-bonding of plates was a concern in some of these studies (Alam and Zumaat, 2009; Aram et al., 2008; Yao and Teng, 2007).

This study examines the flexural response of CFRP strengthened reinforced concrete beams in the presence of different schemes of strengthening. In the present study, through an experimental program, efforts have been made to study the efficiency and effectiveness of different but very practical FRP schemes for flexure strengthening of RC beams. The failure modes and crack patterns are noted to get better understanding on the performance of beams strengthened with multi-layered CFRP laminates.

2. Flexural Strengthening

Analytical approach to evaluate the contribution of FRP composites laminates to concrete structures in flexural behavior is described in the code CEB-FIP (1993). The code uses a rectangular stress block to determine the equilibrium forces those are acting on the reinforced concrete beams. In this code, they adopt the traditional sectional analysis called “plane sections remain plane” for strain compatibility, and the stress-strain relationships of concrete, steel, and FRP laminates are used for equilibrium equations (refer to Figure 1).

\[ M_{cr} = \frac{f_{cr} I}{y_t} \quad \text{Eq. (1)} \]

Where \( y_t \) is the distance from the neutral axis to the tension face of the beam, \( f_{cr} \) is the modulus of rupture of the concrete, and \( I \) is the second moment of inertia of the cross section about neutral axis. The first cracking load \( P_{cr} \) is then calculated from the cracking moment. According to the code provision CEB-FIP (1993), the ultimate moment capacity of the strengthened beams is calculated using equivalent rectangular stress block of the beam cross section and then calculated the failure load. Taking moment at the centroid of
the tension steel, $A_t$ (refer to Fig. 1) and ultimate bending moment is expressed by the following equation:

$$M_u = F_{ct} (d - d') + F_{ct} (d - 0.45x) + F_f * d''$$

Eq. (2)

3. Design of End Anchorage Length

The purpose of end anchoring on plate bonded RC beam is to prevent premature failure of end peeling. Design of the anchorage length of the end anchors is the most attention from the research community for the purpose of strengthens or retrofitting of RC beams. In this study, a design guideline for anchorage length of end anchors is proposed based on the fictitious shear span model by Jansze et al. (1998). According to this model, plate end shear is the governing failure mechanism for end peeling which creates a fictitious shear span on partially bonded composites laminates beam as illustrated in Fig. 2. This fictitious shear span can be calculated by using the Eq. 1.

![Figure 2: Fictitious shear span](image)

Fictitious shear span $a_L = [(1 - (\rho_s)^0.5)^2 dL^3 / \rho_f]^{1/4}$

Eq. (3)

Where, $\rho_s$ = Bar reinforcement ratio ($A_s/bd$)

d = Effective depth of internal bar (mm)

$L$ = Un-plated length of strengthened beam (mm)

$a_L$ = Fictitious shear span (mm)

However, since the shear crack at the end of the laminates is the main reason which causes the plate premature de-bonding, anchors could be provided along the laminates portion of fictitious shear span. Thus, end anchorage length can be obtained using the Eq. 2 and it should not be more than the effective depth ($d$) of the beam.

Anchorage length $x = [a_L - L] \leq d$

Eq. (4)

4. Experimental Investigations
4.1 Material properties

Concrete

The 28-day concrete having average compressive strength of 36MPa is specified for all beam specimens. The concrete was prepared with the mix proportion of 1:1.65:2.45 by the weight of ordinary Portland cement, locally available natural sand, and crushed granite aggregate. The water-cement ratio was maintained 0.45. The beams are cast from the same batch. Standard size specimens were tested in the laboratory to determine the cube’s strength, modulus of elasticity, splitting tensile strength and modulus of rupture of the concrete at 28 days. These characteristics are shown in Table 1 as based on the laboratory test results.

Steel

Two types of mild-steel bars of hot-rolled deformed high yield bars, 6 and 10mm in diameters (T6 and T10) and plain round mild steel bars, 6mm in diameter (R6 as stirrups) were used for all beams fabrication. The tests were conducted in the laboratory using a Universal Testing Machine to obtain the modulus of elasticity and yield strength values of the steel reinforcing bars. Table 2 shows the details of steel reinforcement properties.

CFRP laminates and epoxy adhesive

Unidirectional CFRP laminates (each of 1.2mm thickness) used for the strengthening purposes of the beams and they were cut from the Sika Carbodur S1012/160 (2008) rolled laminate. The CFRP composite laminate was tested in the laboratory to get the tensile strength, yield strength, modulus of elasticity and the percentage of ultimate elongation until at failure. The other properties of the carbon fibers and epoxy adhesive, as supplied by the manufacture are presented in Table 3.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Values found in the laboratory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive strength (MPa)</td>
<td>36.0</td>
</tr>
<tr>
<td>Modulus of elasticity (GPa)</td>
<td>28.6</td>
</tr>
<tr>
<td>Modulus of rupture (MPa)</td>
<td>3.7</td>
</tr>
<tr>
<td>Splitting tensile strength (MPa)</td>
<td>2.95</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reinforcement type</th>
<th>Yield strength (MPa)</th>
<th>Modulus of elasticity (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tension,T10</td>
<td>482</td>
<td>195</td>
</tr>
<tr>
<td>Compression,T6</td>
<td>470</td>
<td>186</td>
</tr>
<tr>
<td>Shear,R6</td>
<td>215</td>
<td>200</td>
</tr>
</tbody>
</table>
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Table 3: CFRP laminates and epoxy adhesive properties

<table>
<thead>
<tr>
<th>Materials</th>
<th>Property</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFRP laminate</td>
<td>Sheet form</td>
<td>Uni-directional roving</td>
</tr>
<tr>
<td></td>
<td>Yield strength (MPa)</td>
<td>1315</td>
</tr>
<tr>
<td></td>
<td>Modulus of Elasticity (GPa)</td>
<td>165</td>
</tr>
<tr>
<td></td>
<td>Elongation at ultimate (%)</td>
<td>2.15</td>
</tr>
<tr>
<td></td>
<td>Design thickness (mm/ply)</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>Tensile strength (MPa)</td>
<td>1685</td>
</tr>
<tr>
<td></td>
<td>Density (g/cm³)</td>
<td>1600</td>
</tr>
<tr>
<td>Epoxy adhesive</td>
<td>Modulus of Elasticity (GPa)</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Elongation at ultimate (%)</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>Tensile strength (MPa)</td>
<td>55</td>
</tr>
</tbody>
</table>

4.2 Test program

Table 4 summarizes the general experimental test program. This program consisted of testing five rectangular beams in order to evaluate the effect of externally bonded CFRP laminates to the different strengthening scheme for the entire beam length. A total of five reinforced concrete beams having different CFRP configurations were fabricated in the laboratory for the strengthening purposes. First beam (designated as CB) was not bonded with CFRP laminates, three beams (FB-1L, FB-2L and FB-3L) were bonded with different layers of CFRP laminates (1, 2 and 3–layers respectively) and the rest one beams (designated as FB-1LU) were bonded with one layer CFRP laminates and having one U-shaped edge strips. These transverse CFRP laminates provide anchorage for the longitudinal plate, and considered effective in preventing de-bonding failure of laminates from the concrete surface.

Table 4: Test Program

<table>
<thead>
<tr>
<th>Strengthening scheme</th>
<th>Control (not bonded)</th>
<th>1-layer bonded</th>
<th>2-layer bonded</th>
<th>3-layer bonded</th>
<th>1-layer with U-side strips</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam designation</td>
<td>CB</td>
<td>FB-1L</td>
<td>FB-2L</td>
<td>FB-3L</td>
<td>FB-1LU</td>
</tr>
</tbody>
</table>

4.3 Specimen size and steel reinforcement details

Fig. 3 shows the reinforcement details of the experimental test beams. All the beam specimens were 150 × 200 mm in cross section and 1900 mm in span length on a simply supported span. They were reinforced with two T10 (10mm in diameter) bars as tensile reinforcement at an effective depth of 168mm and two T6 (6mm in diameter) bars as compressive reinforcement at 30mm from the top surface. R6 stirrups were placed at a constant spacing of 125 mm throughout the entire length of the beams. The stirrups are designed to ensure that none of the beams would fail in shear. The longitudinal
reinforcement ratio is about 0.62% of the beam cross-section. All beams were designed to fail in flexure according to the specification of the BS 8110-1 (1997) code of practice.

Section A – A

Figure 3: Longitudinal and cross-section details of the test beams

4.4 Surface treatment phase

The surface of the beam, where the sheet/strip was to be attached, was first grinded manually and then subjected to sand blasting to be able to develop a sound bond and withstand the imposed stresses. The process included creating somewhat a rough surface on the tension face and two corner sides (for bonding the U-side strips) of the beam to remove laitance, grease and loosely adhering particles. It was ensured that the surface was kept free from any contaminant, air entrapment and unevenness areas and was smooth.

4.5 Attaching the CFRP laminates

After preparing the concrete surfaces and wiping out the CFRP sheets, two-part cold curing epoxy resin sikadur-30 (Part-A and Part-B mixed at a proportion 1:3) adhesive was applied on both cleaned and prepared substrate components. Hence, the composites sheets were bonded to the tension face (bottom) of the concrete beam. The CFRP sheets were attached starting at one end and applying enough pressure by sika carbodur rubber roller to press out any excess epoxy from the sides of the sheets. The prepared specimens were tested after a minimum of 3 days after bonding to ensure the full curing of the
epoxy adhesive. For the beam FB-1L, FB-2L and FB-3L, carbon fiber reinforced polymer (CFRP) laminates were attached at the tension (i.e., bottom) face of the beam as illustrated in Figs. 4(a)–4(c), whereas the beam FB-1LU, after externally bonded a single layer of laminates at the bottom tension face, U-strip anchorages were also provided at the ends of the beam as refer to Fig. 4(d).

4.6 Instrumentation and test procedure

The test procedure consisted of loading monotonically until the failure of the beams. The specimens were tested in four-point static loading over a 1900 mm simply supported span to investigate the flexural performance to different level of CFRP laminates strengthening scheme. The two point loads were positioned using hollow steel sections at one-third span length, and loading was under displacement control. Fig. 5 shows the overall instrumentation details of the test specimens. The static loads were applied at a regular interval by Universal Testing Machine until failure occurred on the specimens. During the testing, the deflections of all beams were measured at mid-span and at the location of the applied loads using three linear variable displacement transducers (LVDTs). The quarter span transducers were used to check the symmetrical nature of the loaded beams. Load at first crack instance was noted down. Also subsequent crack pattern were marked

**Figure 4:** Schematic of Strengthening schemes: CFRP laminates with (a) single (b) double and (c) triple layer (d) anchorage with U-side strips
on the beam surface as they develop during the application of load from first crack appear until the failure of the beam. All transducers were connected to the data acquisition system.

Figure 5: Typical four-point bending test set up

5. Test Results and Discussion

5.1 Ductility characteristics

Ductility is an important factor for any structural element or structure itself especially in the seismic regions. A ductile material is one that can undergo large strains while resisting loads. When applied to RC members, the term ductility implies the ability to sustain significant inelastic deformation prior to collapse. Ductility is also best expressed as an index or a factor, through relationship at some critical stages in the performance characteristics of a structural member. In this study, the displacement ductility was investigated. The displacement ductility index (displacement at failure divided by displacement at yield) can give an estimation of the lack of ductility of these beams. Table 5 shows the displacement ductility of the tested RC beams using different CFRP laminates configurations. It was also observed that un-strengthened beam showed more displacement or ductility as compared to that of different CFRP configurations concrete beam. The maximum deflection prior to the final failure of the CFRP strengthened beams was found about 12.8mm and it indicate that the strengthened beams are less ductile compared to the NWC beams. The lower value of ductility index for the CFRP strengthened beams (FB-1L, FB-2L and FB-3L) indicates the lacking of ductility of such strengthened beams. It was also observed that end anchored strengthened beams showed more displacement or ductility as compared to those of without anchored one. However, the observed improvement of ductility index from U-shaped edge strip beam was not that significant.

5.2 First cracking and ultimate loads
From the experimental investigation, the first cracking load and the ultimate capacity of the strengthened and un-strengthened (control) tested beams are noted. Table 5 presents the flexural performance of theoretical and experimental values of cracking and ultimate load for the tested beams. Theoretical predictions of the first cracking load was calculated from the equivalent transformed section analysis of the beam cross-section and ultimate load carrying capacity was predicted using equivalent stress block of the cracked cross section in accordance to the provision mentioned in BS 8110-1 (1997).

Table 5: Theoretical and experimental results

<table>
<thead>
<tr>
<th>Beam designation</th>
<th>Experimental load (kN)</th>
<th>Theoretical load (kN)</th>
<th>Ultimate load crack spacing (mm)</th>
<th>Ductility index</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB</td>
<td>12.4</td>
<td>40.3</td>
<td>11.3</td>
<td>31.5</td>
<td>105</td>
</tr>
<tr>
<td>FB-1L</td>
<td>15.5</td>
<td>62.0</td>
<td>12.3</td>
<td>82.6</td>
<td>126</td>
</tr>
<tr>
<td>FB-2L</td>
<td>18.6</td>
<td>69.75</td>
<td>13.4</td>
<td>98.8</td>
<td>138</td>
</tr>
<tr>
<td>FB-3L</td>
<td>21.7</td>
<td>74.4</td>
<td>14.4</td>
<td>106.8</td>
<td>149</td>
</tr>
<tr>
<td>FB-1LU</td>
<td>23.25</td>
<td>75.95</td>
<td>12.3</td>
<td>82.6</td>
<td>156</td>
</tr>
</tbody>
</table>

The un-strengthened (control) beam failed by yielding of steel tension reinforcement followed by crushing of the concrete directly under the four-point bending test. When loaded in the laboratory, the control beam (CB) developed flexural tensile cracks in the constant bending region at load of 11.3kN. The tensile steel has yielded at loads near 37.2kN. The beam failed in flexure due to the crushing of extreme compression zone of concrete at a load 40.3kN. In general, different levels of CFRP strengthened reinforced concrete beams (FB-1L, FB-2L, FB-3L and FB-1LU) showed significant increases in flexural stiffness and ultimate capacity as compared to that of control beam. From the experimental investigation, it is identified that the percentage increase of cracking load of 1, 2 and 3-layers CFRP strengthened beams are 25%, 50% and 75% respectively whereas the percentage increase of ultimate load are 54%, 73% and 85% respectively as compared to the control beam. The increase in first crack load of strengthened beams can be attributed to the increase of stiffness due to the laminates restraining effects. The use of transverse U-shaped wrap strips gives an increase of 82% flexural capacity as compared to that of control beam. When compared to that of 1-layer un-wrapped beam, this increase in flexural capacity was 23% more. Thus, it is concluded that the laminate thickness and transverse edge strips significantly influence the structural performance of the strengthened beams. A comparison between experimental and theoretical result shows that the theoretical calculation give conservative estimation of the first cracking load but underestimate the ultimate capacity of the strengthened beams. In general, the experimental results are in close agreement with the theoretical predictions.
5.3 Load-deflection relationship

The load-deflection behavior of the control beam and beam strengthened with different layers of CFRP laminates are shown in Fig.6. Fig.7 displays the load-deflection response of beams strengthened with single layer of CFRP laminate but having different degrees of restrain at the edges against premature de-bonding. It is observed from Fig.6, that initially all the strengthened beams behave like the control beam with the internal steel reinforcing bars carrying the majority of the tensile force in the section. When the internal steel yields, the additional tensile force is carried by the FRP system and an increase of the load capacity of the member is obtained. Eventually, the FRP strengthened beams fail. The failure modes which are observed on the CFRP strengthened beams are different from that of the classical reinforced concrete control beam. CFRP reinforced beams behaves in a linear elastic fashion nearly up-to the failure. The use of second and third layer of CFRP plates can lead to significant increase in the ultimate load and stiffness of the beam. The load deflection plots of strengthened beams with U-shaped edge strips shows nearly similar response to that of strengthened beam without transverse edge strips. However, a significant increase in the ultimate strength was noted in this beam, although it still showed sign of de-bonding just before ultimate failure.

Figure 6: Load-deflection responses of control beam
Figure 7: Load-deflection response of single layer strengthened beam with different edge restraint beams

5.4 Crack spacing and distribution

Table 5 shows the summarized values of ultimate loading stage crack spacing. For all the beams, the first crack appeared in the middle third zone of the beam. It can be seen from Table 5, crack spacing of un-strengthened beam was highest then the different level of CFRP strengthened reinforced concrete beam. It was also observed that the increase in CFRP layer on reinforced concrete beams then the increased crack spacing. Moreover, closed spaced cracks or more number of cracks, leads to smaller crack width. The reason for this behavior is that the crack spacing is a function of both the tensile strength and the bond strength of the concrete, reinforcing steel and CFRP laminates. The increase in the tensile strength of concrete due to the increase in its strength for the contribution of CFRP laminates then the increase in the bond strength of concrete. When the multi-layered CFRP laminates attach on the soffit of the beams, thus the crack position a longer distance is required for the tensile force in the steel reinforcement and CFRP laminates to be retransferred to the surrounding concrete, which implies larger crack spacing.

5.5 Crack pattern and failure modes

The failure modes which are observed on the CFRP strengthened beams are different from those of the classical control beam. The failure modes of the experimental beams have been tabulated in Table 5. It was observed from the experimental investigation that all beams strengthened with CFRP laminates have failed in the same manner. The failure
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The crack patterns and modes of failure of the control beam, one and two layers CFRP strengthened beams and CFRP strengthened beams with U-shaped transverse strips are shown in Figs. 8 (a), 8 (b), 8 (c) and 8 (d) respectively. During the testing, the un-strengthened (control) beam exhibited widely spaced and greater number of cracks compared to the strengthened beams.

The cracks have appeared on the surface of the strengthened beams at relatively close spacing. This behavior shows the enhanced concrete confinement due to the influence of the CFRP laminates. Also the composite action had resulted in shifting of failure mode from flexural failure (steel yielding) in case of control beam to peeling of CFRP laminates for the strengthened beams. A crack normally initiates in the vertical direction and as the load increases it extended upward drastically due to the combined effect of shear and flexure. If the load is increased further, cracks propagate to top and the beam splits. This type of failure is called flexure-shear failure. Finally, the beam failed due to the separation of CFRP sheet by giving cracking sound along with the flexural-shear cracks.

**Figure 8:** Mode of failure (a) Control beam (b) beam strengthened with 1-layer CFRP laminate (c) 2-layer CFRP laminates (d) Strengthened beam with U-shaped edge strip
6. Conclusions

Based on the experimental test results, following conclusion can be made:

1. The result of the experimental study indicates that externally bonded CFRP laminates can be used effectively to strengthen the reinforced concrete beams. Regarding the effect of number of layers, an increase in stiffness and flexural strength is achieved with the increase of CFRP layers. All the strengthened beams didn’t show any inter-layer de-lamination in any cases.

2. Regarding the effect of transverse edge strip, significant improvement in flexural strength was noted and the de-bonding of laminates occurred just before the final failure. Nevertheless, the possible brittle failure of the strengthened beams still needs to be considered.

3. The ductility reduction of the beams after strengthening with CFRP laminate was observed in experimental results. However, this drawback was improved by means of adding the anchorage system with U-shaped edge strips at the end of the laminate in order to avoid both de-bonding and peeling of laminate.

4. The crack pattern at the final loads was observed from the experimental reinforced concrete beams. Furthermore, more distribution and smaller crack amplitude were detected for strengthened beams with respected to the control beam. These effects were more evident for strengthened beams anchorage with U-shaped CFRP edge strips.

5. In general, flexural model based on strain compatibility in the concrete, steel and CFRP reinforcement gave a reasonable prediction of the experimental results. A closer agreement for the ultimate load achieved provided the premature de-bonding of CFRP laminates was prevented by using the transverse edge strips in the beam.

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7. References


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Nomenclature

\( a_L \) = fictitious shear span

\( b \) = width of beam

\( d' \) = compression effective depth

\( d'' \) = tension depth (beam bottom to the center of tension steel)

\( d \) = effective depth of beam section (tension steel)

\( d_f \) = effective depth of beam in FRP (tension FRP)

\( F_{st} \) = force in tension steel

\( F_f \) = force in tension FRP

\( F_{cc} \) = force in compression concrete

\( F_{sc} \) = force in compression steel

\( f_r \) = modulus of rupture of the concrete

\( h \) = total beam height

\( I_g \) = gross moment of inertia of the cross section about neutral axis

\( M_{cr} \) = cracking moment of the RC beam

\( M_u \) = ultimate moment capacity of the RC beam

\( x \) = neutral axis depth

\( x' \) = anchorage length (Jansze et al., 1998)
\( \bar{x} \) = neutral axis depth for un-cracked section

\( y_t \) = distance from the neutral axis to the tension face of the beam