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Research paper

An experimental study on flexural strengthening of RC beams using CFRP sheets

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Abstract

The use of carbon fiber reinforced polymer (CFRP) sheets is becoming a widely accepted solution for strengthening and repairing reinforced concrete (RC) structures. To date, the behavior of RC beams, strengthened with 60° and 45° inclined CFRP sheets, has not clearly explained. An experimental program is proposed in this paper to investigate the flexural behavior of RC beams strengthened with CFRP sheets. CFRP sheets were epoxy bonded to the tension face to enhance the flexural strength of beams inducing different orientation angles of 0°, 45°, 60° and 90° with the beam longitudinal axis. The study shows that strengthening RC beams with CFRP sheets is highly influenced by the orientation angle of the sheets. The orientation angle plays a key role in changing the crack pattern and hence the failure mode. The influence of CFRP sheets was adequate on increasing the flexural strength of RC beams but the ductility of the beams was reduced. The best performance was obtained when strengthening RC beam obliquely using 45° inclined CFRP sheets where the specimen experienced additional deflection and strength of 56% and 12% respectively and the reduction in its ductility was the least. It is recommended to strengthen RC beams, which are weak in flexure, using 45° inclined CFRP sheets.

Keywords: *Angle; CFRP; Flexure; RC; Strengthening.*

1. Introduction

Fiber reinforced polymer (FRP) composites are widely used for strengthening and retrofitting reinforced concrete structures due to its corrosion resistance, durability and flexibility [1]. Great deal of research has been carried out to investigate the experimental response of reinforced concrete beams strengthened with CFRP sheets and laminates. Previous experimental studies have shown that strengthening RC beams with CFRP sheets can be greatly influenced by the configuration, orientation and properties of CFRP sheets [2], [3].

Previous tests have shown that externally bonded CFRP is very effective in upgrading the flexural strength of RC beams. An additional flexural strength in the range of 41–125% was gained by the presence of CFRP sheets [4].

Ashour and Garrity [5] tested 16 reinforced concrete (RC) continuous beams with different arrangements of internal steel bars and external carbon fiber reinforced polymer (CFRP) laminates. Three different failure modes were observed in the strengthened beams, namely laminate rupture, laminate separation and peeling failure of the concrete cover attached to the laminate. The ductility of all strengthened beams was reduced compared to the un-strengthened control beam [5], [6].

Kharatmol et al tested RC beams strengthened in flexure with CFRP and they suggested that wrapping beams with CFRP sheets is more desirable at their tension side. CFRP sheets that were wrapped at tension side gave better strength as compared to CFRP sheets wrapped at two parallel sides [7].

In addition, previous experimental studies [8] showed that CFRP sheets can increase the strength and ductility of the strengthened RC beams. They also suggested that the magnitude of the increment and the failure mode are highly affected by the direction of the reinforcing fibers. If CFRP sheets were wrapped perpendicular to cracks in the beam, a large increase in strength was observed while a brittle behavior is detected [8].

Previous tests conducted by Bukhari et al. [9] showed that shear enhancement and failure mode are related to the carbon sheet orientation. They suggested that shear strength of beams can significantly increase by the presence of CFRP sheets when the sheets are oriented at 45° to the axis of the beam. Other experimental research showed that if CFRP sheets were placed obliquely at an angle of 45° to the cracks, a smaller increment in the strength were observed while failure mode was more ductile [8]. A direct relationship was observed between the increment in strength and the number of CFRP sheets layers and the depth of sheets across the beam section [10].

Hana et al., found that the presence of CFRP sheets and laminates can enhance shear and flexural capacity of deep beams. They suggested that the efficiency of FRP depends on the strengthening scheme. They proposed using 2 layers of CFRP sheets for flexural strengthening of RC beams. An additional flexural strength of 51% was observed when using 2 layers of CFRP sheets compared to the control beam while 27% was recorded when using 1 layer of CFRP sheets [11].

Zhang et al., reported that strengthening reinforced concrete beams with CFRP can significantly increase their serviceability, ductility, and ultimate shear strength [12], [13]. Other experimental research reported that the flexural strength can increase up to 58% on concrete beams strengthened with anchored CFRP sheets [14].

Issa and AbouJouadeh conducted an experimental program and observed that strengthening RC beams with CFRP can increase their load capacity and stiffness. [15]. Further research is required to investigate the flexural behaviour of RC beams strengthened using CFRP sheets under more different orientation angles.

2. Experimental program

Five simply supported RC beams with a rectangular cross-section of 150 mm by 200 mm are tested. Each beam is 2 m long. The specimens are designed to promote flexural failure by choosing two longitudinal bars N0.10 at the top and two longitudinal bars No.14 at the bottom of each beam as illustrated in Fig. 1. The specimens are strengthened in shear by using No.10 stirrups spaced at 150 mm. The yield strength of the longitudinal bars and the stirrups is 500 MPa and 280 MPa respectively. The mean compressive strength of the concrete mix is 30 MPa and the corresponding failure load of the beams is between 93 kN and 106 kN. Four beams are strengthened with CFRP sheets while the control beam F-C is not strengthened. Different arrangements of CFRP sheets are adopted.

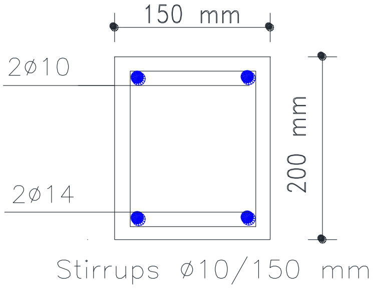

Fig. 1: Detailing of the Test Specimens.

2.1. CFRP properties

The width and thickness of CFRP sheets are 500 mm and 0.166 mm respectively. Fiber weight is 300 g/m^2 and its elongation at break is 2.1%. The elastic modulus of the carbon fibres and their ultimate tensile strength are 4900 MPa and 230 GPa respectively.

CFRP sheets were fixed to the surface of concrete beams using an epoxy resin. The efficiency of CFRP sheets depends on the bond strength between the concrete beam and CFRP sheets. The epoxy resin is used in conjunction with CFRP sheet to produce a high performance composite system for use in structural strengthening and upgrade. The mixed density of the epoxy is 1.06 kg/ Lt, the bond strength is greater than 2.5 MPa and it needs 7 days for full cure at 20° C.

2.2. Strengthening scheme

Fig. 2 shows the strengthening scheme of all test specimens. The strengthening details of the RC beams are illustrated in Fig. 3 to Fig. 6. CFRP sheets are used to strengthen RC beams under different orientation angles. The beam surfaces are cleaned of loose particles before strengthening. The CFRP sheets are epoxy bonded to the tension face to enhance the flexural strength of the beams. Fig. 3 illustrates the strengthening scheme of specimen F-45 where CFRP sheets are fixed obliquely to the beam up to its half depth inducing an angle of ± 45° to the longitudinal axis of the beam. Specimen F-60 is wrapped in the same manner inducing angle ± 60° to the longitudinal axis of the beam as shown in Fig. 4. Specimens F-90 and F-0 are also wrapped in the same way inducing angles of 90° and 0° to the beam longitudinal axis as shown in Fig. 5 and Fig. 6 respectively.

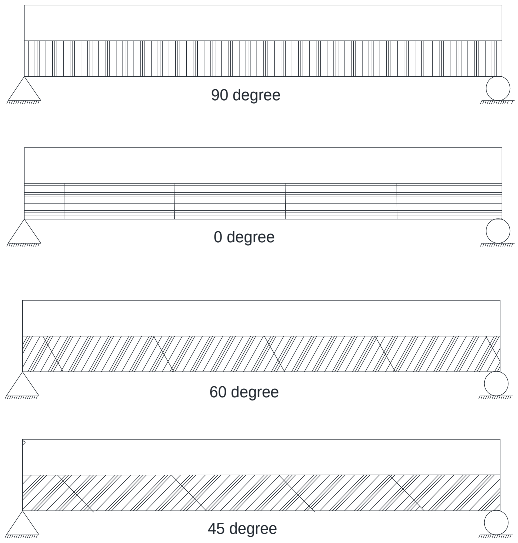

Fig. 2: Strengthening Configuration Scheme.

Fig. 3: Strengthening Details of Specimen F-45 that was Partially Wrapped with CFRP Inducing Angle of ± 45° to the Longitudinal Axis of the Beam.

Fig. 4: Strengthening Details of Specimen F-60 that was Partially Wrapped with CFRP Inducing Angle of ± 60° to the Longitudinal Axis of the Beam.

Fig. 5: Strengthening Details of Specimen F-90 that was Partially Wrapped Perpendicular to the Longitudinal Axis of the Beam.

Fig. 6: Strengthening Details of Specimen F-0 that was Partially Wrapped with CFRP Parallel to the Longitudinal Axis of the Beam.

2.3. Test setup

The length of each beam is 2 m. All specimens are simply supported where horizontal translation is permitted at one end only. The distance between the support and the concentrated load is kept to 640 mm and the distance between the two applied concentrated loads is 720 mm as shown in Fig. 7. Static loads are applied using a 1000 kN capacity hydraulic jack. The deflection of the specimens is expressed with respect to the variation in the vertical displacements. The vertical displacement is measured at mid-span using Linear variable displacement transducers (LVDT).

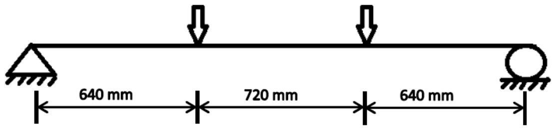

Fig. 7: Illustration of the Test Specimens Dimensions, Supports, and Loads.

3. Experimental results and discussion

3.1. Behaviour of specimens

The experimental results indicate that the influence of CFRP is adequate on increasing the flexural strength of reinforced concrete beams but the ductility is reduced. Ductility can be measured using displacement ductility index (ultimate displacement/ yield displacement). The ultimate displacement in the ductility index is taken as the displacement at which the load, after reaching the peak, dropped to 0.8 of the peak load while the yield displacement is taken as the displacement at 0.75 of the peak load divided by 0.75.) [16]. Table 1 summarizes the ductility indices for all test specimens. The variation in strength and ductility is highly influenced by the orientation angle of CFRP sheets.

3.1.1. Specimen F-C

Five simply supported beams were tested under two concentrated loads. Beam F-C was a control beam which was not strengthened with CFRP sheets. The first crack appeared at a load of 20 kN while tension flexural cracks were gradually extended by the increment of the applied load. Beam F-C sustained a maximum load of 93 kN and experienced 101 mm mid vertical deflection before flexure-tension failure as shown in Fig. 8. Beam F-C failed in a relatively ductile manner as shown in Fig. 8 where the flexural cracks captured in a blue colour. The beam displacement ductility index is 2.71 as shown in Table 1.

3.1.2. Specimen F-0

Beam F-0 was strengthened with CFRP sheets fixed horizontally to the beam up to its half depth inducing 0˚ to the longitudinal axis of the beam as shown in Fig. 6. The first crack appeared at 41 kN load and flexural-shear cracks gradually extended until failure occurred at a maximum load of 99 kN and 51 mm mid vertical deflection after formation of a major flexural-shear crack and CFRP rupture as shown in Fig. 9. The presence of CFRP decreased the beam ductility and ultimate deflection by 37 % and 50% respectively while it increased the flexural strength by 6% compared to the control beam.

Table 1: Ductility Index of the Tested Beams

Beam	Ductility index
F-C	2.71
F-0	1.70
F-90	1.81
F-45	2.49
F-60	2.50

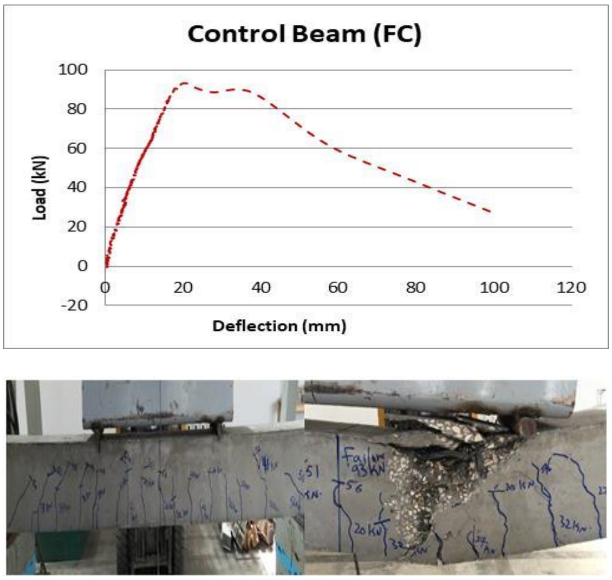

Fig. 8: The Load Displacement Curve of the Control Beam F-C and Its Crack Pattern.

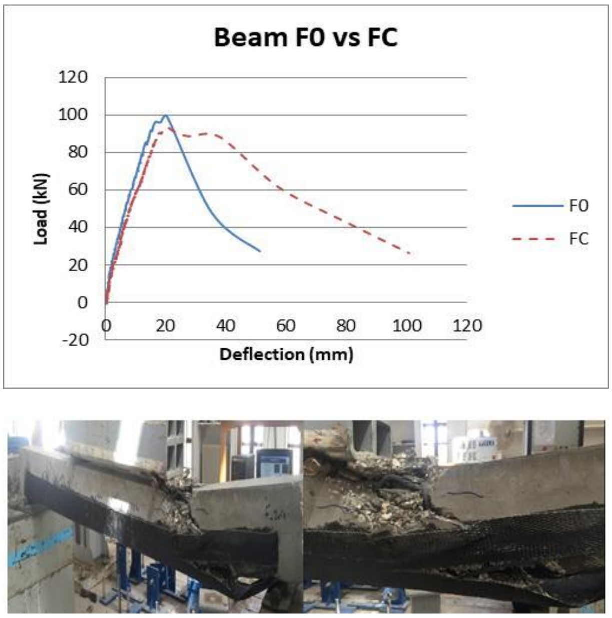

Fig. 9: The Load Displacement Curve of Beam F-0 and Its Crack Pattern.

3.1.3. Specimen F-90

Beam F-90 was strengthened with CFRP sheets oriented perpendicular to the beam longitudinal axis up to the beam half depth as shown in Fig. 5. The first crack appeared at 42 kN load and flexural-shear cracks propagated with the increment of loading. The influence of CFRP was obvious on postponing the appearance of the first crack. Flexural-shear failure and rupture of CFRP sheets occurred at a maximum load of 93 kN and 67 mm mid-vertical deflection after formation of a major flexural-shear crack as shown in Fig. 10. The influence of CFRP was obvious on increasing the beam strength by 4% and decreasing the ductility and deflection by 33 % and 34% respectively compared to the control beam. The increment in strength and the reductions in ductility and deflection in beam F90 due to CFRP sheets was less than that found in beam F0.

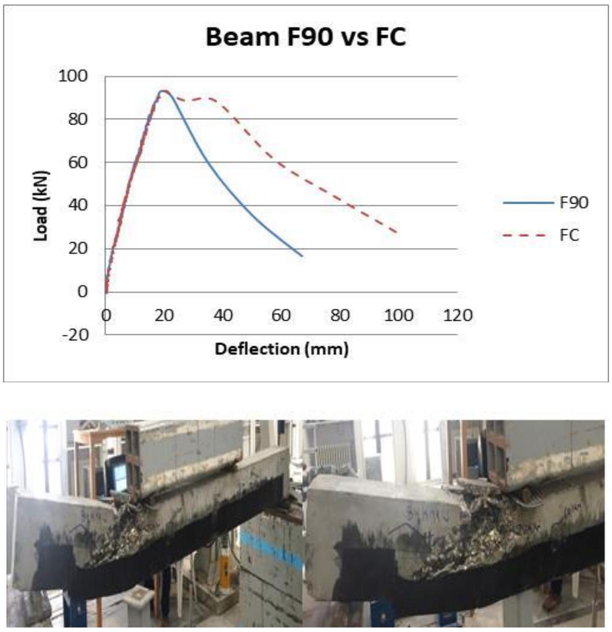

Fig. 10: The Load Displacement Curve of Beam F-90 and Its Crack Pattern.

3.1.4. Specimen F-60

The CFRP sheets were fixed obliquely to beam F-60 inducing an angle of 60˚ to the beam longitudinal axis as shown in Fig. 4. The first crack appeared at a load of 31 kN and tension-flexural cracks propagated by load increments. Failure occurred after formation of a major tension-flexural crack and CFRP rupture at a maximum load of 99 kN and 110 mm mid-vertical deflection as shown in Fig. 11. The strengthened beam experienced 7.8% reduction in ductility with 6% and 9% increments in flexural strength and deflection respectively compared to the control beam as shown in Table 1 and Fig. 11. Furthermore, the presence of the 60˚ inclined CFRP sheets changed the crack pattern where failure occurred in beam F-60 after formation of tension-flexural cracks while failure happened after formation of shear-flexural cracks in beam F-0 and F-90 which were strengthened with horizontal and vertical CFRP sheets respectively.

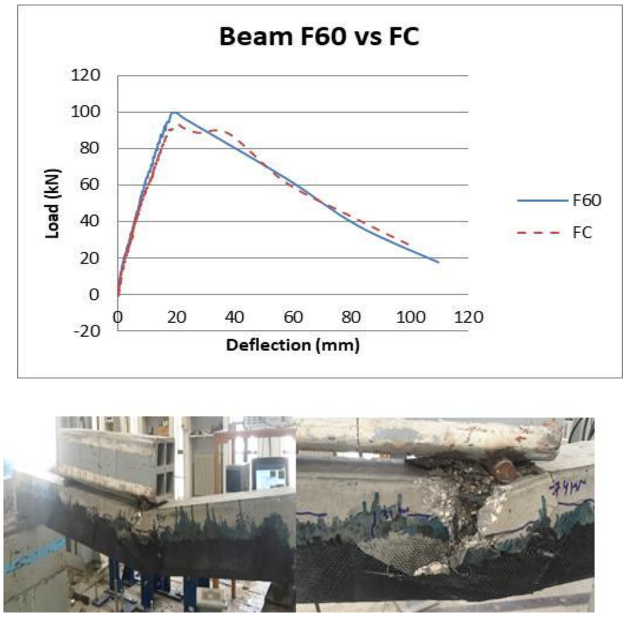

Fig. 11: The Load Displacement Curve of Beam F-60 and Its Crack Pattern.

3.1.5. Specimen F-45

Beam F-45, which was strengthened obliquely with 45˚ inclined CFRP sheets as shown in Fig. 3, had the best performance among all other beams. The presence of the 45˚ inclined CFRP sheets, that were perpendicular to the diagonal shear cracks, changed the crack pattern and hence the failure mode. The inclined CFRP promoted aggregate interlock and hence prevented the shear cracks from propagation. Failure occurred in beam F-45 after the formation of tension-flexural cracks while failure happened after the formation of shear-flexural cracks in beam F-0 and F-90 which were strengthened with horizontal and vertical CFRP sheets respectively. The presence of CFRP sheets postponed the appearance of the first crack which was firstly appeared at 32 kN load. Failure occurred after formation of a major tension-flexural crack and de-bonding of the CFRP sheets at a maximum load of 106 kN and 115 mm mid-vertical displacement as shown in Fig. 12. The influence of the 45˚ inclined CFRP sheets was remarkable on increasing the beam strength and deflection by 12% and 14% respectively but 8% loss in ductility was measured in F-45 compared to the control beam. The reduction in ductility of beams F-45 and F-60, which were strengthened with inclined CFRP, was significantly less than that found in beams F-0 and F-90.

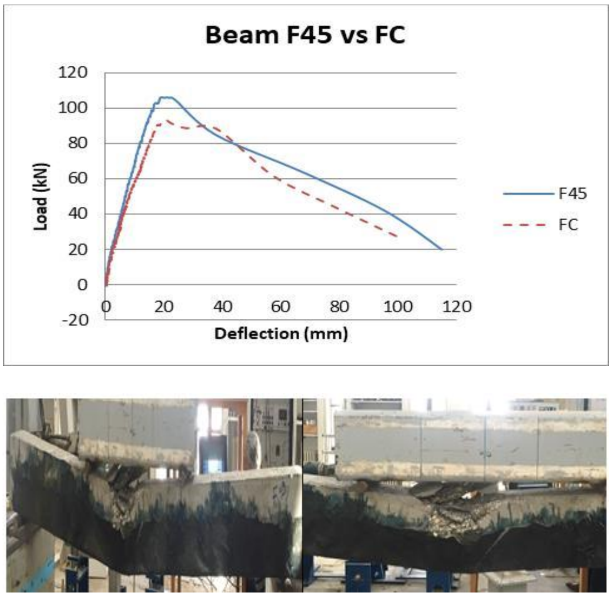

Fig. 12: The Load Displacement Curve of Beam F-45 and Its Crack Pattern.

Fig. 13 compares between the load-displacement curves of all test specimens. It is obvious that the presence of CFRP sheets enhanced the flexural strength of all RC beams and reduced their ductility. Beam F-45 had the best performance in compared to the other strengthened beams.

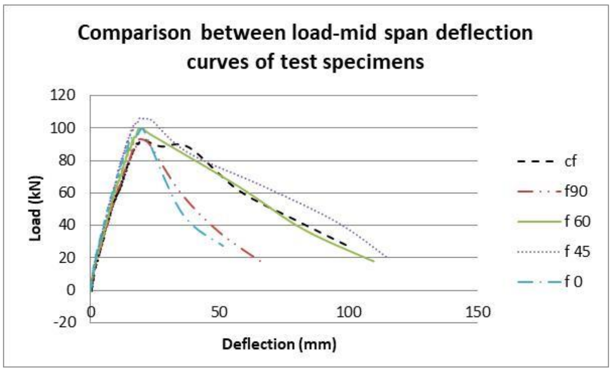

Fig. 13: Comparison between the Load-Displacement Curves of All Test Specimens.

3.2. The influence of CFRP orientation angle

The influence of CFRP orientation angle on RC beams' flexural strength, ductility, deflection and failure mode is investigated in detail in this section.

3.2.1. Flexural strength

The experimental study showed that strengthening RC beams which are weak in flexure, using CFRP sheets that were epoxy bonded to the beam tension side up to its half depth, increased their flexural strength. The increment in strength depends significantly on the orientation angle of the sheet. The highest increment in the flexural strength was found in the beam strengthened with 45˚ inclined CFRP sheets where 12% additional strength was detected while the least increment was 4% measured in the beam strengthened with longitudinal CFRP sheets (angle = 90˚). The use of transverse and 60˚ inclined CFRP sheets increased the flexural strength of RC beams by 6%.

3.2.2. Ductility

Strengthening RC beams which are weak in flexure using CFRP sheets increased their flexural strength but it reduced their ductility. The reduction in ductility depends significantly on the orientation angle of the sheet where the reductions, measured in beams strengthened with inclined CFRP sheets, were less than that found in those strengthened with transverse and longitudinal CFRP sheets. The ductility of beams F-45 and F-60 was reduced 8% compared to the un-strengthened beam. The reduction in ductility was 33% and 37% in the beams strengthened with longitudinal and transverse CFRP sheets respectively.

3.2.3. Failure mode

Beams F-0 and F-90 experienced flexural-shear cracks before failure while tension-flexural cracks propagated in beams F-60 and F-45 when reaching their ultimate capacity. The inclined CFRP sheets are almost perpendicular to the angle of diagonal shear cracks as a result this can promote aggregate interlock, reduce the width of shear cracks, possibly change the failure mode and hence improve the ductility of the beams and postpone cracks propagation. The use of inclined CFRP sheets enhanced the beam in shear and hence sole flexural cracks propagated in these beams before failure. Flexural-shear cracks were detected in the beams strengthened with horizontal and vertical CFRP sheets where shear strength is relatively less than that found in F-45 and F-60 due to the orientation angle of CFRP sheets. In addition, CFRP sheets postponed the appearance of the first crack and crack propagation.

3.2.4. Deflection

Strengthening RC beams with inclined 45˚ and 60˚ CFRP sheets increased the ultimate deflection of the beams by 14% and 9 % respectively. By contrast, using transverse and longitudinal CFRP sheets decreased the ultimate deflection to 50 % and 34% respectively compared to the control beam.

4. Conclusion

An experimental study was carried out in order to investigate the influence of CFRP sheets on the overall response of RC beams. The study focuses on the effect of CFRP orientation angles thus the beams were strengthened with CFRP sheets oriented at 0˚, 45˚, 60˚ and 90˚ to the longitudinal axis of the beam. These points are summarised based on the experimental study:

1) Flexural strengthening of RC beams with CFRP sheets is highly influenced by the orientation angle of CFRP sheets.
2) The presence of CFRP sheets increased the flexural strength and reduced the ductility of all test specimens.
3) The largest flexural strength was measured in the beam strengthened with 45˚ inclined CFRP which had an additional flexural strength of 12% compared to the control beam.
4) Ductility, flexural strength, and ultimate deflection measured in beams strengthened with longitudinal and transverse CFRP sheets were less than that found in beams strengthened with inclined CFRP sheets.
5) The ductility of beams F-45 and F-60 was reduced 8% compared to the un-strengthened beam. The reduction in ductility was 33% and 37% in the beams strengthened with longitudinal and transverse CFRP sheets respectively.
6) Strengthening RC beams with inclined 45˚ and 60˚ CFRP sheets increased the ultimate deflection of the beams by 14% and 9 % respectively. By contrast, using transverse and longitudinal CFRP sheets decreased the ultimate deflection to 50 % and 34% respectively compared to the control beam.
7) The presence of CFRP sheets postponed the appearance and propagation of the cracks.
8) The orientation angle of the CFRP sheets plays a key role in changing the crack pattern and hence the failure mode. Beams F-45 and F-60 failed after formation of a major tensile-flexural crack while beams F-0 and F-90 failed after formation of a major shear-flexural crack.
9) It is beneficial to strengthen RC beams obliquely using 45˚ inclined CFRP sheets. Beam F-45 had the best performance among all other beams and experienced an additional deflection and strength of 56% and 12% respectively while its ductility was reduced 8%.

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