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Structural strengthening of RC beams externally bonded with different CFRP laminates configurations

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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. A total of five beams having different CFRP laminates configurations are tested to failure in four-point bending over a clear span 1900mm. Four beams are strengthened by changing the levels of CFRP laminates whereas the last one is 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, CFRP, 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. This implies that these factors are contributed to infrastructure becoming either structurally inefficient or functionally obsolete. Before the introduce of fibre reinforced polymer (FRP) strengthening technologies, one popular technique for upgrading reinforced concrete beams was the use of external epoxy-bonded steel plates (Swamy et al., 2003, Hamoush et al., 1990). In recent years, FRP sheets have shown great promise as an alternative to steel plates for concrete structure 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 (Saadatmanes and Ehsani, 1991, Meier and Kaiser, 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 debonding 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 debonding of FRP plate or ripping of the concrete cover. These failure modes are undesirable because the FRP plate cannot be fully utilized. In addition, such premature failures are generally associated with a reduction in deformability of the strengthened members. 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 covercrete 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 et al., 1997, Rabinovich et al., 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 (Barnes et al., 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 Holloway, 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)

Some recent work (Alam and Zumaat 2009, Siddiqui, 2009, Alsayed et al., 2002, Meier and Kaiser, 1991) have shown that external bonded of FRP to structural concrete members is an effective and simple method to increase the their structural capacity, for example as in reinforced concrete columns or reinforced concrete beams retrofitted by FRP laminates. The results of CFRP strengthened reinforced concrete beams verified with those obtained from inelastic analysis as well as finite element analysis (Ziraba et al., 1994,). 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 debonding of plates was a concern in some of these studies (Aram et al., 2008, Alam and Zumaat 2009, 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 approaches to evaluate the flexural behavior of FRP laminates to concrete structures are described in this code. CEB-FIP (1993) uses a rectangular stress block similar to that used in normal reinforced concrete beams. This code also considers a linear strain variation over the depth of sections, and uses the value of 0.0035 for the maximum concrete compressive strain. In this codes 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 Fig.1).

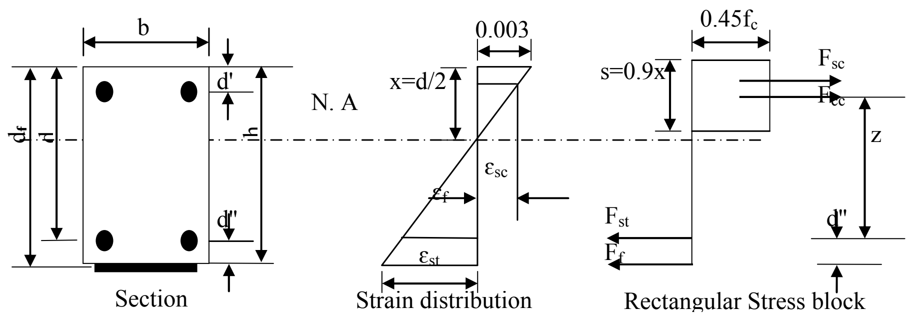


Figure 1. Linear Strain Variation over the Depth of the Section and Rectangular Stress Block.

The cracking moment M_{cr} of the strengthened beams may be computed as follows

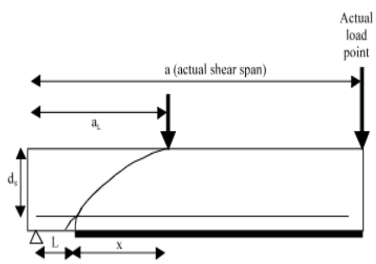
$$M_{cr} = \frac{f_r I_g}{y_t} \qquad \text{(A)}$$

where y_t is the distance from the neutral axis to the tension face of the beam, f_r 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 provision of the 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_s (refer to Fig. 1) and ultimate bending moment is expressed by the following equation:

$$M_u = F_{sc}(d - d^{'}) + F_{cc}(d - 0.45x) + F_f * d^{"} \qquad \text{(B)}$$

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 forend 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.



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

where

ρ_s= Bar reinforcement ratio (A_s/bd); d_s = Effective depth of internal bar (mm); L = Unplated 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 debonding, 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_s)* of the beam.

Anchorage length $x = [a_L - L] \le d_s$ (2)

4. Experimental Program

4.1 Material properties

4.1.1 Concrete

The 28-day concrete having average compressive strength of 36MPa is specified for all beam specimens. The concrete is 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 nominal size of coarse aggregate was used 10mm to cast all the beams. The beams are cast from the same batch. After demoulding, they are cured in fresh water for 28 days. Standard size specimens were tested in the laboratory to determine the cube's strength, modulus of elasticity, splitting tensile strength and modulus of rupture at 28 days. The characteristics concrete strengths are shown in Table 1 as based on the laboratory test results.

4.1.2 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 steel reinforcing bars. Table 2 shows the details of steel reinforcement properties.

4.1.3 CFRP laminates and epoxy adhesive

Unidirectional CFRP laminates (each of 1.2mm thickness) used for the strengthening purposes of the beams are cut from the Sika Carbodur S1012/160 rolled laminate (Edition 0308/2, 2008).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 the failure. The other properties of the carbon fibers and epoxy adhesive, as supplied by the manufacture, are presented in Table 3.

Table 1
Concrete properties

Properties	Values found in the laboratory
Concrete cube strength (MPa)	36.0
Modulus of elasticity (GPa)	28.6
Modulus of rupture (MPa)	3.7
Splitting tensile strength (MPa)	2.95

Table 2
Steel properties

Reinforcement type	Yield strength (MPa)	Modulus of elasticity (GPa)
Tension,T10	482	195
Compression,T6	470	186
Shear,R6	215	200

Table 3
CFRP laminates and epoxy adhesive properties

Materials	Property	Values
CFRP laminate	Sheet form	Uni-directional roving
	Yield strength (MPa)	1315
	Modulus of Elasticity (GPa)	165
	Elongation at ultimate (%)	2.15
	Design thickness (mm/ply)	1.2
	Tensile strength (MPa)	1685
	Density (g/cm^3)	1600
Epoxy adhesive	Modulus of Elasticity (GPa)	3
	Elongation at ultimate (%)	2.6
	Tensile strength (MPa)	55

4.2 Preparation of the test specimens

4.2.1 Test matrix

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. In addition, a 300 mm region of the beam from the supports was wrapped with 1-layer of CFRP as shown in Fig. 3(d). These transverse CFRP laminates provide anchorage for the longitudinal plate, and considered effective in preventing debonding failure of laminates from the concrete surface.

Table 4
Test program

	Strengthening scheme				
	Control (not bonded)	1-layer bonded	2-layer bonded	3-layer bonded	1-layer with U-side strips
Beam designation	CB	FB-1L	FB-2L	FB-3L	FB -1LU

4.2.2 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 code of practice (BS 8110-1, 1997).

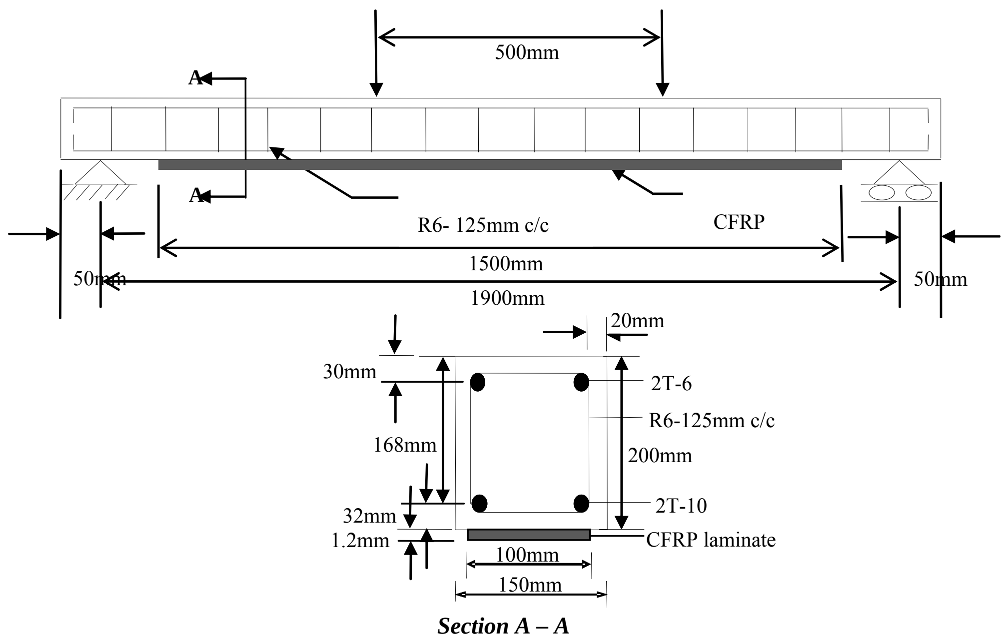


Figure 3. Longitudinal and Cross-section details of the test beams

4.2.3 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. After that the surface of the concrete was cleaned with sika colma cleaner several times until no longer blackness is shown on the beam surface. At this point the CFRP sheets were also wiped using colma cleaner to remove dust or any adhered substances.

4.2.4 Attaching the CFRP sheets

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. It was ensure that to prevent the formation of air bubbles while spreading the adhesive from one surface to the other. Then the CFRP sheets were placed onto the prepared concrete surface. Hence, the composites sheets were bonded to the tension face (bottom) of the concrete beams and can be cured at room temperature. 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. Excess epoxy was removed from the sides of the sheets. The prepared specimens were tested to failure using an Universal Testing Machine 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)–3(c), whereas the beam FB-1LU, after externally bonded a single layer of composite laminates at the bottom tension face, U-strip anchorages were also provided at the ends of the beam as refer to Fig. 3(d).

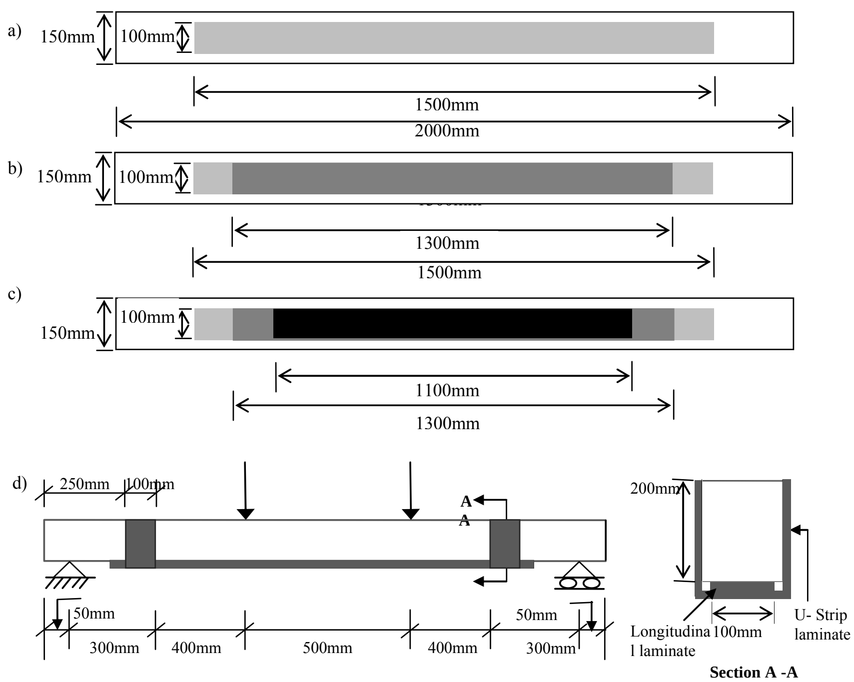


Figure 4. Schematic of Strengthening schemes: CFRP laminates with (a) single (b) double and (c) triple layer (d) anchorage with U- side strips

4.3 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 (LVDT). 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 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.

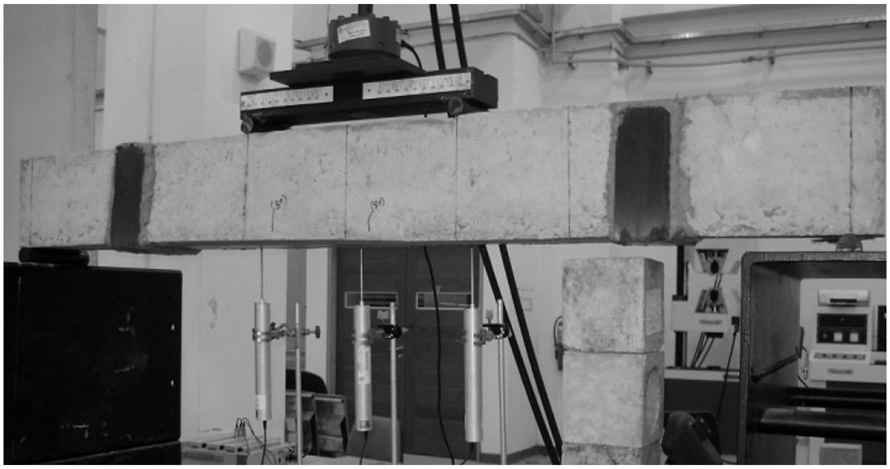


Figure 5. Typical four-point bending test set up

5. **Test results and analysis**

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 last column of Table 5 show the displacement ductility index calculated for the beams. The lower value of ductility index for the CFRP strengthened beams (FB-1L, FB-2L and FB-3L) indicate 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 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 unstrengthened (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 is calculated from the equivalent transformed section analysis of the beam cross-section and ultimate load carrying capacity is predicted using equivalent stress block of the cracked cross section in accordance to the provision mentioned in British Standard (BS 8110 Part 1, 1997).

Table 5
Theoretical and experimental results

Beam designation	Experimental load (kN)		Theoretical load (kN)		*Ultimate load crack spacing (mm)*	*Ductility index*	Failure mode
	P_{cr}	P_{ut}	P_{cr}	P_{ult}			
CB	12.4	40.3	11.3	31.5	105	3.81	Concrete crushing
FB-1L	15.5	62.0	12.3	82.6	126	1.65	Debonding
FB-2L	18.6	69.75	13.4	98.8	138	1.48	Debonding
FB-3L	21.7	74.4	14.4	106.8	149	1.29	Debonding
FB-1LU	23.25	75.95	12.3	82.6	156	2.28	Concrete crushing and debonding

The unstrengthened (control) beam failed by yielding of steel tension reinforcement followed by crushing of the concrete directly under 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 37.1kN. The beam failed in flexure due to the crushing of extreme compression zone concrete at load 40.3kN.

In general, different level 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 control beam and beam strengthened with different layers of CFRP laminates are shown in Fig.6. Fig.7 plots the load-deflection response of beams strengthened with single layer of CFRP laminate but having different degrees of restrain at the edges against premature debonding. It is observed from Fig. 6, 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. This brittle mode of failure is considered as a drawback for this way of reinforcement. The use of second and third layer of CFRP plates can lead to significant increase in the ultimate load and stiffness of the beam.

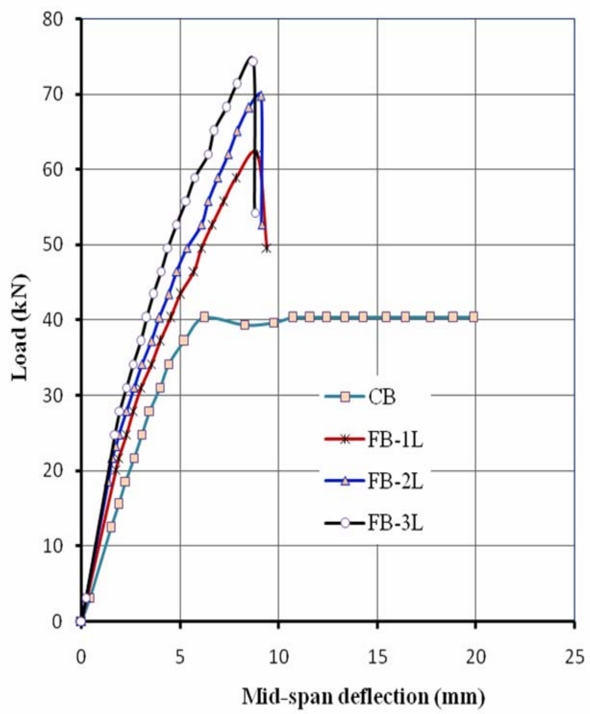


Figure 6. Load-deflection responses of control beam and multi-layer CFRP strengthened beams

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 debonding just before final failure.

5.4 Crack spacing and distribution

Generally, in beams cracks occur when the stress in the tensile zone reaches the modulus of rupture of the concrete beam. 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. The vertical pattern of cracks indicates that they were flexural cracks. 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.

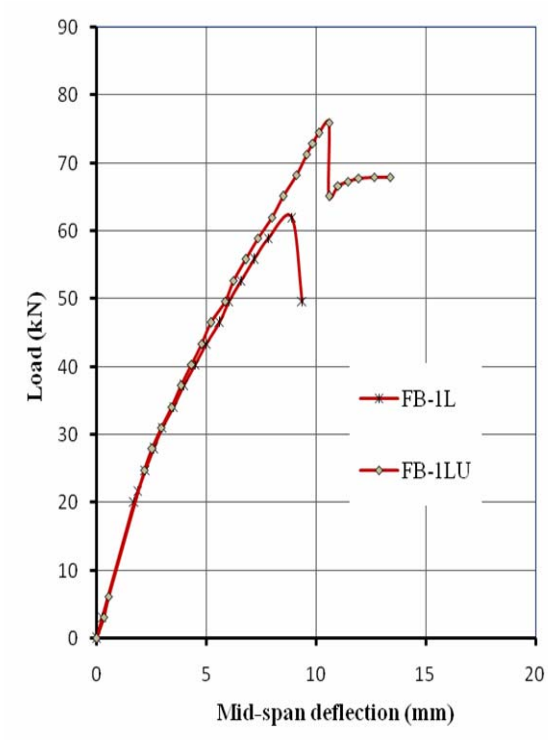
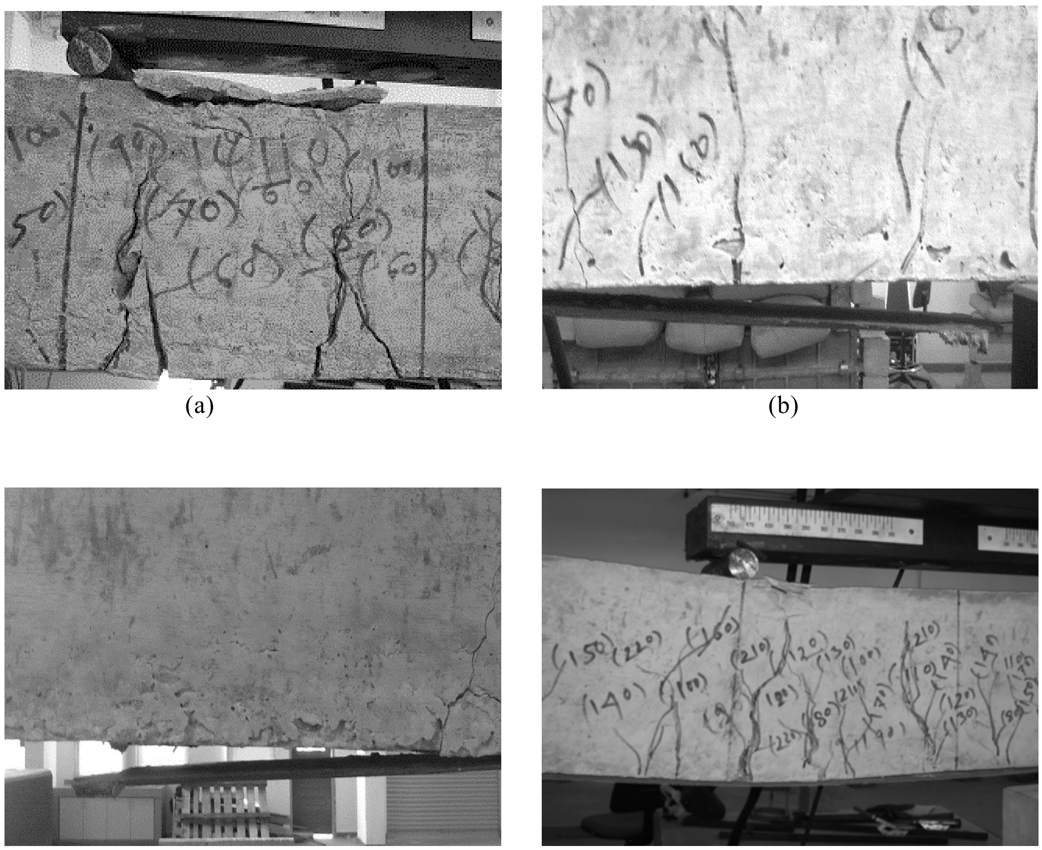


Figure 7. Load-deflection response of single layer strengthened beam with different edge restraint beams.

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 mode of specimens with transverse edge strip was different from that of un-wrapped one. The crack patterns and modes of failure of control beam, one and two layers CFRP strengthened beams and CFRP strengthened beams with U-shaped transverse strips are shown in Figs. 8 (a) to 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 has 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) (b) (c) (d)

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

This paper presented the results of an experimental program investigating the flexural performance of reinforced concrete beams strengthened with different CFRP laminates configurations. 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 delamination in any cases.

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

3) The bond between the laminates and concrete, combined with the additional end strips provided by easily applied at the end, ensured failure of either the concrete in compression or the laminates in tension. Both of these failure modes displayed in a lower ductility compared with control beam prior to failure.

4) Failure mode of beam strengthened with CFRP sheets and end anchorage was by debonding of the strips and concrete crushing in compression zone and the time to delaminate of CFRP was shortened.

5) In general, the experimental results are in very good agreement with the theoretical predictions; especially for the third layers and U-side strips anchorage CFRP strengthened reinforced concrete beams.

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References

Alam, M.A. and Zumaat, M.Z. (2009). "Eliminating premature end peeling of flexurally strengthened reinforced concrete beams", Journal of applied sciences, 9 (6), 1106-1113.

Aram M. R., Czaderski, C., Motavalli, M. (2008). "Debonding failure modes of flexural FRP-strengthened RC beams", Composites: Part B, 39, 826–841.

Ascione L, Feo L. (2000). "Modeling of composite/concrete interface of RC beams strengthened with composite laminates", Composites Part B: Engineering, 31:535–40.

Alsayed, S.H., Al-Salloum, Y.A., and Almusallam, T.H.(2002). "Rehabilitation of the infrastructure using composite fabrics", final report – research project no. AR-16-52. Technical report, King Abdul Aziz City for Science and Technology (KACST), Riyadh, Saudi Arabia.

Bonacci JF, Maalej M. (2001). "Behavioral trends of RC beams strengthened with externally bonded FRP", Journal of Composite for Construction, 5(2): 102–13.

Bonacci JF, Maalej M. (2000). "Externally bonded fiber-reinforced polymer for rehabilitation of corrosion damaged concrete beams", ACI Structural Journal, 97(5):703–11.

Barnes, R. A., and Mays, G. C. (1999). "Fatigue performance of concrete beams strengthened with CFRP plates", Journal of Composites for Construction, Vol. 3, No. 2, pp. 63-72.

BS 8110-1 (1997). "Structural Use of Concrete- Part 1: Code of practice for design and Construction British Standard".

CEB-FIP, Model Code 1990 (1993). "Design Code, Comité Euro-International duBéton", Thomas Telford Services Ltd, London.

Eshwar, N., Ibell, T., and Nanni, A. (2003). "CFRP strengthening of concrete bridges with curved soffits", Proceedings of International Conference on Structural Faults and Repairs, London.

El-Badry, M., ed.(1996). "Advanced composite materials in bridges and structures, Canadian Society for Civil Engineering, Montreal.

Garden, H. N., and Hollaway, L. C. (1998). ''An experimental study of the influence of plate end anchorage of carbon fiber composite plates used to strengthen reinforced concrete beams". *Compos. Struct.,* 42(2), 175–188.

Hussain, M., Sharif, A., Basunbul, I. A., Baluch, M. H., and Al- Sulaimani, G. J. (1995). ''Flexural behavior of precracked concrete beams strengthened externally by steel plates.'' *ACI Struct. J.,* 92(1), 14–22.

Hamoush, S.A. and Ahmed, S.H. (1990). "Debonding of steel plate-strengthened concrete beams", Journal of Structural Engineering, 116 (2), 356-371.

Jansze, W., J.A.D. Uijl and Walraven, J. C. (1998). "Flexural strengthening with externally bionded steel pltes: Design for beam shear and plate anchorage", Challenges for concrete in the next millennium, Stoelhorst, D. and G. L. Boer den (Eds.).

Jones, R., Swamy, R. N., and Charif, A. (1988). ''Plate separation and anchorage of reinforced concrete beams strengthened by epoxybonded steel plates". *Struct. Eng.,* 66 (5), 85–94.

Jones, R., et al. (1988). ''Plate separation and anchorage of reinforced concrete beams strengthened with epoxy-bonded steel plates.'' *The Struct. Engr*., 66(5), London, 85–94.

Meier, U., and Kaiser, H. (1991). "Strengthening of structures with CFRP laminates", Advanced composites materials in civil engineering structures, ASCE, New York, 224–232.

Product data sheet Edition 0308/2 (2008). "Sika carbudur plates. Sika Kimia Sdn. Bhd.", Malaysia.

Rabinovich, O., and Frostig, Y. (2000). ''Closed-form high-order analysisof RC beams strengthened with FRP strips.'' *J. Compos. for Constr*., ASCE, 4(2), 65–74.

Siddiqui, N. A. (2009). "Experimental investigation of RC beams strengthened with externally bonded FRP composites", Latin American Journal of Solids and Structures, 6, 343 – 362.

Spadea, G., Bencardino, F., and Swamy, R. N. (1998). ''Structural behavior of composite RC beams with externally bonded CFRP", *J. Compos. Constr.,* 2(3), 132–137.

Saadatmanesh, H., and Malek, A. M. (1997). ''Prediction of shear and peeling stresses at the ends of beams strengthened with FRP plates.'' *Proc., 3rd Int. Symp. on Non-Metallic (FRP) Reinforcement for Concrete Struct*., 1, Japan Concrete Institute, Sapporo, Japan, 311–318.

Saadatmanesh, K., Ehsani, M.R. (1991). "R/C Beam Strengthened with GFRP Plates 1: Experimental Study", Journal of Structural Engineering, pp.3434-3455.

Swamy, R.N., Jones, R. and Bloxham, J.W. (1987). "Structural behavior of reinforced concrete beams strengthened by epoxy-bonded steel plates", Structural Engineering, Part A, 65 (2), 59-68.

Tamuzs, V., and Tepfers, R. (2004). "Strengthening of concrete structures with advanced composite materials: Prospects and problems", J. Mater. Civ. Eng., 16(5), 391–397.

Teng JG, Smith ST, Yao J, Chen JF.(2003). "Intermediate crack-induced debonding in RC beams and slabs", Construction and Building Materials, 17:447–62.

Triantafillou,T. C. (1998). "Strengthening of structures with advanced FRPs", Prog. Struct. Eng. Mater., 1,126–134.

Yao, J., Teng, J.G. (2007). "Plate end debonding in FRP-plated RC beams—I: Experiments", Engineering Structures, 29, 2457–2471.

Ziraba, Y. N., Baluch, M. H., Basunbul, I. A., Sharif, A. M., Azad, A. K.,and Al-Sulaimani, G. J. (1994). ''Guidelines toward the design of reinforcedconcrete beams with external plates.'' ACI Struct. J., 91(6),639–646.