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Eliminating Premature End Peeling of Flexurally Strengthened Reinforced Concrete Beams

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Abstract: This study presents the results of an experimental study investigating the effect of U-shaped end anchors on flexurally strengthened reinforced concrete beams for the prevention of premature end peeling. A simple design guideline for the anchorage length of end anchor is proposed. A total of five beams, each 2300 mm long, 125 mm wide and 250 mm deep with a tension steel reinforcement ratio of 0.73%, was cast and tested. One beam was left un-strengthened and used as a control, two beams were strengthened with steel plates and the remaining two beams were strengthened with Carbon Fibre Reinforced Polymer (CFRP) laminates. One each of the steel plate and CFRP laminate strengthened beams were further strengthened with mild steel U-shape end-anchors at both ends of the beams. The beams were then tested under two-point loading. The experimental results revealed that the U-shaped end anchors of designed anchorage length eliminated premature end peeling and it had significant effects on the failure mode, ultimate load, deflections and strain characteristics of the strengthened beams. It is seen from the results that the end-anchored strengthened beams showed higher ultimate load and more ductile behaviour compared to the un-anchored strengthened beams.

Key words: Steel plate, CFRP, debonding, U shape end anchorage

INTRODUCTION

A large number of civil infrastructures around the world are in a state of serious deterioration today due to durability problems. Quite a number of these structures are also no longer considered safe due to increase load specifications, overloading, under design of existing structures or due to lack of quality control. These structures must either be replaced, repaired or strengthened in order to fulfil their functions effectively. It is becoming both environmentally and economically preferable to repair or strengthen these structures rather than replacements, particularly if rapid, effective and simple strengthening methods are available. Many research works have been carried out in this field. Use of steel plate and Carbon Fibre Reinforced Polymer (CFRP) are the most widely applied in this field due to several advantages. Which include easy construction work, minimum change in the overall size of the structure after plate bonding and less disruption to traffic while strengthening work is being carried out. In recent years, with the development of structurally effective adhesives, the use of plating methods has increased tremendously.

The plate bonding methods, however, often poses a serious premature failure problem due to separation of plates and rip off concrete along the tensile reinforcing bars. Thus, other alternative methods are relatively preferred. In this regard, many studies have been conducted to explore the failure behaviour of plate bonded strengthened beams. Premature failure due to excessive stress concentration can be classified into two phenomena. One is the separation that occurs within the interface layer of the plate and the concrete and the other is the rip off of the concrete cover along the tensile reinforcing bar due to the initiation of shear cracking at the ends of plate. These two phenomena are closely related to the shear and normal stress at the interface layer of plate-bonded beams as reported by Oh *et al*. (2003). Saadatmanesh and Malek (1998) pointed out that shear and normal (peeling) stress concentrations at the cut-off point or around the flexural cracks were the main reasons for local failures. Failure due to plate separation starts at the ends of the plates and is referred to as shear peeling. Shear peeling according to Oehlers and Moran (1990) is normally induced by the formation of diagonal shear cracks which is associated with rapid separation of the plate. This debonding mechanism is initiated by a shear crack at the plate-end which induces a horizontal crack at the level of the tension reinforcement which propagates rapidly towards the load point and eventually causes the separation of the plate.

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In view of these, some researches were done on end anchorage to prevent the plate end debonding of strengthened beams. Jones *et al*. (1988) first studied the effects of bolt and partial L-shape end anchorage details on the failure behaviour of strengthened beams with steel plates. They reported that the anchorage details had some effects on the ultimate strength and failure modes. However, they also found that anchor bolting did not prevent the debonding of strengthened plates, but instead complete plate separation was avoided. An increase in strengths of up to 8% over the un-plated beam was achieved. They also experimented with glued anchor plates and found it to be the most effective. However, sudden plate separation still occurred, producing yielding of the tensile plates and achieving the full theoretical strength of about 36% above the unplated beam. Similarly, Hussain *et al*. (1995) and Garden (1998) reported that anchor bolting could not totally prevent premature failure. Chahrour and Soudki (2005) also studied the effects of end anchorage details on the failure behaviour of CFRP strengthened beams. They used mechanical anchors consisting of top and bottom 10 mm thick steel plates fastened together using two M12 tightened bolts for the end anchorage of the CFRP strengthened beams. They reported that beams strengthened with end anchors consisting partially bonded CFRP strips gave higher strengths than the fully bonded beam with no end anchorage.

In general, the findings from these studies indicated that these anchors increased the ultimate strength slightly but still showed sign of debonding of the strengthened plates. Further, a design guideline for the anchorage length of end anchors was seldom found. The main goals of the research reported in this study are; to investigate the effect of U-shaped end anchors on steel plate and CFRP laminate flexurally strengthened r.c. beams and to develop a design guideline for the anchorage length of end anchors to eliminate premature end peeling.

DESIGN OF END ANCHORAGE LENGTH

The purpose of end anchoring on plate bonded strengthened r.c. beam is to prevent premature end peeling. Design of the anchorage length of end anchors is the current interest of this field. In this study, a design guide line for anchorage length of end anchors is proposed based on the fictitious shear span model of Jansze (1998). According to his model, plate end shear is the governing failure mechanism for end peeling which creates a fictitious shear span (Fig. 1) on partially bonded plated beam. This fictitious shear span can be calculated by using the Eq. 1.

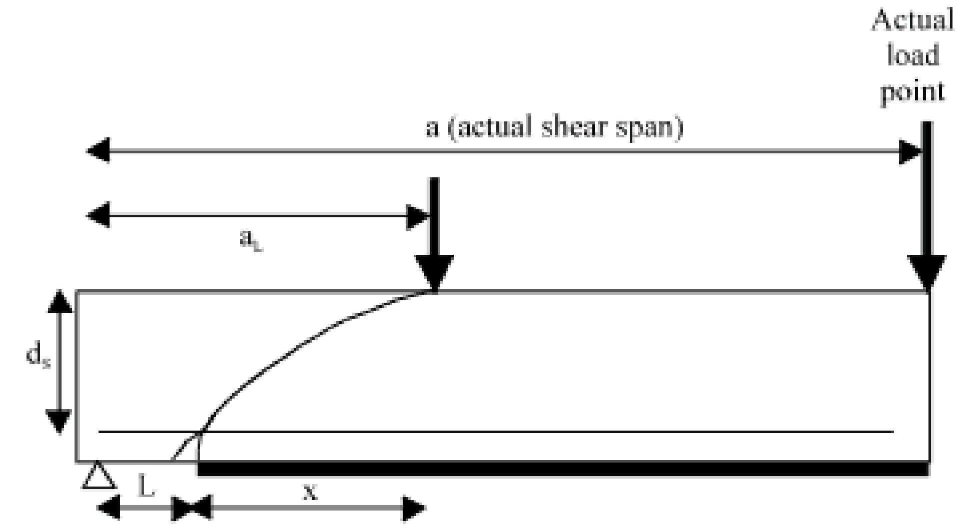


Fig. 1: Fictitious shear span (Jansze, 1998)

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

Where:

ρ_s = Bar reinforcement ratio (As/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 plate is the main reason which causes the plate debonding, anchors could be provided along the plated portion of fictitious shear span. Thus, end anchorage length can be obtained from the Eq. 2 and it should not be more than the effective depth (d_s) of beam.

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

MATERIALS AND METHODS

Test specimens: A total of five identical reinforced concrete beams were cast. Each beam was of 2300×125×250 mm (length/width/depth) in dimensions as shown in Fig. 2.

The beams had 12 mm deformed steel bars in the tension zone. Ten millimeter mild steel bars were used as hanger bars. Six millimeter diameter stirrups were positioned equally along the beam's length, as shown in Fig. 2.

Major test variables: The main test variables considered in the study were steel plate and CFRP laminate strengthened beams with or without end anchorage. The cross section of steel plate and CFRP laminate were 2.76×73 and 1.2×80 mm, respectively. U-shaped mild steel plates of 2 mm thickness were used for end anchoring of the steel plate and CFRP laminates. The length and height of the end anchorage was 200 and 250 mm, respectively. The anchorage length of end anchors is obtained from Eq. 1. These test variables are shown in Table 1.

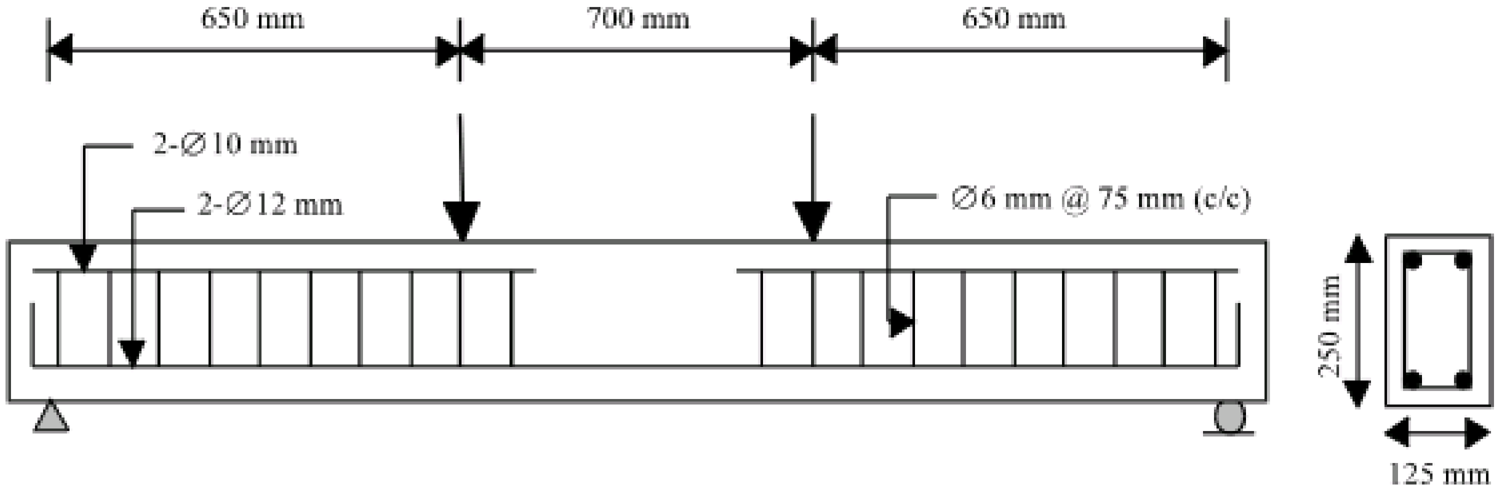


Fig. 2: Typical reinforcement details of the r.c. beams

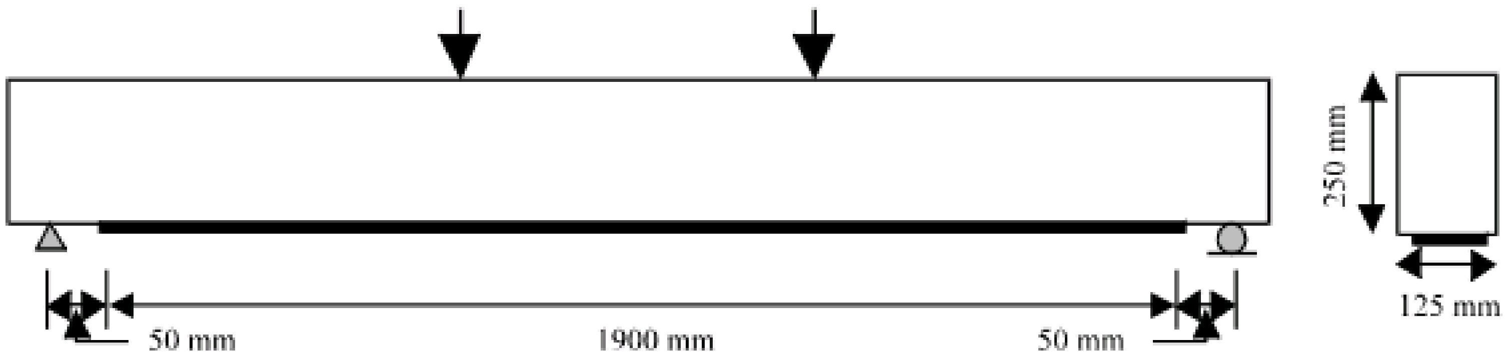


Fig. 3: Strengthening details

Table 1: Specimen details

		Strengthening material			End anchorage	
Specimen	Designation	Type	Thickness (mm)	Width (mm)	Materials	Shape
1	B1					
2	B2	Steel plate	2.73	73	---------	--------
3	B3	Steel plate	2.73	73	Steel plate	U
4	B4	FRP	1.2	80	----------	--------
5	B5	FRP	1.2	80	Steel plate	U

Table 2: Mix proportion of concrete

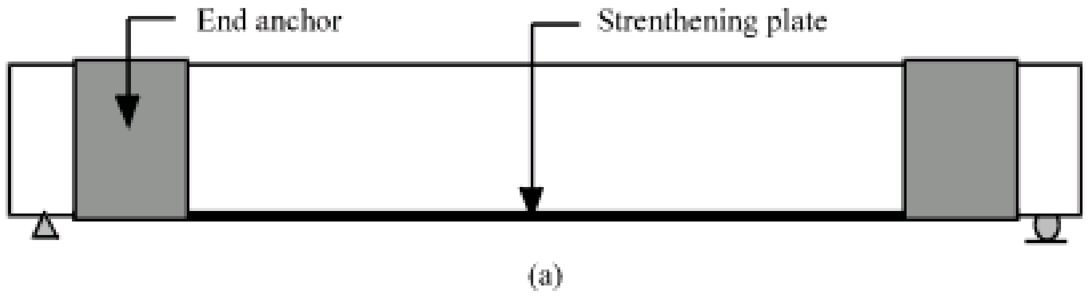
		Contents (kg m^{-3})			
Slump (mm)	Water cement ratio	Water	Cement	Coarse aggregate	Fine Aggregate
60-180	0.65	208	320	740	1120

For all strengthened beams, the length of the bonded plate was maintained at 1900 mm, which covered almost the full-span length between the supports of the beams (Fig. 3). The reason for the full span-length strengthening with steel plates and CFRP laminates was to maximize the strengthening effects.

Materials: Ordinary Portland Cement was used in the concrete mix. The maximum size of coarse aggregate was 20 mm. The mix proportion is as shown in Table 2.

The compressive strengths of concrete were measured from three cubes after 28 days curing in accordance with British Standard (BS 1881). The average compressive strength of all specimens was 33 MPa. Two tensile reinforcing deformed bars of diameter 12 mm were used. The measured yield strength was 551 MPa and measured tensile strength was 641 MPa. Two 10 mm mild steel bars were used as hanger bars. The modulus of elasticity of steel bar was 200 GPa. The 6 mm stirrups were positioned along the beam as shown in Fig. 2. The measured yield strength of the stirrup was 520 MPa, the tensile strength was 572 MPa and the modulus of elasticity was 200 GPa. For strengthening, mild steel plates and Sika CarboDur S812 laminates (CFRP) were used. The yield and tensile strengths of the steel plates were found to be 320 and 375 MPa, respectively. The tensile strength and modulus of elasticity of CFRP laminates were 2800 MPa and 165 GPa, respectively. U-shaped mild steel plates were used for end anchorage of strengthened beams. The steel plates and CFRP laminates were glued to the beam soffits before the end anchoring plates were placed of the bottom and the two sides of the beam using epoxy Sikadur 30 adhesive.

Bonding procedure: Proper concrete surface treatment prior to plating works has a significant effect in guarantying a perfect bonding between the concrete and the strengthening plates. For perfect bonding, the concrete surface was first ground using a diamond cutter to expose the coarse aggregates. Concrete dusts were then blown out using an air compressor. The surface of the steel plate was also sand blasted to expose the original texture of steel and to eliminate any rust. Dusts on the steel and carbon plates were removed using acetone.



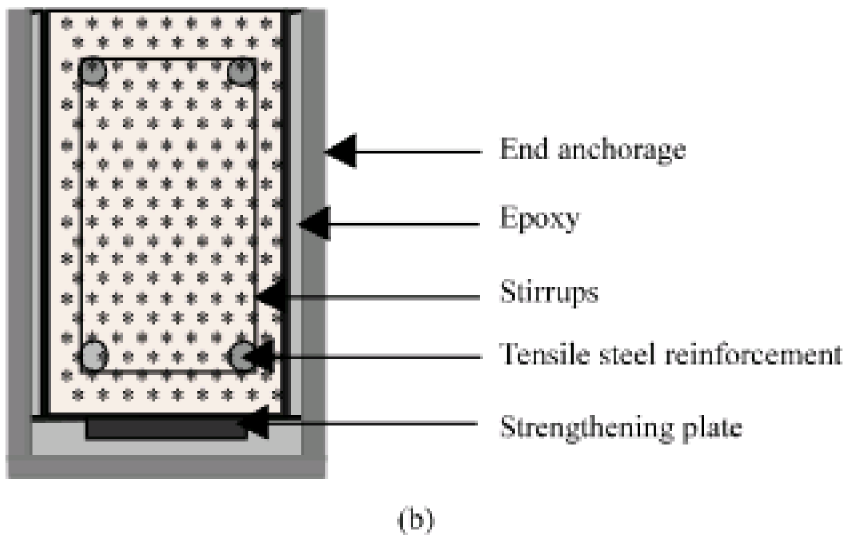


Fig. 4: End anchorage details, (a) front view showing the positions of end anchorage and (b) cross-section of the end of the beam showing the end anchorage

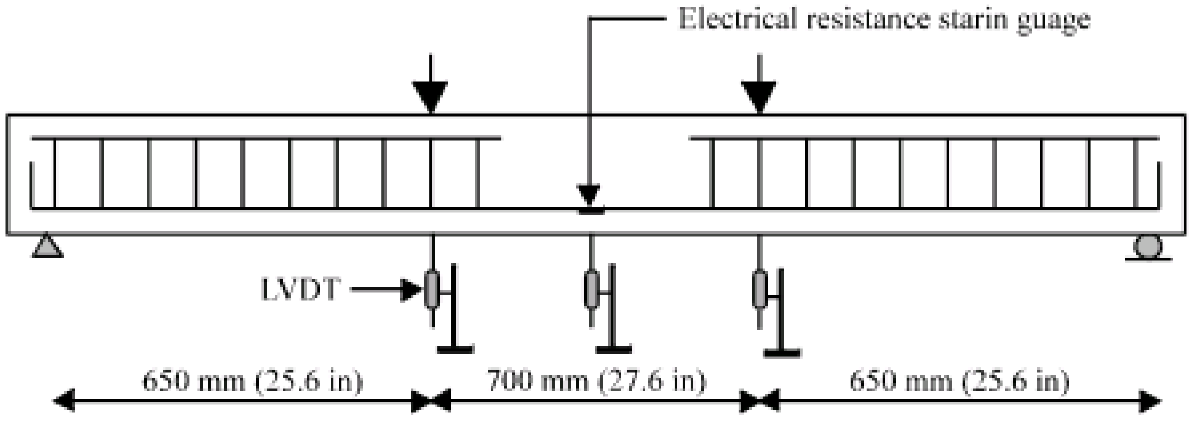


Fig. 5: Typical strengthened beams showing the position of LVDT and electrical resistance strain gauge (front elevation)

After the surface treatment, a putty was applied to fill up the cavities or holes on the concrete surface. The well mixed sikadur (an adhesive produced by Sika) was then troweled on to the surface of the concrete specimens to form a thin layer. It was also applied onto the steel plate and CFRP laminate using a special dome-shape spatula. The thickness of the applied sikadur ranged from 2-3 mm in line with the varying of roughness of the beams surface. The strengthening plates were then placed on to the soffit face of the beam (Fig. 3). Using a rubber roller, the plates were then gently pressed into the adhesive until the material was forced out on both sides of the laminates. The surplus adhesive was then removed.

End anchoring: Sikadur was also applied to the inner face of the U-shaped anchoring plates. An excessive amount of adhesive was applied to the beam surface as well as inner face of the anchoring plate to avoid any risk of gaps in the adhesive. The anchor-plates were then positioned on the beam and clamped for 3 days. The end anchorage detailing is shown in Fig. 4.

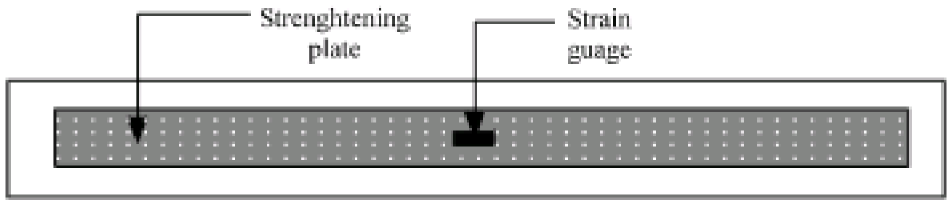


Fig. 6: Typical strengthened beams showing the position of the strengthening laminate and electrical resistance strain gauge (bottom view)

Instrumentation and test procedure: Figure 5 and 6 show the location of the instruments used to record data during the test. Thirty millimeter electrical resistance strain gauges were used to measure the tensile strains of steel bar, steel plate and CFRP laminate. These strain gauges were also placed at the top of the beam to measure the concrete compressive strains. All strain gauges were positioned at the mid-span of the beam.

Demec gauges were attached along the depth of beam at mid span region to measure the concrete strains. Three Linear Variable Displacement Transducers (LVDTs) were used to measure the deflection of the beam at mid-span and under the load points (Fig. 5).

The beams were tested in four-point bending as shown in Fig. 2. Initially the load was applied step-by-step using the load control command of the Universal Testing Machine (UTM). Before failure of the test specimens, the load was applied using the position control command of UTM to observe the actual failure mode of the specimens.

EXPERIMENTAL RESULTS

Experimental results on the effect of end anchorage on steel plate and CFRP laminate strengthened beams are presented and discussed subsequently in terms of the observed mode of failure, failure load, deflection, cracking pattern and ductile characteristic.

Mode of failure: Figure 7a-e show the failure modes for various test beams. The control beam without strengthening plates or laminates showed the conventional flexural failure as it was designed to fail in flexure. The steel plate and CFRP laminate strengthened beams without end anchorage (B2 and B4) were found to fail by debonding of the plate or laminate even though the beams were strengthened for full-span length between the supports. This debonding failure was initiated due to shear cracks from the end of the plate. Due to the discontinuity of the joint between the r.c. beams and the plate, excessive shear stresses normally develop near the end of the plate. When this shear stress exceeds the shear resisting capacity of the concrete shear crack would occur. Because of this shear crack, the plate debonded either at the level of the reinforcement or at the level of the bonding interface. Both of these debonding failure modes occurred suddenly and showed brittle characteristics.

However, U-shaped end anchored steel plate and CFRP laminate strengthened beams (B3 and B5) failed in flexure and shear, respectively. U-shaped end anchor with designed anchorage length prevented premature end peeling. The mechanism could be explained in such a way; because of the U-shape of anchor both sides of the plates were attached firmly on the beams and resulted in an increase in the shear strength in that portions of the beams. As the shear strength increased, the number of shear cracks at the ends of the plate was reduced. Furthermore, due to the U-shaped of end anchorages, the strengthened plates were firmly clamped to the beam till time of failure. Due to this mechanism, debonding caused by normal stress was also minimized. Thus plate debonding did not occur and the failure modes showed ductile characteristics.

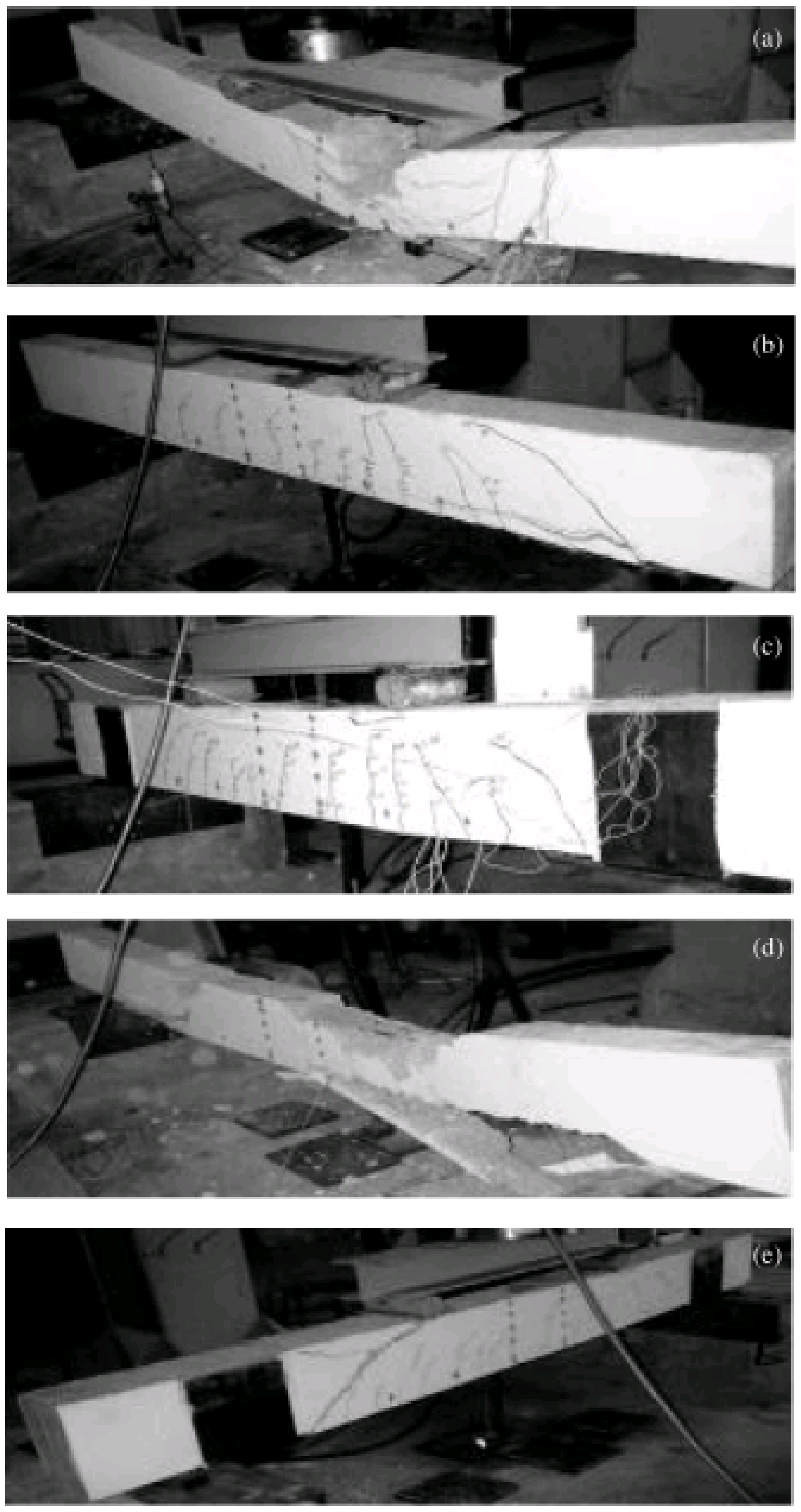


Fig. 7: Failure mode of the r.c. beams tested. (a) Beam B1: control beam, (b) Beam B2: Steel plate strengthened beam without end anchorage, (c) Beam B3: Steel plate strengthened beam with end anchorage, (d) Beam B4: FRP laminate strengthened beam without end anchorage and (e) Beam B5: FRP laminate strengthened beam with end anchorage

Failure load: All test results are shown in Table 3. The results show that, all strengthened beams i.e., B2, B3, B4 and B5 showed 29, 55, 54 and 89% increase in failure load, respectively compared to the control beam (B1).

The test results also showed that the end anchored strengthened beams carried more loads compared to the unanchored strengthened beams. The failure loads of the U-shaped end anchored steel plate and CFRP laminate strengthened beams (B3 and B5) were 20 and 23% higher

Table 3: Test result

Specimen	1st crack load (kN)	1st crack load increase over control beam (%)	Ultimate load (kN)	Ultimate load increase over control beam (%)	Mid-span deflection (mm) at 70 kN load	Crack width (mm) at 70 kN load	Concrete compressive strain (μ) at 70 kN load	Mode of failure
B1	14		80.59		28.50	0.90	1149	Flexural
B2	35	150	104.30	29	20.39	0.14	775	Peeling
B3	37	164	125.00	55	18.88	0.14	765	Flexural
B4	27	93	123.90	54	20.00	0.16	944	Peeling
B5	25	79	152.00	89	20.60	0.14	1030	Shear

Table 4: Measured and theoretical failure loads

Specimen	Designation	Theoretical design load P_d (kN)	Theoretical failure load $P_{n, BS}$ (kN)	Measured failure load $P_{n, m}$ (kN)	$P_{n, m}/P_{n, BS}$
1	B1	62.6	76 .0	80.59	1.06
2	B2	91.2	122.3	104.30	0.85
3	B3	91.2	122.3	125.00	1.02
4	B4	91.2	119.0	123.90	1.04
5	B5	91.2	119.0	152.00	1.28

than the failure load of the beams without end anchorage (B2 and B4). This was because of the presence of U-shaped end anchorage that prevents premature plate debonding. Table 4 shows the comparison between the measured failure load and the theoretical failure load. The measured failure load of the U-shaped end anchored steel plate strengthened beam (B3) was found to be almost similar to that of the theoretical value. The strengthened beam without end anchorage (B2) showed a smaller value compared to the theoretical value. The explanation for these phenomena could be attributed to the prevention of premature debonding failure of the end anchored strengthened beams which allowed the beams to achieve their full strengths before failure. For the strengthened beam without end anchorage, premature plate debonding occurred before the beams could achieve their full strength.

For CFRP laminate strengthened beams (B4, B5), the experimental failure loads were higher than the theoretical failure loads both for the end-anchored and the non end-anchored strengthened beams. This could be explained in terms of the properties of the CFRP laminates which possess high strength and flexible characteristics. Due to the nature of the CFRP laminate which is less stiffer than the steel plate, the CFRP laminate strengthened beams without end anchorage showed a delayed laminate debonding properties which allowed the beams to carry more loads before failure. However, due to the high strength nature of the CFRP laminate the strengthened beam with end anchorage (B5) also showed higher failure loads compared to theoretical values.

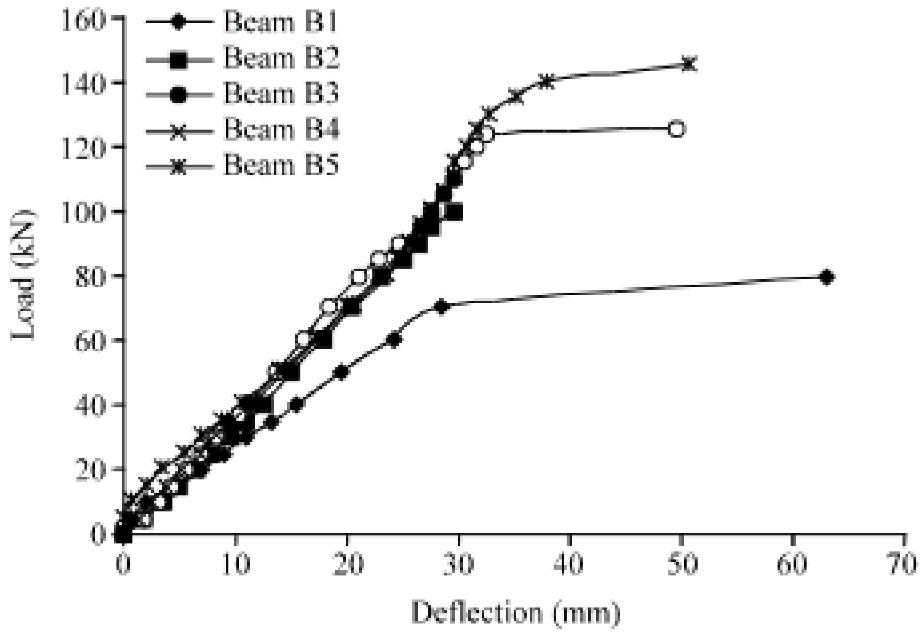


Fig. 8: Load vs deflection plots for all beams

Deflection: Figure 8 shows the load versus mid-span deflection plots for all the beams. At all load levels, all the strengthened beams showed smaller deflections compared to the control beam due to their higher stiffness. At failure the end anchored strengthened beams showed higher deflections compared to un-anchored strengthened beams because of the prevention of plate debonding.

Cracking patterns: The first crack loads, obtained experimentally, are shown in Table 4. The strengthened beams in general showed the higher cracking loads compared to un-strengthened control beam. Since first crack load depends on the modulus of rupture of the concrete and the stiffness of strengthening materials, the first crack loads of both the steel plate strengthened beams (end anchored and un-anchored) were found to be similar. The same was also noted on the CFRP laminate strengthened beams.

Figure 9 shows the load versus crack width of all the beams. The strengthened beams showed smaller crack widths compared to the control beam. The crack widths of all steel plate strengthened beams were similar. This was also the case for the CFRP laminate strengthened beams.

Ductile characteristics: Figure 10 shows the load versus steel bar strains of all the beams. Due to the higher stiffness of the strengthened beams, at all load levels, the bar strains of all the strengthened beams were found to be less than the control beam. Figure 10 also shows that the bar strain of the steel plate strengthened beams (B2 and B3) was identical due to the similar material properties of both of the beams. This was also true for CFRP laminate strengthened beams. Figure 10 also shows that the bars

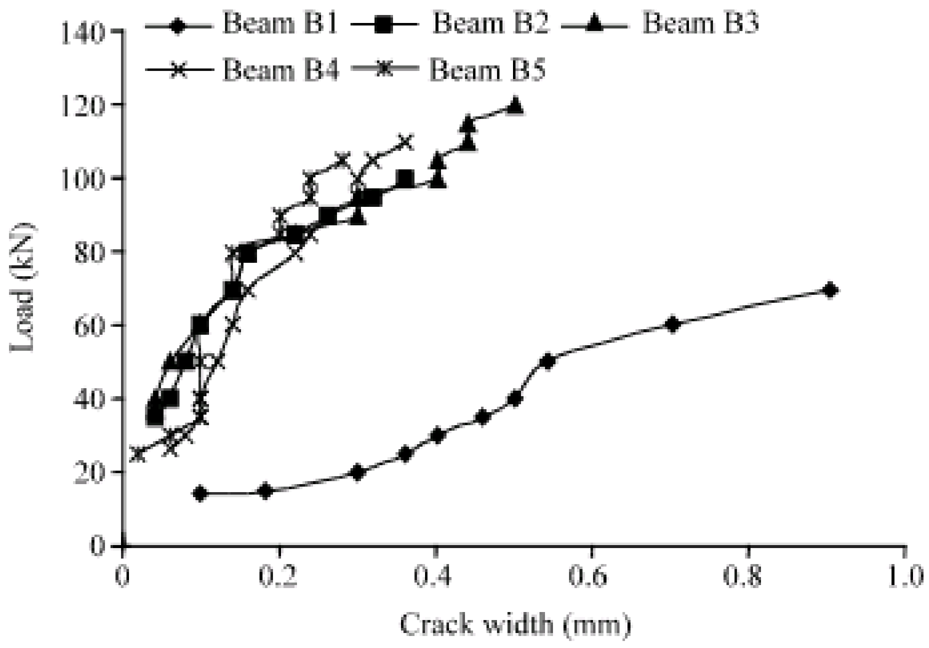


Fig. 9: Load vs crack width plots for all beams

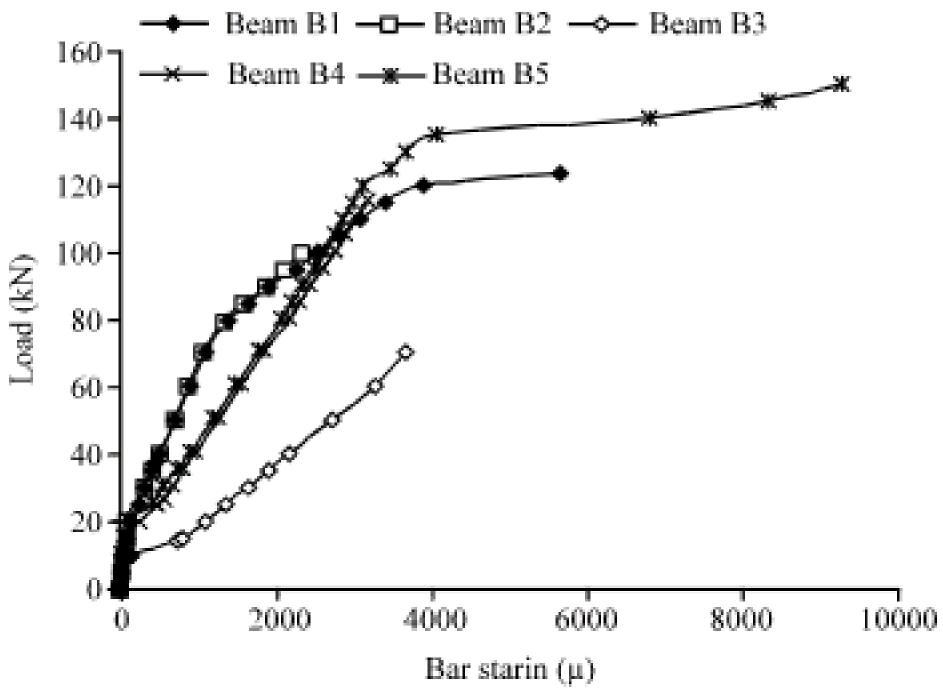


Fig. 10: Load vs bar strain plots for all beams

of end anchored strengthened beams were yielded before the beam's failed and the approximate yield load is 120 kN. It is the sign of ductile failure. However, bar yield loads of the un-anchored strengthened beams (B2 and B4) were not found due to their premature debonding failure.

CONCLUSIONS

From the study the following conclusions can be drawn:

- The steel plate and CFRP laminate flexurally strengthened beams without end anchorage exhibited premature shear-type plate debonding failure in a brittle manner. The control beam and steel plate strengthened beam with U-shaped end anchorages showed a conventional ductile flexural failure mode. The CFRP laminate flexurally strengthened beam with end anchorages exhibited a conventional ductile shear failure mode
- The failure loads of the non end-anchored and the end anchored steel plate strengthened beams were found to be 30% and 55% respectively higher than the control beam. End anchored steel plate strengthened beam recorded a 20% higher failure load compared to non end-anchored strengthened beam. The failure loads of the non end-anchored and end-anchored CFRP laminate strengthened beams were found 54 and 89%, respectively higher than the control beam. The failure load of end anchored CFRP laminate strengthened beam was 23% higher to that of the non end-anchored strengthened beam
- All strengthened beams showed less deflection compared to the control beam due to higher stiffness of strengthened beams. End anchorage had a significant effect on the deflection at failure load. The bars of end anchored strengthened beams were yielded before the beam's failed. Thus, the beams with end anchors failed with ductile manner
- All strengthened beams possessed higher cracking loads and better cracking patterns. Since, cracking loads and widths depend on the modulus of rupture of the concrete and stiffness of the strengthening material, the cracking loads and widths of the strengthened beams with end anchorages were found to be similar to those strengthened beams without end anchorages
- The designed anchorage length of end anchors is sufficient to prevent premature end peeling

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