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Behaviour of U and L Shaped End Anchored Steel Plate Strengthened Reinforced Concrete Beams

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Abstract

Flexural strengthening of reinforced concrete (r.c.) beam is now becoming more and more important in the field of structural maintenance and retrofitting. Plate bonding methods using steel plates are very widely used in this field. However, premature debonding at plate ends i.e. end peelings have been a major concern in using these methods. Researchers in general concluded that shear and normal stress concentrations at the plate cut-off point are the main reasons causing end peeling. For minimizing these stresses to prevent end peeling, end anchoring using U and L shape metal plates is proposed in this paper. This paper presents the results of experimental studies carried out to investigate the effect of U and L shaped end anchors on steel plate strengthened reinforced concrete beams. A total of four beams were cast. One beam was left un-strengthened as the control; the remainder three beams were strengthened with steel plates. From the strengthened beams, one was simply strengthened without end anchors and two were end anchored using U and L shaped anchor plates respectively. The results indicate that, all strengthened beams exhibited higher failure and cracking loads with less strain, deflection and crack width and better crack patterns than the control beam. It is also indicate that the strengthened beams with end anchors recorded the highest failure loads and their modes of failure were seen to be more ductile compared to the un-anchored strengthened beam. Results also shows that premature end peeling was completely prevented by U and L shaped anchor plates. In comparison, the L shaped end-anchor gave better performance compared to the U shape end anchor.

Keywords: Reinforced concrete beam, steel plate, debonding, end anchors.

1. Introduction

Strengthening of reinforced concrete beam increases the capacity of an existing beam element. Thus, of great importance in the field of structural maintenance. However, this work is very important because most existing structures are subjected to loads beyond the initial design specification due to inevitable present and future needs and demands. In order to maintain efficient serviceability, older structures must be repaired or strengthened so that they meet the demands of the present and future needs. It is both environmentally and economically preferable to repair or strengthen a structure rather than replacement, especially if fast, effective and simple strengthening methods are available. Strengthening materials currently available in the market are ferrocement, sprayed concrete, steel plate and fibre reinforced polymer (FRP) laminate. Out of these, steel plate is one of the most common and popular material due to its availability, low cost, easy application, uniform materials property (isotropic), high ductility and high fatigue strength.

In recent years, with the development of effective structural adhesives, plating methods have been widely used in the strengthening of existing concrete structures. The most common form of plating is to glue steel plate to the tension faces of beams where the plate is at its farthest from the compression region. Hence, the composite flexural action is at its maximum (Oehlers, 1997). It should also preserve composite action between the plate, glue, and concrete, until failure (Swamy, 1987). However, plates bonding method often has a serious premature failure problem due to separation of plates and rip off concrete along the tensile reinforcing bars before reaching its ultimate capacity. This is an extremely important issue because debonding of adhesive joints is a brittle and catastrophic failure mechanism. In view of this, many studies have been conducted to explore the failure behaviour of beams strengthened with plates. It is reported that premature failure occurs mainly due to shear and normal (peeling) stress concentrations at the cut-off point or around the flexural cracks (Saadatmanesh, 1998). Oh et al. (2003) and EI-Mihilmy (2001) also reported that shear and normal stress at the interface layer of plate-bonded beams are the main reasons to cause the premature failure. And this premature debonding mechanism is initiated by a shear crack at the plate-end which induces either a horizontal crack at the level of the tension reinforcement or at the level of interface, which then propagates rapidly towards the load point and eventually causes separation of the plate.

To minimize these debonding problems, research works have been carried out on end anchorages since the last twenty years. However, relative few works on end anchoring have been carried on steel plate strengthened beams compared to carbon fibre reinforced polymer (CFRP) laminate. Jones et al. (1988) first studied the effects of bolt and partial L-shaped end anchorage details on the failure behaviour of strengthened beams with steel plates and they reported that the anchorage details did have some effect on the ultimate strength and failure modes. They also found that though anchor bolting does not prevent the debonding of strengthened plates, complete plate separation was avoided. The glued anchor plates were the most effective, even though sudden plate separation still occurred, producing yielding of the tensile plates and achieving the full theoretical strengths. Hussain et al. (1995) and Garden (1998) also reported that the anchor bolting cannot totally prevent premature failure. Adhikary (2002) who had also examined the effect of end anchoring bolt on steel plate strengthened beams and developed a finite element computational modelling for that programme. They reported that, anchoring bolts have a significant effect on failure load both in experimental and computational modelling. Though it does not completely change the failure mode of beam, it delays the failure in debonding mode significantly. Garden and Hallaway (1998) also reported that, U-shape end anchorage in the form of a fixing at the end of the plates prevents the separation of the plate and the concrete cover layer. This reduces the peeling action at the end of the plate.

However, the summary of past research works concludes that the complete end peeling could not be prevented by using conventional anchors (i.e. bolt, partial L shape). In this study glued end anchors of U and L-shaped steel plates are proposed. These shapes may have significant effect to prevent end peeling. It may prevent plate separation in two ways. Firstly, the two sides of U and L-shaped plates which will be attached to the beam will increase the shear capacity of this section of the beam. Secondly, due to their shapes, the strengthened plate will need to be clamped properly and this will help to minimize plate debonding due to normal stress.

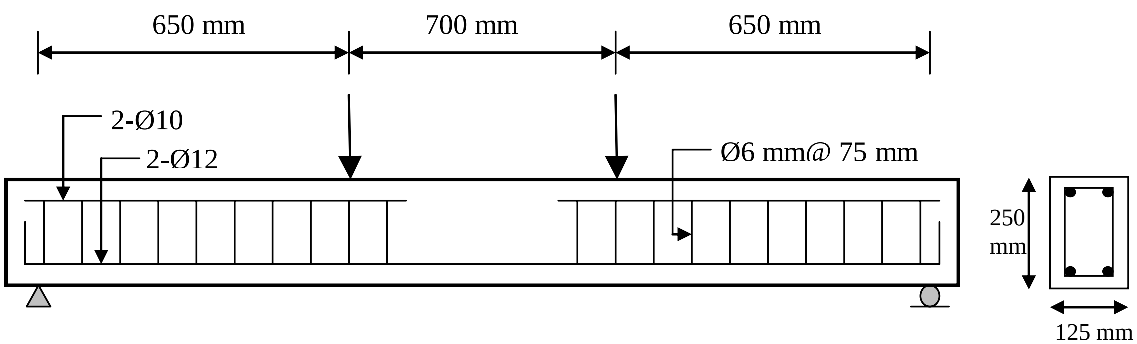
The main goal of this research is to evaluate the behaviour of U and L-shaped end anchored steel plate on flexurally strengthened reinforced concrete (r.c.) beams in view of failure loads, failure modes, strain characteristics, deflections and cracking patterns.

2. Research Method and Materials

2.1 Test specimens

A total number of four reinforced concrete beams were tested at four-point bending. Each beam was 2,300 x 125 x 250 mm (length, width and depth) in dimension as shown in Figure 1. Further reinforced with D12 (diameter 12 mm) steel bars in the tension zone. D10 steel bars were used as hanger bar. The stirrups were symmetrically placed as shown in Figure 1 with the spacing of 75 mm.

Figure 1: Beam Details



2.2 Major test variables

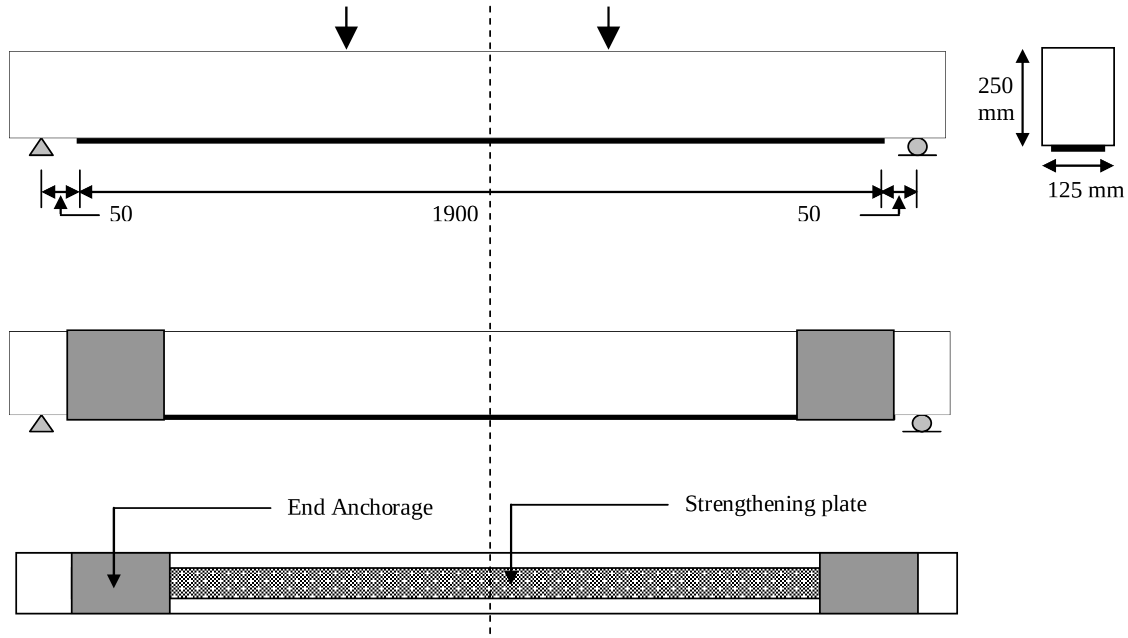
The main test variables considered in this present study are steel plate strengthened beams without end anchorage, with U shaped end anchorage and with L shaped end anchorage respectively. The cross section of strengthened steel plate was 2.76 mm x 73mm. U and L shaped mild steel plates of thickness 2 mm were used as end anchorages. The length and height of end anchorage were 200 mm and 250 mm respectively. These test variables are summarized in Table 1.

Table 1: Specimen details

Specimen	Designation	Strengthening Materials			End Anchorage	
		Type	Thickness (mm)	Width (mm)	Materials	Shape
1	A1					
2	B1	Steel Plate	2.76	73	---------	--------
3	B2	Steel Plate	2.76	73	Steel Plate	U
4	B3	Steel Plate	2.76	73	Steel Plate	L

For all beams, the length of the bonded plate was 1900 mm, which covers almost the full-span length between the supports of the beams (see Figure 2). The reason for the full span-length strengthening was to maximize the strengthening effects.

Figure 2: Strengthened beam details



2.3 Materials

The Ordinary Portland Cement (Type 1) was used and the maximum size of coarse aggregate was 20 mm. The mix proportion is given in Table 2. The compressive strengths of concrete were measured from three cubes after 28 days curing according to British Standard (BS 1881). The average compressive strength was 33 MPa.

Table 2: Mix Proportion of Concrete

Slump	Water Cement ratio	Contents (kg/m^3)			
		Water	Cement	Coarse Aggregate	Fine Aggregate
60-180	0.65	208	320	740	1120

Two tensile reinforcing deformed bars of diameter 12 mm (D 12) were used, of which the measured yield strength was 551 MPa, and measured tensile strength was 641 MPa. The modulus of elasticity of steel bars was 200 GPa.

The measured yield strength of a stirrup was 520 MPa, the tensile strength 572 MPa and the modulus of elasticity 200 GPa. The yield and tensile strengths of the steel plates were 320 MPa and 375 MPa. The steel plates were bonded to the beam soffit and end anchorage plates were bonded to the bottom and two sides of the beam using epoxy Sikadur 30 adhesive. The bonding procedure was done after standard surface preparation.

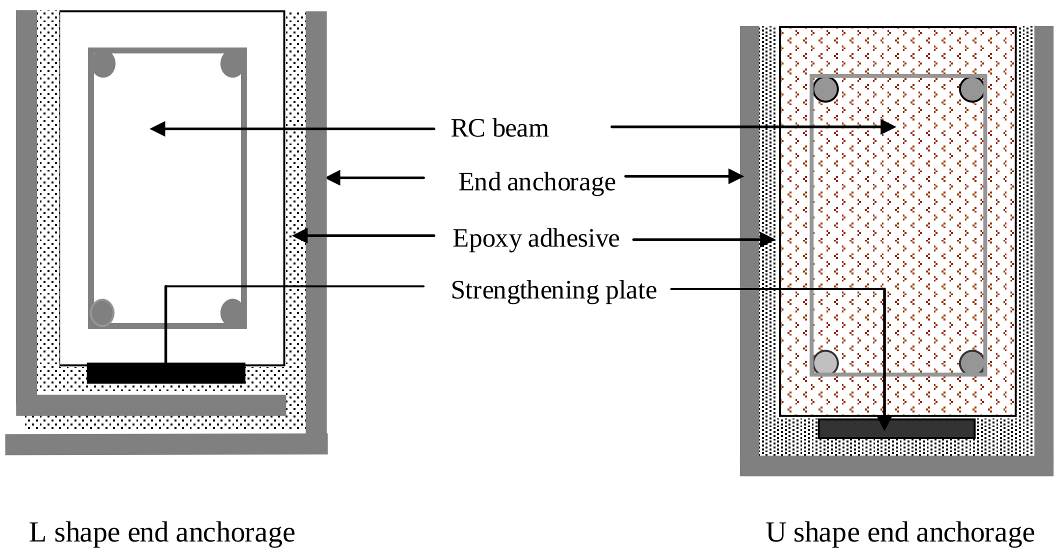
2.4 Bonding procedure

The concrete surface treatment prior to plating works was very important to guarantee the perfect bonding between two materials. Concrete was ground with a diamond cutter to expose the coarse aggregates and dusts were blown out using an air compressor. After the surface treatment, putty was applied to fill up the cavities or holes. The surface of steel plate was sand blasted to eliminate any rust. The well mixed sikadur was then trawled on to the surface of the concrete specimens to form a thin layer. The sikadur was also applied with a special “dome” shaped spatula onto the steel plates. The thickness of the applied sikadur ranged from 2 mm to 3 mm due to the varying roughness of the beam surface. The plates were positioned on the prepared surface. Using a Sika rubber roller, the plates were gently pressed onto the adhesive until the excessive adhesive was squeezed out on both sides of the plates. The surplus adhesive was then removed.

2.5 End anchoring

For end anchoring, Sikadur-30 was applied in a "dome" shape to the inner face of the U and L shaped plates. Excessive amount of adhesive was applied to the edge of the structure to avoid any risk of gaps in the adhesive. The anchor-plates were fixed to the beam and then pressed by rubber roller. It was then clamped for 3 days. The end anchorage details are shown in Figure 3.

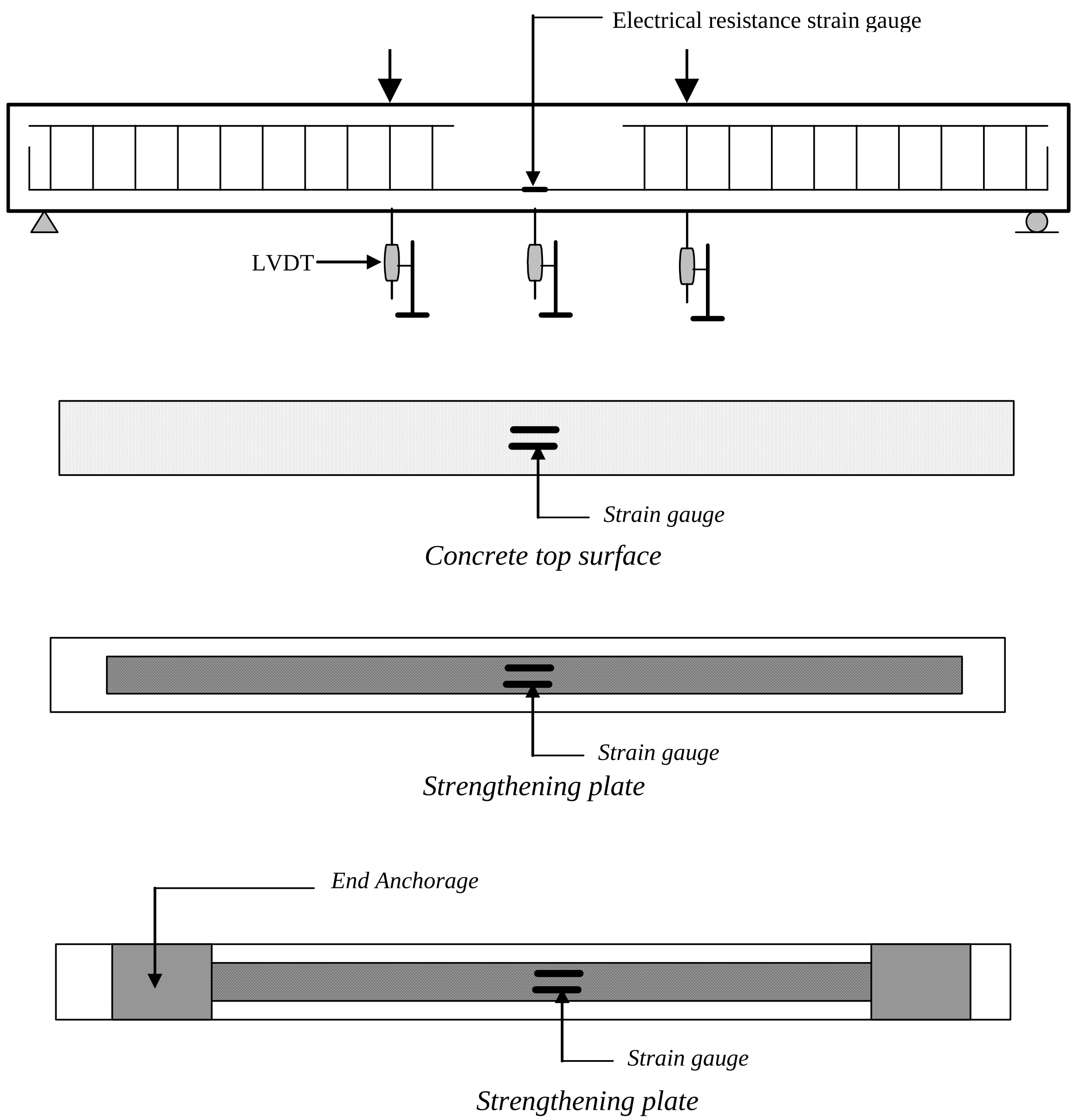
Figure 3: End anchorage details



2.6 Instrumentation and test procedure

Figure 4 shows the location of the different instruments used to record data during testing. Electrical resistance strain gauges measured the strains in the steel bar, steel plate and the concrete. A 30 mm gauge was used to record the tension strain in the steel plate at beam mid-span, while a 30 mm gauge was placed on the beam top surface to measure the concrete compressive strain. A 30 mm strain gauge was also attached to the middle of internal reinforcing bars. The demec gauges were also attached along the height of the beam at mid span to measure the horizontal strains. Three linear variable displacement transformers (LVDTs) were used to measure the vertical deflection of the beam at mid-span and under the two load points (Figure 4).

Figure 4: Beam instrumentation



All beams were tested in four-point bending as shown in Figure 1. The load was applied progressively in a load controlled manner of Instron up to the failure of test beams. The beams were loaded to failure point which was defined by the either crushing of the concrete, tensile rupture of steel plate, shear rupture of the steel plate at the epoxy adhesive level, concrete rip-off at the level of bottom tension reinforcement, or shear failure of strengthened beam as the beam was only flexurally strengthened.

3. The Results and Discussions

The experimental results on the effect of end anchorages on steel plate strengthened beams will be presented and discussed in terms of the observed mode of failure, ultimate load, strain characteristics, deflection and cracking patterns.

3.1 Mode of failure

Plate 1 shows the failure modes for test beams A1, B1, B2 and B3. The control beam without strengthening plate (A1) showed the traditional flexural and ductile failure mode as it was designed to fail in flexure. However, steel plate strengthened beam without end anchorage (B1) showed debonding failure even though the beam was strengthened for full-span length between supports. This debonding failure was initiated by the shear cracks from the end of the plates. Due to the discontinuity of the plate, excessive shear and normal stress normally develop near the end of the plates. When this shear stress exceeds the shear resisting capacity of the concrete itself, shear crack occurs. Therefore, the plate debonds either at the level of internal reinforcement or at the level of bonding interface. This debonding failure also exhibited brittle and catastrophic failure modes.

Plate 1: Failure modes of beams

Beam A1

Beam B1

Beam B2

Beam B3

U and L shaped end anchored steel plate strengthened beams (B2 and B3) showed the conventional flexural failure. The U and L shaped end anchorages kept the sides of the plates attached to the beam. This increased the shear strength in that portion of the beam. As shear strength increased, the shear crack minimized at the end of the plates. Also the shapes of the U and L end anchorages ensured that the plates remain clamped to the beam up-to point of failure. Due to this mechanism debonding due to normal stress was also minimized. However, due to using of U and L shape end anchorages shear and normal stress at the end of the plate was minimized. Thus, plate debonding was prevented and it allowed the beam to fail by flexurally as per its reinforced design.

3.2 Ultimate loads

The experimental failure loads carried by all the beams are as shown in the Table 3. The results show that, the failure load of beams A1, B1, B2 and B3 were 80.59 kN, 104 kN, 125 kN and 130.9 kN respectively.

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 (load) at 70 kN load	Crack Width (mm) at 70 kN load	Steel bar strain (micro) at 70 kN load	*Mode of Failure*
A1	14		80.59		28.5	0.9	3685	*Flexural*
B1	35	150	104.3	29.4	20.39	0.14	1062	*Peeling*
B2	37	164	125	55.1	18.44	0.14	1097	*Flexural*
B3	*35*	*150*	*130.9*	*62.4*	*16.29*	*0.22*	*1101*	*Flexure*

The failure load of U and L shaped end anchored steel plate strengthened beams (B2 and B3) is 19.8% and 25.5% higher than the failure load of beam without end anchorage (B1). This is due to the plate debonding failure of B1 before reaching its ultimate strength. The U and L shaped end anchorages prevented plate debonding and B2 and B3 failed by flexure and thus, a higher failure load compared to B1. It was noted that the failure load of B3 was relatively higher than B2. This could be happened due to the difference in steel area; to get a uniform cross sectional area of steel bar is very difficult.

Table 4: Measured and theoretical failure loads

Specimen	Designation	Theoretical Design Load P_d (kN)	Measured Failure Load $P_{n,m}$ (kN)	Theoretical Failure Load $P_{n,BS}$ (kN)	$P_{n,m}$ / $P_{n,BS}$
1	A1	62.6	80.59	76	1.06
2	B1	91.2	104.3	122.3	0.85
3	B2	91.2	125	122.3	1.02
4	B3	91.2	130.9	122.3	1.07

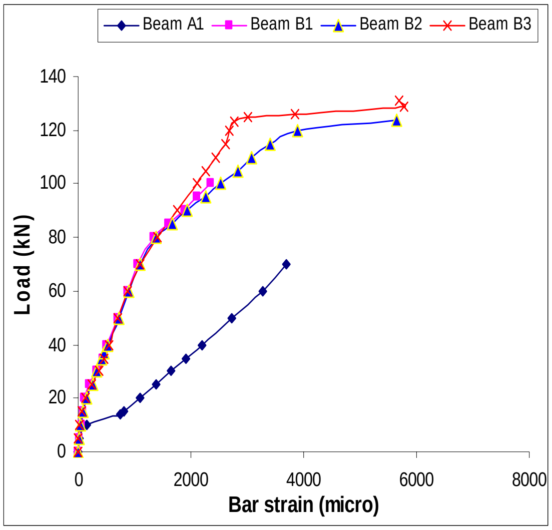
Table 4 shows the comparisons between the measured and theoretical failure loads. The measured failure load of end anchored steel plate strengthened beam is about the same as the theoretical failure load, whereas the failure load of the strengthened beam without end anchorage is relatively smaller than the theoretical value.

3.3 Strains characteristics

3.3.1 Bar strain

The steel load- bar strain was recorded at the mid span of the beam. The bar strain of the strengthened beams were less than the bar strain of control beam due to the higher stiffness of the strengthened beams. However, steel plate strengthened beams with and without end anchorage show similar bar strain character (Figure 5). It is as expected due to same material properties of strengthened beams. Figure 5 also shows that the rate of strain increase for control beam (A1) and strengthened beams (B1, B2 and B3) are suddenly higher at about 10 kN and 20 kN load respectively. This may due to the first cracking (invisible) of the concrete section which transfers the tensile stress to the steel bar. This sudden release of stress by the concrete acts as an impact stress on the steel bar. Thus, the sudden increase in the strain of steel bar. This increment is more prominent in the control beam than the strengthened beams due to larger crack width on the control beam.

Figure 5: Loads versus bar strain

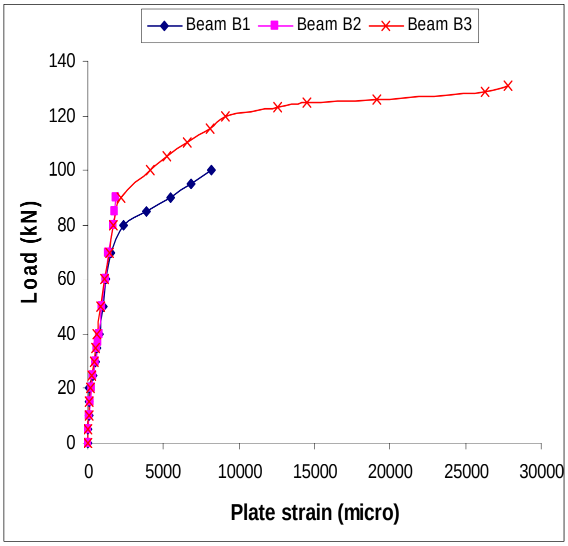


The bar yield load of B2 is around 120 kN according to proof method. And the bar yield load of B3 is also around 120 kN. However, the bar of B1 was not yield, because of its plate debonding failure before yielding of the bar. At failure load, the steel bar strain of strengthened beams with U and L shaped end anchorage are higher than the strengthened beam without end anchorage. End anchoring has a significance effect on the deflection and failure mode.

3.3.2 Plate strain

The load-steel plate strain is shown in Figure 6. End anchorage has a significant effect on plate strain. Before yielding, all plates have the same strain due to the same material properties. After 90 kN load, the plate strain of B2 is not available. The yield load of beams B1 and B3 are around 80 kN and 90 kN respectively. Theoretically, since both beams are of the same materials, the yield load of both beams should be the same. This anomaly is still very much a puzzle. Due to the higher effective depth and lower yield stress of steel plate than the steel bar, the yield load of plate is much lower than the bar yield load of same beam.

Figure 6: Loads versus plate strain



The Figure 6 also shows that, at failure load the plate strain of B3 is higher than that of B1; thus a sign of full utility of strengthening plate as well as ductile failure mode. End anchorage indeed has a great effect on optimum utility of plate strain.

3.3.3 Concrete strain

The load-concrete compressive strains at the top of the beams are shown in Figure 7. The concrete strains of all strengthened beams are less than the concrete strain of control beam due to higher stiffness of strengthened beams. Also strengthened beams (B1, B2 and B3) have shown the same strain on a particular load. This may due to the same stiffness of these beams.

Figure 7: Loads versus concrete strain

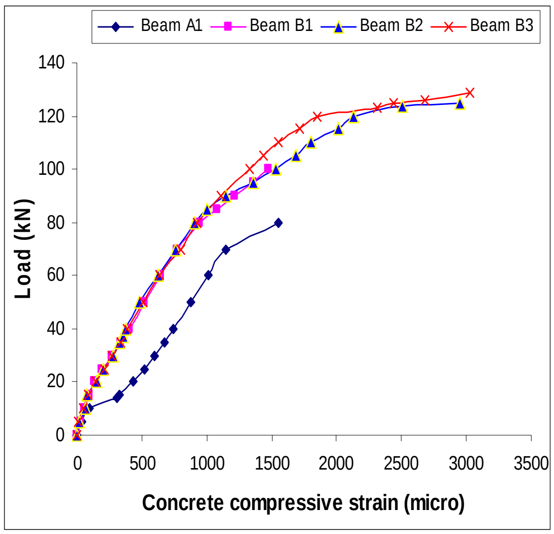
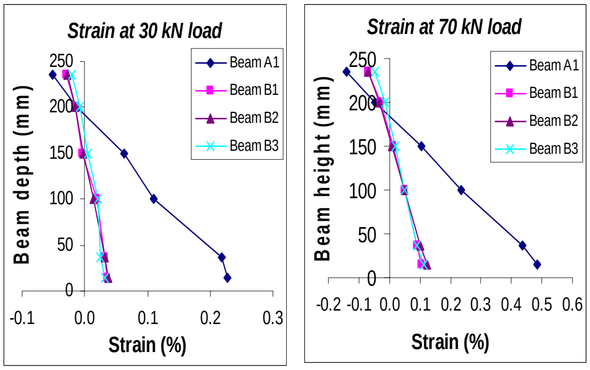


Figure 7 shows that after 120 kN load, the concrete compression strain is rapidly increases, probably due to yielding of steel bars. After bar yield, as bar strain increases rapidly, concrete strain also increases rapidly due to strain compatibility as shown in figure Figure 7. After 120 kN load, the concrete compression strain of about to 0.0035 due to small amount of load increment. It is the sign of compression failure followed by flexural failure.

Figure 8 shows the strain variation over the heights of the beams A1, B1, B2 and B3 at 30 and 70 kN load. The strain variation of strengthened beams (B1, B2 and B3) is less than control beam (A1) due to higher stiffness of strengthened beam. Since the strain of strengthened beams is less than the strain of control beam, the neutral axis depth of strengthened beams is more due to internal equilibrium of force. The strain variation and neutral axis depth of all strengthened beams are the same due to same materials and stiffness of strengthened beams.

Figure 8: Strain variation on beam depth



3.4 Deflection

Figure 9 shows the test obtained load-midspan deflection curves for beams A1, B1, B2 and B3. All beams show linear increment of deflection before failure. However, strengthened beams show less deflection than the control beam due to the higher stiffness of strengthened beams over the control beam. This is advantageous, in terms of controlling the deflection at service load level, but is quite disadvantageous once the tension steel has yielded, as the beams would fail in a brittle manner without any warning.

Figure 9: Load vs deflection

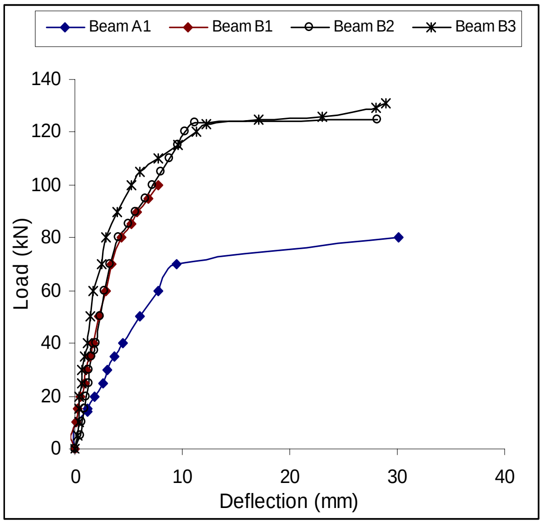
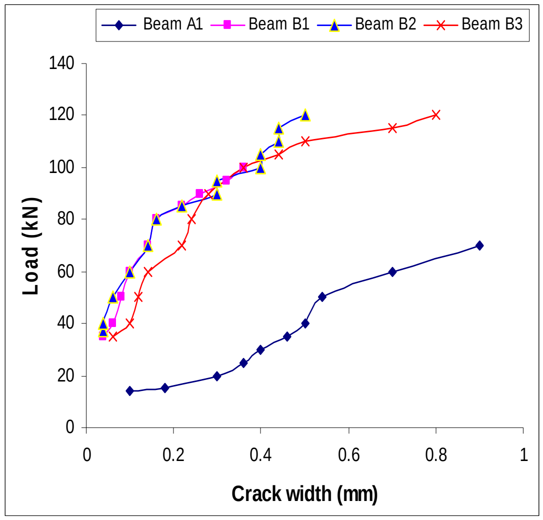


Figure 9 also shows deflections of B2 and B3 suddenly increase after 120 kN, this is due to the yield of steel bar. The deflection at failure load of U and L shaped end anchored steel plate strengthened beam is higher than unanchored strengthened beam, a sign of ductile failure mode. On the other hand, the strengthened beam without end anchorage shows less deflection at failure; a sign of brittle and catastrophic failure mode.

3.5 Crack

The experimental first crack loads, obtained visually, are shown in Table 4. The first crack load of beams A1, B1, B2 and B3 are 14 kN, 35 kN, 37 kN and 35 kN respectively. All strengthened beams show a higher cracking load than the control beam. However, end anchorages don't have any effect on cracking load as cracking load depends only on strengthening materials as well as concrete properties. Therefore, B1, B2 and B3 have similar the first crack load.

Figure 10: Load vs crack width



The total number of cracks of beams A1, B1, B2 and B3 are 11, 15, 13 and 13 respectively. The average crack spacing over the span of the beams A1, B1, B2 and B3 are 182 mm, 133 mm, 154 mm and 154 mm respectively. It is noted that, B2 and B3 show less crack number and more crack spacing than B1. This is due to the use of end anchors which also prevented cracks in beam ends. Therefore, the end anchorage affects crack spacing but not crack width. Figure 10 shows the load-crack width of beams A1, B1, B2 and B3. All strengthened beams show less crack width than the control beam. This is very good for concrete structures. A large crack would allow moisture to penetrate and cause the internal bars to rust and eventually corrode. The crack width of beams B1, B2 and B3 is more or less same, this is expected since beams B1, B2 and B3 are of same materials and stiffness. End anchorages don't have any effect on crack width.

4. Summary and Concluding Remarks

The following conclusions have been drawn from the present study.

The steel plate flexurally strengthened beam without end anchorage exhibits plate end debonding shear-type brittle failure with many diagonal cracks. While those with end anchors exhibit conventional flexural failure with ductile failure mode and in this case no plate end debonding was noticed.

The ultimate load of strengthened beam without end anchor, with U-shaped end anchor and with L-shaped end anchor were found to be 29.4%, 55.1% and 53.7% respectively higher than the control beam. The failure load of U and L shaped end anchored steel plate strengthened beams were 19.8% and 25.5% respectively higher than the failure load of beam without end anchor.

Due to higher stiffness, strengthened beams had less tensile reinforcement strain and concrete compressive strain compared to the control beam. At failure, end anchorages seemed to have significant effect on strain of reinforcement and concrete compressive strain. This is because the strengthened beams with U and L-shape end anchors did not fail by plate separation, and failed at a relatively higher failure load; Strengthened beams with end anchors showed a larger reinforcement strain and concrete compressive strain compared to the non-anchored strengthened beam. Furthermore, the plate strains of all strengthened beams were found to be similar due to their similar material properties. However, before failure, U and L-shaped end anchored beams had shown larger plate strain compared to un-anchored strengthened beam.

All strengthened beams showed less deflection compared to the control beam due to higher stiffness of strengthened beams. End anchorages of U and L-shape had a significant effect on the deflection at failure load. At failure, both U and L-shaped end anchored strengthened beams gave larger deflection compared to beams without end anchorage.

All strengthened beams possessed higher cracking loads and better cracking patterns. The cracking load of strengthened beams without end anchor, with U-shaped and L-shaped end anchors are 150%, 164% and 150% respectively higher than control beam. 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 that of strengthened beams without end anchorage.

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