

L Shaped End Anchors to Eliminate Premature Plate End Debonding in Strengthened RC Beams

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Abstract—This paper presents an investigation into the performance of L shaped steel plate end anchors for preventing plate end debonding in flexurally strengthened RC beams. Plate end debonding is a common failure mode for RC beams flexurally strengthened with external plates or laminates, and prevents the full structural capacity of strengthened structures from being realized. Most end anchorage systems delay but do not prevent plate end debonding. However, L and U shaped end anchors may effectively prevent premature debonding failure. In this study, ten RC beams (two control beams, four beams strengthened with steel plate and four beams strengthened with CFRP laminate) of 2300mm length, 125mm width and 250mm depth were tested under four point bending. Three of the steel strengthened beams and three of the CFRP strengthened beams were end anchored with epoxy bonded L shaped steel plate anchors of varying widths. The investigation found that all strengthened beams had higher failure and cracking loads, smaller crack widths and more cracks, less concrete and bar strains, and smaller deflections than control beams. End anchorage significantly increased ultimate strength and effectively prevented premature plate end debonding with anchored beams failing in flexure.

Keywords—*premature failure; plate end debonding; L shaped end anchors*

I. INTRODUCTION

The strengthening of reinforced concrete (RC) structures is an important area of research as many existing structures will require rehabilitation at some point in their life span to meet current standards and service conditions. Strengthening provides a more economical choice than replacing and reconstructing structures to meet current conditions. A number of different methods and materials have been developed to strengthen structures. One of the most popular methods is the use of externally bonded plates which are applied to the surface of structural elements which require strengthening. Steel plates and carbon fibre reinforced polymer (CFRP) laminates are the most commonly used strengthening materials. Structural adhesives are used to apply plates and laminates to concrete elements for strengthening.

However, although the plate bonding method offers an effective strengthening method that can greatly increase the ultimate capacity of a beam, it also suffers from some disadvantages. The main disadvantage of externally bonded reinforcement is that it often suffers from premature failure, usually plate end debonding failure [1, 2]. Beams flexurally strengthened with steel plate are more likely to suffer from plate end debonding than beams strengthened with CFRP laminates due to the greater stiffness of steel [3]. Plate end debonding is an extremely serious problem as it can cause sudden and catastrophic failure of a strengthened structure before ultimate capacity is reached. Plate end debonding occurs due to the high concentration of interfacial shear stress at the ends of the bonded plate [4]. Failure usually occurs with the formation of a shear crack at the plate end which rapidly extends towards the load point into a horizontal crack between the plate and the internal reinforcement, eventually leading to separation of the plate from the concrete element [5].

Researchers have investigated a number of methods to reduce and eliminate plate end debonding in strengthened beams. End anchorage is one method that has received considerable attention. Some researchers have reported that end anchors have a significant effect on plate end debonding [6, 7]. End anchors can take various forms, such as anchor bolts, bonded angle sections, end plates, and extending the strengthening plate under the beam supports. However, most of these anchoring systems were found to be able only to delay, not prevent, plate end debonding. Most tested specimens still failed by plate end debonding failure [6, 8, 9, 10]. These anchoring systems failed to prevent plate end debonding mainly because they failed to minimize the shear stress concentrations at the plate ends. Further research led to the development of L and U shaped plate anchors, and U wrap, which were found to significantly reduce premature plate end debonding failure [4, 11].

In this study, an experimental investigation was carried out to eliminate plate end debonding using L shaped steel plate anchors placed at the ends of flexural strengthening plates on RC beams. The expected outcome of this investigation was that the beams would be able to carry the maximum designed load before failure and that the beams would fail by either plate/laminate rupture or by concrete

compression. The beams were strengthened using steel plates or CFRP laminates. In this program a total of ten RC beams were tested. Two beams were used as unstrengthened control specimens and the rest were flexurally strengthened using steel plates (4 beams) and CFRP laminates (4 beams). Of the steel plate strengthened beams, 1 beam did not have end anchorage and 3 beams had L shaped end anchors. Of the 4 CFRP laminate strengthened beams, 1 beam did not have end anchorage and 3 beams had L shaped end anchors. The anchors were of varying widths. The specimen details are presented in Table 1.

II. METHODOLOGY

A. Specimen Fabrication

The beams fabricated in this program were 2300mm long, 125mm wide and 250mm deep as shown in Fig. 1. Two 12mm diameter steel bars were used as tension reinforcement. Two 10mm steel bars were used as hanger bars and 6mm bars spaced 75mm apart centre to centre were used as shear reinforcement as shown in Fig. 1. The designed compressive strength of the concrete was 30MPa.

B. Strengthening and Anchoring

The length of all strengthening steel plates and CFRP laminates was maintained at 1900mm, which was nearly the full span of the beams, as shown in Fig. 2. Near full span strengthening was done to maximize the effects of strengthening. The width of the steel plates was 73mm and the thickness was 2.76mm. The CFRP laminates had a width of 80mm and a thickness of 1.2mm.

Before the application of the strengthening materials, the concrete surface of the soffit of the beam was prepared by grinding with a diamond cutter to expose the coarse aggregate and then cleared of dust using compressed air. The

surfaces of the strengthening materials were also prepared. The steel plates were sand blasted to remove rust and the CFRP laminates were cleaned using a solvent based cleaner (Colma Cleaner) to remove carbon dust and grease. An epoxy adhesive was used to bond the CFRP laminates and steel plates to the prepared concrete surfaces of the beams.

The L shaped end anchors were made of steel plate with a thickness of 2mm. The preparation and application of the anchors to the beams were done in a manner similar to the strengthening steel plates. The anchors were sand blasted and the concrete bonding surfaces were grinded and cleaned to expose the coarse aggregate. Then epoxy adhesive was applied to the prepared bonding surfaces of the beam and the inner face of the anchors, and the anchor were then fixed to the beam by pressing with a rubber roller. The anchors were then clamped for 3 days to allow the bond to set.

C. Instrumentation and Test Procedure

To measure strain in the internal steel bars, the strengthening plate and the concrete during testing, 30mm electrical resistance strain gauges were used. Two strain gauges were placed on the strengthening plate or laminate at the midspan of the beam to record tensile strain in the plate or laminate. Another gauge was placed on the top surface of the beam at midspan to measure the concrete compressive strain. Two strain gauges were also attached to the middle of the internal reinforcing bars to measure tensile strain. To measure horizontal strains in the concrete, demec gauges were attached along the height of the beam at midspan. To measure the vertical deflection of the beam, three linear variable displacement transformers (LVDTs) were used at midspan and under the two load points. Fig. 3 shows the placement of the strain gauges and the LVDTs.

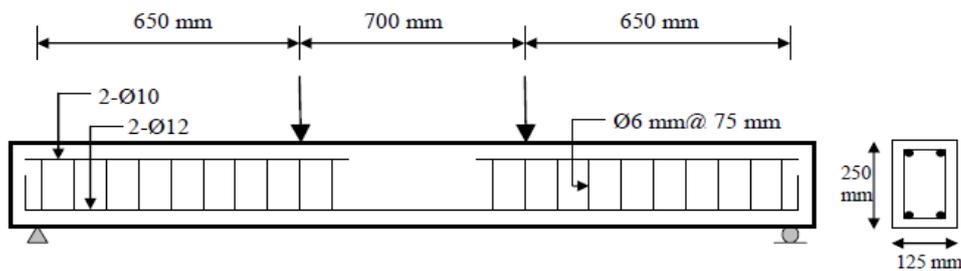


Fig. 1. Beam details

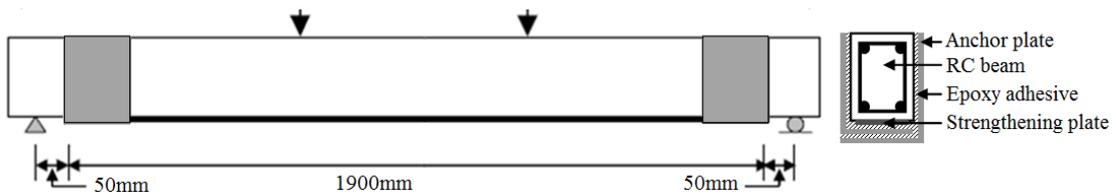


Fig. 2. Strengthening and L shaped anchorage details

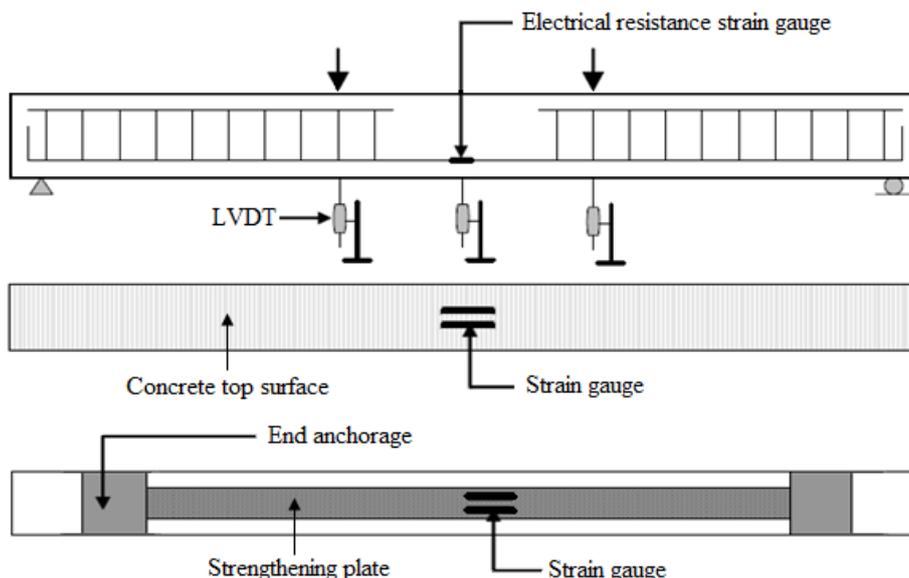


Fig. 3. LVDT and strain gauge placement

All beam specimens were tested under four-point loading. The loading was applied gradually in a controlled manner by the Instron testing machine up to failure of the beams. The beams were loaded to failure point. Failure of the beams was identified with concrete crushing, tensile rupture of the strengthening plate or laminate, shear rupture of the plate or laminate at the epoxy adhesive level, concrete rip-off at the level of the bottom reinforcement, or shear failure of the strengthened beam.

III. RESULTS OF THE EXPERIMENTAL INVESTIGATION

The experimental investigation found that all strengthened beams had higher failure and cracking loads, smaller crack widths and more cracks, less concrete strains, less bar strains and smaller deflections than the control beams. Table 1 presents the test results for all beam specimens.

The study also found that the strengthened beams with L shaped steel plate end anchors failed in a ductile manner rather than in premature plate end debonding failure.

TABLE 1. SPECIMEN DETAILS AND TEST RESULTS

Beam ID	Width of L Shaped End Anchors (mm)	Strengthening Materials		1 st Crack Load (kN)	Failure Load (kN)	Midspan Deflection at 70 kN (mm)	Crack Width at 70 kN (mm)	Failure Mode ^a	
		Thickness (mm)	Width (mm)						
Control Beam	CB1	-	-	14	80.6	9.52	0.9	FL	
	CB2	-	-	12	83	7.58	0.5	FL	
Strengthened Beams with Steel Plate	SF0	-	2.76	73	35	104.3	3.46	0.14	PED
	SF85	85	2.76	73	30	140	4.1	0.12	FL
	SF100	100	2.76	73	30	137	3.68	0.12	FL
	SF200	200	2.76	73	35	130.9	2.56	0.22	FL
Strengthened Beams with CFRP	CF0	-	1.2	80	27	123.9	4.25	0.16	CS
	CF75	75	1.2	80	21	155	5.14	0.16	FL + ICD
	CF100	100	1.2	80	25	148	5.18	0.18	SH
	CF200	200	1.2	80	27	145.8	4.72	0.28	SH

^a. FL = Flexural failure, PED = Plate end debonding, CS = Concrete cover separation, ICD = Intermediate crack debonding, SH = Shear failure

Strengthened beams without end anchorage exhibit plate end debonding shear-type brittle failure with many diagonal cracks. Strengthened beams with end anchors exhibit conventional flexural failure with ductile failure mode and with no noticeable plate end debonding. Fig. 4 to Fig. 9 show the failure modes of unstrengthened, strengthened, and end anchored beams.

The ultimate load of steel plate strengthened beams without end anchors and with L shaped end anchors were

found to be about 30% and 65% higher respectively than the control beams. The failure loads of the end anchored strengthened beams were approximately 30% higher than the failure load of the strengthened beam without end anchors.

The ultimate load of CFRP laminate strengthened beams without end anchors and with L shaped end anchors were found to be about 50% and 80% higher respectively than the control beams. The failure loads of L shaped end anchored CFRP laminate strengthened beams were approximately



Fig. 4. Failure mode for control beam CB1

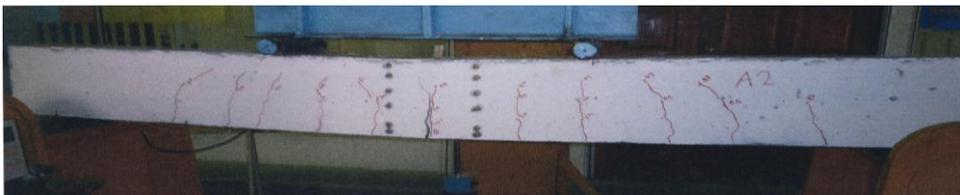


Fig. 5. Failure mode for control beam CB2



Fig. 6. Failure mode for strengthened beam without end anchorage S-F-0



Fig. 7. Failure mode for strengthened beam with end anchorage S-F-85



Fig. 8. Failure mode for strengthened beam without end anchorage C-F-0



Fig. 9. Failure mode for strengthened beam with end anchorage C-F-75

20% higher than the failure load of the CFRP laminate strengthened beam without end anchors.

As the strengthened beams had greater stiffness than the control beams, the strengthened beams had less tensile reinforcement strain and concrete compressive strain compared to the control beams. However, strengthened beams with end anchors showed a higher reinforcement strain, concrete compressive strain and plate strain compared to the strengthened beams without end anchors. This is because the end anchored beams did not fail by plate separation and failed at a much higher load compared to the beams without end anchorage.

Less deflection was seen in all strengthened beams compared to the control beams. This was due to the greater stiffness of the strengthened beams. However, the beams with L shaped end anchors had significantly larger deflections at failure than the beams without end anchorage due to the higher failure load. The load deflection diagrams for the end anchored beams are presented in Fig. 10 and Fig. 11.

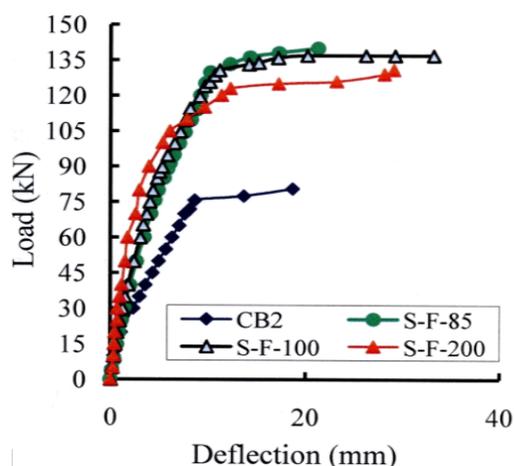


Fig. 10. Load-deflection diagram for end anchored steel plate strengthened beams

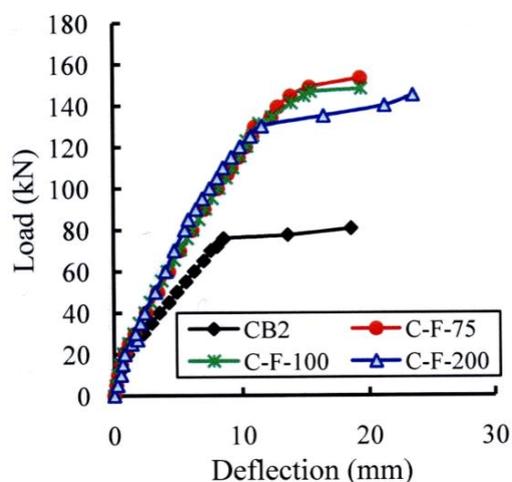


Fig. 11. Load-deflection diagram for end anchored CFRP laminate strengthened beams

Higher cracking loads and better cracking patterns were seen in all strengthened beams compared to the control beams. The cracking loads of steel plate strengthened beams both without end anchors and with L shaped end anchors were found to be around 150% higher than the control beams. The cracking loads of CFRP strengthened beams both without end anchors and with L shaped end anchors were found to be around 90% higher than the control beams. Cracking loads and crack widths depend on the modulus of rupture of the concrete and the stiffness of the strengthening material. Thus, the cracking loads and crack widths of the strengthened beams with end anchors were found to be similar to that of the strengthened beams without end anchorage.

IV. CONCLUSION

This study investigated the use of L shaped steel plate end anchors to overcome plate end debonding failure. The following conclusions can be drawn from the results of this study.

- The proposed use of L shaped steel plate end anchors effectively prevented premature plate end debonding failure, greatly increased the ultimate capacity of the strengthened beams and ensured flexural failure.
- All strengthened beams had higher failure and cracking loads, smaller crack widths and more cracks, less concrete and bar strains and smaller deflections.
- This strengthening method can enhance the performance of EBR strengthened structural elements and contribute to the successful rehabilitation of RC structures.

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