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PERFORMANCE OF END ANCHORED STEEL PLATE AND CFRP LAMINATE FLEXURALLY STRENGTHENED R.C. BEAMS

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ABSTRACT

Strengthening of reinforced concrete structures is an important task in the field of structural maintenance. Different types of strengthening materials and methods are available in the market for this purpose. These include Ferro cement, sprayed concrete, steel plate and fibre reinforced polymer (FRP) laminate. However, plate bonding methods using steel plates and carbon fibre reinforced polymer (CFRP) laminates are popular and most widely used in this field. The main objective of this research is to investigate the behaviour of steel plate and CFRP laminate flexurally strengthened reinforced concrete beams. A total of five beams, each 2300 mm long, 125 mm wide, and 250 mm deep, were fabricated and tested. One beam was left un-strengthened to act as the control beam. Out of four beams two beams were strengthened with steel plates and another two beams were strengthened with CFRP laminates. From each of the steel plate and CFRP laminate strengthened beams, one beam was anchored using L shape end anchors to avoid premature failure. The anchorage length of end anchors is obtained from the design calculation. The experimental results showed that the strengthened beams had higher failure load, good failure modes, less deflections and better cracking patterns over the control beam. It is also seen that strengthened beams with end anchors showed higher failure loads and more ductile behaviour compared to the un-anchored strengthened beams.

Keywords: *Premature debonding, end peeling, CFRP laminate, steel plate, end anchor.*

INTRODUCTION

Strengthening of reinforced concrete structures is an important task in the field of structural maintenance. Reinforced concrete structures need to be strengthened due to a number of factors which include the increase in loads as a result of functional changes of the structures, overloading, under-designed of existing structures or to the lack of quality control. Different types of strengthening materials are available in the market for this purpose. These include Ferro cement, sprayed concrete, steel plate and fibre reinforced polymer (FRP) laminate. Generally, the use of steel plate and FRP laminates, referred to as plate bonding, are preferred due to their advantages such as easy construction work, minimum change in the overall size of the structure and less disruption to traffic. Strengthening by steel plate is a popular method due to its availability, cheapness, uniform materials properties (isotropic), easy to work, high ductility and high fatigue strength. Investigations into the performance of members strengthened by this technique started in the 1960s. This method has been used to strengthen both r.c. buildings and bridges since then. The most common form of plate bonding is to glue steel plates to the tension faces of the r.c. structures. However, steel plate has many disadvantages. These include the problem in transportation, handling and installation of the heavy plates, corrosion of plates, and limited lengths of plates. The need for massive and expensive false works to hold the plates in position during the curing of the adhesive, and the need to carefully prepare the steel surfaces for bonding are also inherent problem. Carbon fibre reinforced polymer (CFRP) laminate is nowadays gaining popularity in the field of strengthening reinforced concrete structures. CFRP is also effective due to its high strength to weight ratio and corrosion resistance. FRP composite materials were first introduced in the early 1940s. In 1986, the world's first highway bridge using FRP reinforcing tendons was built in Germany [1]. Meier and Kaiser [2] were the first authors to report on the application of carbon fibre reinforced polymer (CFRP) as a rehabilitative method. In recent years, with the advanced development of structurally effective adhesives, the usages of plate bonding methods based on steel plates and CFRP laminates in the strengthening of existing concrete structures has increased tremendously.

However, plate bonding method often has a serious premature debonding failure problem due to separation of plates. These debonding can be broadly classified into plate end debonding (end peeling), axial peeling and debonding at the interface level. Amongst these, plate end debonding failure mode is the most common and serious problem [3]. This debonding causes a premature failure problem due to separation of plates and concrete

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rip off along the tensile reinforcing bars. Saadatmanesh and Malek [4] reported that shear and normal stress concentrations at the cut-off point or around the flexural cracks were the main reason for end peeling. However, researchers would find a solution to minimize this problem using proper end anchors. To minimize the end peeling of flexurally strengthened r.c. beams, research works were done on different end anchoring systems. Jones *et al*. [5] first studied the effects of bolt and partial L-shape end anchorage details on the failure behaviour of strengthened r.c. beams with steel plates. Hussain *et al*. [6] and Garden [7] also used anchor bolt to prevent premature failure. Chahrour and Soudki [8] studied the effects of end anchors details on the failure behaviour of CFRP strengthened beams using mechanical anchors consisting of top and bottom 10-mm thick steel plates fastened together using two M12 bolts for the end anchors of the CFRP strengthened beams. Unfortunately, although a lot of research works had been carried out on strengthening r.c. structures using steel plates and CFRP laminates, but the study on proper end anchoring systems and their effects on the strengthened r.c. beams were very limited. The main goal of the research work reported in this paper is to discuss the performance of designed L shaped end anchored steel plate and CFRP laminate flexurally strengthened r.c. beams.

EXPERIMENTAL INVESTIGATION

Description of Specimens

Five r.c. beams of rectangular cross-sections were tested in this study. These beams are designated as beams A1, B1, B2, C1 and C2. Beam A1 was left as the un-strengthened control beam's specimen; beams B1 and B2 were strengthened by steel plate (2.76 mm x 73 mm x 1900 mm) and beams C1 and C2 were strengthened by CFRP laminate (1.2 mm x 80 mm x 1900 mm). From the strengthened beams, B2 and C2 were end anchored using L shape anchoring plates. The end anchors were of steel plates, 2 mm in thickness with the vertical dimension of 250 mm (the full height of the beam) and horizontal dimension of 125 mm (the full width of the beam). The anchorage lengths used was 100 mm. The test variables are summarized in Table 1.

Table 1: Test specimens

Specimen	Designation	Strengthening Material			End Anchors	
		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	L
4	C1	FRP	1.2	80	----------	--------
5	C2	FRP	1.2	80	Steel Plate	L

Fabrication of Specimens

All beam specimens were of 2,300 mm long, 125 mm wide, and 250 mm deep as shown in Fig.1. These beams were reinforced with two12 mm diameter high yield steel bars in the tension zone. Ten mm mild steel bars were used as hanger bars and 6 mm bars were used for shear reinforcements which were symmetrically placed as shown in Fig. 1. The spacing of the shear reinforcements was 75 mm.

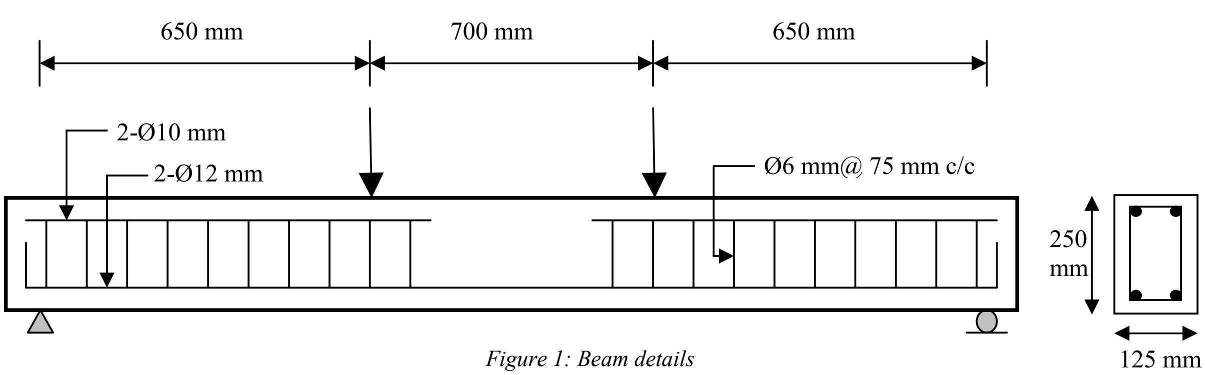

Figure 1: Beam details

Strengthening and Anchoring

For all beams, the length of the bonded plate was maintained at 1900 mm, which covered almost the full-span length of the beams (Fig.2). The main reason for the full span-length strengthening with steel plates and CFRP laminates was to maximize the strengthening effects.

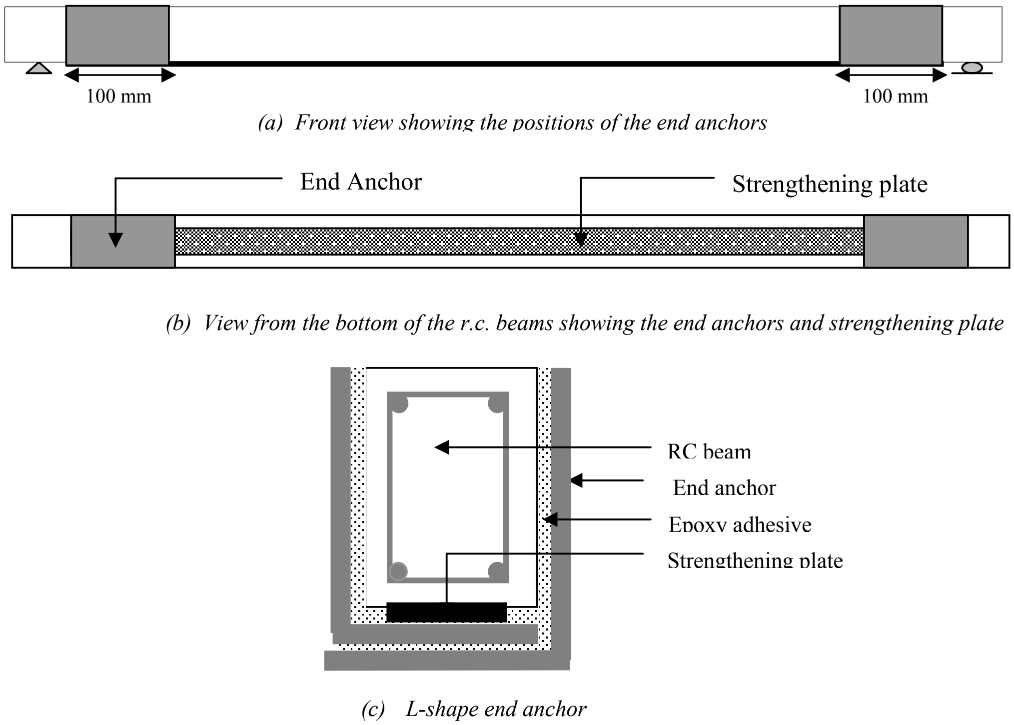

Figure 2: Strengthening and anchoring details

The concrete surface treatment prior to plating works was very important to guarantee the perfect bonding between concrete and strengthening plates. Concrete was ground with a diamond cutter to expose the coarse aggregates. Dusts were then blown out by compressed air. The surface of the steel plate was sand blasted to eliminate the rust while colma cleaner was used to remove carbon dusts form the bonding face of the CFRP laminate. The well mixed sikadur adhesive was then trawled on to the surface of the concrete specimens to form a thin layer. The adhesive was applied with a special "dome" shaped spatula onto the steel plates and CFRP (Sika CarbaDur) laminates. The plates were positioned on the prepared surface. Using a rubber roller, the plates were gently pressed into the adhesive until the material was forced out on both sides of the laminates. The surplus adhesive was then removed.

L shape end anchors were placed at the end of both of the strengthened beams (B2 and C2). The plates were sand blasted and the surface preparation and application methods were similar to that of the plating method. Before placing the end anchors, the adhesive was applied on the prepared bonding face of the beams and an inner face of the anchors. The anchor-plates were fixed on to the beam and then pressed by a rubber roller. After fixing, they were clamped for 3 days for setting.

Materials

Ordinary Portland Cement (OPC) was used in casting the beams. The maximum size of coarse aggregate used was 20 mm. The concrete mix was designed with a targeted strength of 30 MPa. The mix proportion adopted is as shown in **Table 2**. The compressive strengths of the concrete were obtained from three cubes after 28 days curing according to British Standard (BS 1881).

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Table 2: Mix design

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

Two 12 mm diameter of high yield deformed bars were used as the tensile reinforcement. The measured yield and tensile strength of these bars were 551 MPa and 641 MPa respectively. Ten millimetre diameter mild steel bars were used as hanger bars in shear span zone. Six mm diameter bars were used for stirrups. The measured yield and tensile strength of the stirrups were 520 MPa and 572 MPa respectively. The modulus of elasticity of all steel bars was 200 GPa. For beam strengthening, mild steel plates and CFRP laminates (Sika CarboDur S812) were used. The yield strength, tensile strength and modulus of elasticity of the steel plates were 320 MPa, 375 MPa and 200 GPa respectively. The tensile strength and modulus of elasticity of CFRP laminates were 2800 MPa and 165 GPa respectively. The design and ultimate strain of CFRP laminates were 0.0085 and 0.017 according to the manufacturer's instruction.

Instrumentation and test procedure

Fig. 3 shows the location of the different instruments used to record data during testing. Electrical resistance strain gauges were used to measure the strains in the steel plate, CFRP laminate and the top of the r.c. beams. Demec gauges were attached along the height of beam at the mid-span region to measure the horizontal strains. Three linear variable displacement transducers (LVDTs) were used to measure the vertical deflection of the beam at mid-span and under the two load points (Fig. 3). The load was applied incrementally under a load control procedures up to failure using the Instron 8505 Universal Testing Machine.

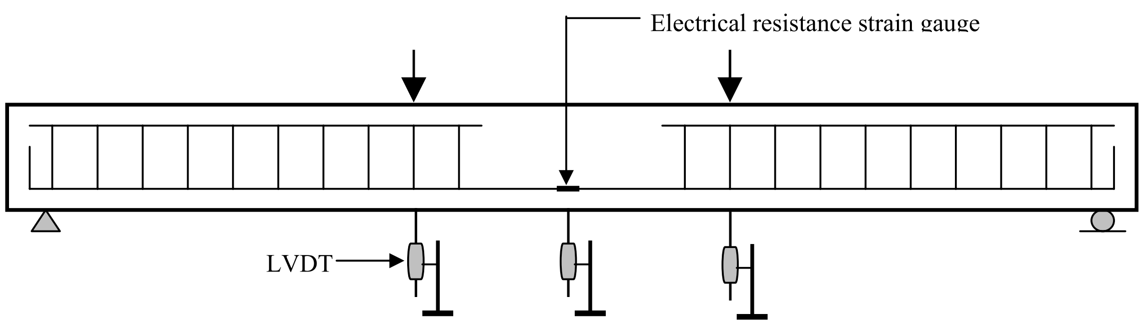

Figure 3: Beam instrumentations

EXPERIMENTAL RESULTS AND DISCUSSION

Mode of Failure

Plate 1 shows the beams specimens at failure. The control beam (A1) showed a flexural and ductile mode of failure. The un-anchored steel plate and CFRP laminate strengthened beams were found to fail by debonding of the plate or laminate in brittle manner even though the beams were strengthened for the full-span. The end anchored steel plate strengthened beam (B2) and CFRP laminate strengthened beam (C2) failed in a more ductile manner by flexure and shear respectively. For the case of the strengthened beams with end anchors debonding did not occur. The CFRP laminate strengthened beam failed in a shear mode of failure probably due the high flexural strength of the beam induced by the CFRP laminates.

Beam A1

Beam B1

Beam B2

Beam C1

Beam C2

Plate 1: Failure mode of tested specimens

Failure load

The experimental failure loads recorded by all the beams are shown in Table 3. The results showed that the failure loads of all the strengthened beams were higher compared to the control beam. It can be also seen that the end anchored steel plate and CFRP laminate strengthened beams (B2 and C2) gave higher failure loads over the unanchored strengthened beams (B1 and C1).

Table 3: Results

Specimen	Experimental results				
	1st Crack load (kN)	Increase over Control Beam (%)	Ultimate load (kN)	Increase over control beam (%)	Mode of failure
A1	14		80.59		Flexure
B1	35	150	104.3	29.4	Debonding
B2	30	114	137	70	Flexure
C1	27	93	123.9	53.7	Debonding
C2	25	78	148	83.6	Shear

The failure load of beam C2 was higher than beam B2. This would be due to the over reinforcement of the beam C2 because of the high strength of CFRP laminate.

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Ductility

Fig. 4 shows the load versus mid-span deflection curves for all the beams. All the beams indicated linear, elastic portions of the curves at the initial stages. All the strengthened beams showed smaller deflection compared to the control beam due to their higher stiffnesses. Fig. 4 also shows that the deflection of beam B2 and C2 suddenly increased after around 120 kN and 130 kN load. This might due to steel bar yielding (Fig.5). When the bar was yielding, the strain of the bar increased suddenly and would deflect the beam further which influenced the beams (B2 and C2) to fail in ductile manner. Whereas, the un-anchored strengthened beams (B1 and C1) failed at pre-yield stage of bars which lead the beams to fail in brittle manner.

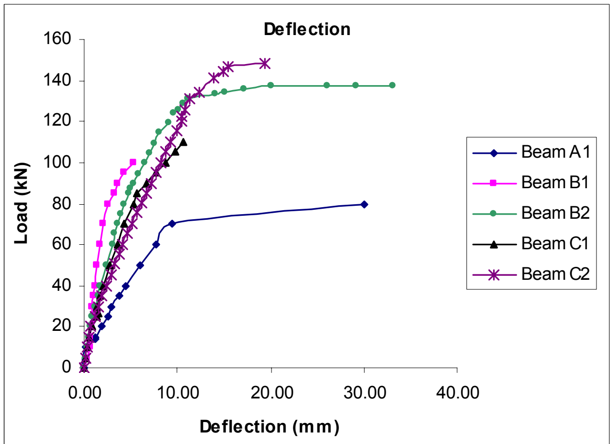


Figure 4: Load vs deflection

Further, Fig. 5 shows the load versus steel bar strains of all the beams. It can be seen from the figure that, at all load levels, the bar strains of all the strengthened beams were found to be less than the control beam. It also shows that the bar strain of the steel plate strengthened beams (B1 and B2) was identical due to the similar material properties of both of the beams. This was also true for CFRP laminate strengthened beams. Fig.5 also shows that the bars of end anchored strengthened beams (B2 and C2) yielded before failure and the approximate bar yield loads of those beams were about 120 kN. On the other hand, the bars of un-anchored strengthened beams did not yield because of the premature failures of beams. Since the bar of end anchored strengthened beams yielded before failure, ductile failure modes were noticed for beams B2 and C2.

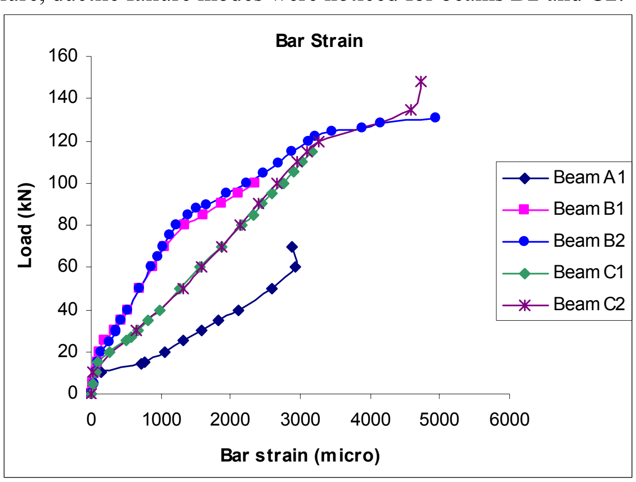
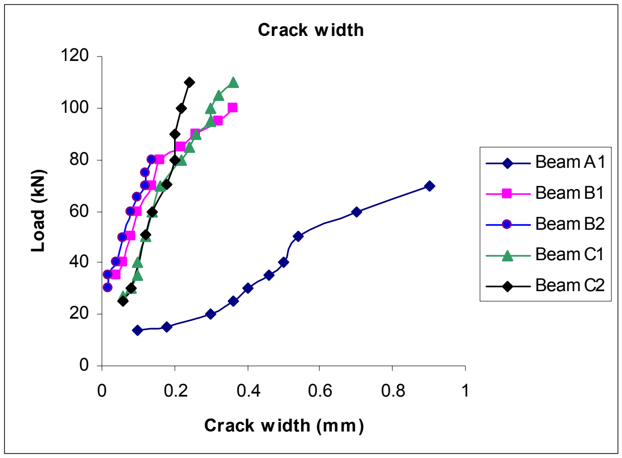


Figure 5: Load vs Bar strain

Cracking patterns

The first crack loads are shown in Table 3. The strengthened beams in general showed higher cracking loads compared to the 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.



Rigure 6: Load vs Crack width

Fig. 6 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.

The total number of cracks of beam A1, B1, B2, C1 and C2 were 11, 15, 13, 20 and 18 respectively. The average crack spacings of the beam A1, B1, B2, C1 and C2 were 182 mm, 133 mm, 153 mm, 100 mm and 111 mm respectively. The strengthened beams showed less crack spacing than the control beam.

CONCLUSIONS

The conclusions that can be drawn from the present study are,

1. All strengthened beams gave higher failure loads compared to the control beam.
2. The L-shape end anchored steel plate and CFRP laminate flexurally strengthened beams gave higher failure loads than the un-anchored strengthened beams.
3. The control beam and end anchored steel plate strengthened beam failed in ductile flexural manner. End anchored CFRP laminate strengthened beam failed in ductile shear mode. Whereas, un-anchored strengthened beams showed brittle plate debonding failures.
4. All strengthened beams showed lesser deflections compared to the control beam.
5. All strengthened beams showed less bar strain compared to the control beam.
6. The cracking load of the control beam was found to be less than the strengthened beams. The steel plate strengthened beam gave a higher cracking load and smaller crack widths compared to the CFRP laminate strengthened beam. Both end anchored and un-anchored strengthened beams showed similar cracking loads widths.

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