

## Strengthening of R.C. Beams Using Externally Bonded Plates and Anchorages.

<sup>1</sup>Mohd Zamin Jumaat and <sup>2</sup>Md. Ashrafal Alam

<sup>1</sup>Professor, Dept. of Civil Engineering, University of Malaya, 50603 Kuala Lumpur.

<sup>2</sup> Ph.D student, Dept. of Civil Engineering, University of Malaya, 50603 Kuala Lumpur.

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**Abstract:** This paper presents a study on strengthened reinforced concrete beams using externally bonded plates and anchorages. Strengthening materials and methods, failure modes of strengthened beams, effect of end anchorages and effect of intermediate anchorages are reviewed. An experimental programme to evaluate the structural behaviour of anchored steel plate and CFRP laminate flexurally strengthened reinforced concrete beams is also reported. 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, two beams were strengthened with steel plate and another two beams were strengthened with CFRP laminate. From each of the steel plate and CFRP laminate strengthened beams, one beam was left unanchored and another beam was anchored at the end and shear spans (intermediate anchored) by L shape plates to avoid premature failure. The experimental results overall showed that the strengthened beams had higher failure loads and good failure modes over the control beam. Results also illustrated that the end with intermediate anchored strengthened beams gave higher failure loads and better failure modes compared to unanchored strengthened beams.

**Key words:** *reinforced concrete, beam, strengthening, plate, debonding, anchors*

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### INTRODUCTION

Reinforced concrete beam strengthening is an important task of maintenance. The aim of strengthening is to increase the capacity of an existing beam element. Different types of strengthening materials are available in the market for this purpose such as ferrocement, sprayed concrete, steel plate and fibre reinforced polymer (FRP) laminate. Generally the use of steel plate and FRP are preferred in this field due to their several advantages such as easy construction work, minimum change in the overall size of the structure after plate bonding and less disruption to traffic while the strengthening is being carried out. In recent years, with the development of structurally effective adhesives, plating methods of steel plates and FRP laminates have been widely used for the strengthening of existing concrete structures. However, the plate bonding method often has a serious premature debonding and shear failures problems before reaching its ultimate capacity. These are extremely significant problems. In this regard, many studies have been conducted to overcome these problems of strengthened beams with steel plates and FRP laminates. It has been reported by the reviewers that appropriate anchors could minimize the premature failure. In general end anchorage of L shapes is more effective in preventing premature debonding. An addition intermediate anchorage in the shear span zone is sometimes required to prevent shear failure occurring before flexural failure.

The objective of this study is to,

- review the main methods of strengthening of reinforced concrete beams, effect of end and intermediate anchorages.
- study the behaviour of steel plate and CFRP laminate flexurally strengthened reinforced concrete beams using externally bonded anchorages.

#### *Literature Review:*

#### *Materials and methods of strengthening:*

Among the strengthening materials, steel plate is one of the most common materials for strengthening of reinforced concrete beam. Steel plate is very effective for increasing the flexural and shear capacity of

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**Corresponding Author:** Md. Ashrafal Alam, Ph.D student, Dept. of Civil Engineering, University of Malaya, 50603 Kuala Lumpur.  
E-mail: ashraf\_arif2003@yahoo.com

reinforced concrete beam. Strengthening by steel plate is also a popular method due to its availability, cheapness, uniform materials properties (isotropic), easy to work, high ductility and high fatigue strength. However, several disadvantages of steel plate including the transportation, handling and installation of heavy plates, corrosion of plates, and limited delivery lengths of plates which necessitates the work and difficulty of forming joints, the need for massive and expensive false work to hold plates in position during adhesive cure, and the need to prepare for steel surface for bonding are very apparent. Carbon fibre reinforced polymer (CFRP) laminate is an alternative advanced popular material in the field of strengthening reinforced concrete beam. Using CFRP is also effective because of its high strength to weight ratio and corrosion resistance; the latter results in low maintenance costs.

#### **Failure Modes:**

A number of failure modes for reinforced concrete beams bonded with soffit plates have been observed in numerous experimental studies to date. Smith and Teng (2002) have identified some failure modes of plate bonded strengthened reinforced concrete beams. These are namedly grouped under,

- flexural failure by FRP rupture
- flexural failure by crushing of compressive concrete
- shear failure
- concrete cover separation
- plate end interfacial debonding and
- intermediate crack induced interfacial debonding

It is also reported that, the three failure modes i.e. iv, v and vi are not found in conventional r.c. beams and are instead modes unique to beams bonded with a soffit plate. These modes have often been referred to as premature debonding failures modes, as they occur before the flexural failure.

#### **Effect of End Anchorages:**

End anchorages have significant effects on minimizing premature end peeling. A number of research works have been carried out on end anchorages to examine their effect on strengthened reinforced concrete beams. It is reported by the researchers that the anchorages applied at the ends of externally bonded plate can be of several forms. These include bolted anchorage systems, bonded angle section to provide anchorage of reinforcing plate to the sides of beam, and trapping the plate under the beam supports. 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. Ritchi *et al.* (1991) had used various bonded anchorage system in an attempt to shift the location of failure away from the composite plate ends and to alter the mode of failure and ultimate capacity. Sharif *et al.* (1994) examined the effect of end anchorage using FRP plate strengthened damaged reinforced concrete beams. For end anchoring, they used the anchoring bolt, bolt with side plates in shear span and I jacket FRP strengthening plates. Hussain *et al.* (1995) investigated the effect of end anchorage on pre-cracked reinforced concrete steel plate strengthened beams. The end anchorage was applied onto bonded steel plates using anchor bolts. Garden (1998) tested a few carbon fibre reinforced polymer strengthened beams with bolted end anchorage. They used two types of plate end anchorage system, i.e. bolts and clamping force. Swamy and Mukhopadhyaya (1999) carried out an extensive work on anchorage system on carbon fibre reinforced polymer (CFRP) laminate strengthened beams to avoid debonding. All the plated beams were fixed with 1.5 mm thick steel U-shaped end anchorages, and additional short U-shaped anchorages, of the same thickness, along the span. Adhikary and Mutsuyoshi (2002) have examined the effect of end anchoring bolt on steel plate strengthened beams. Xiong *et al.* (2007) had examined the effect of different types of end anchorages on CFRP strengthened r. c. beams. For end anchoring purposes, they had used CFRP-U strip of 250 mm anchoring length, CFRP-U wrap in the whole span and GFRP-L wrap in the whole span.

#### **Effect of Intermediate Anchorages on Shear Span Zone:**

Anchor in shear span provides shear strengthening of r.c. beams. Shear strengthening has a significant effect on failure mode and failure load for low shear capacity beam. Furthermore, in flexural strengthening sometimes it is important to prevent the shear failure to get the maximum flexural capacity. Swamy and Mukhopadhyaya (1999) examined the effect of intermediate anchorage on five CFRP flexural strengthened r.c beams. They had used U shape steel strip of 50 mm length over the whole span with different spacing. It was reported that, the intermediate anchorage has a good effect on preventing plate debonding failure in the shear

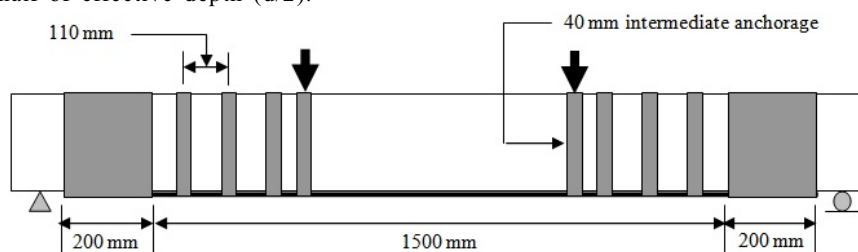
span and flexural zone. Diagana *et al.* (2003) used the 40 mm wide U shape carbon fibre fabric (CFF) strips for shear strengthening of r.c. beams. They had strengthened the beams for shear by using vertical and 45 degree CFF strip. However, L shape plate is the preferable choice as intermediate anchorage for shear strengthening due to its easy placement.

**Experimental Investigation:**

**Description of Specimens:**

Five r.c. beams of rectangular cross-sections (125 mm x 250 mm x 2000 mm) were tested in this study namely, beam A1, B1, B4, C1 and C4. The test variables are summarized in

Table 1. 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. 1). L shape end and intermediate anchorages were only used at the end of the strengthened beams of B4 and C4 as shown in Fig. 1. All anchorages were made from steel plates. The thickness of the plate was 2 mm. The spacing of the intermediate anchor was chosen to be 110 mm, which was equal to half of effective depth (d/2).



**Fig 1:** Strengthening and anchoring details

**Table 1:** Test variables

Serial No	Specimen	Strengthening Materials			Anchor	
		Type	Thickness (mm)	Width (mm)	End(200 mm)	Intermediate (40 mm @110 mm c/c)
1	A1	-----	-----	-----	-----	-----
2	B1	Steel Plate	2.73	73		
3	B4	Steel Plate	2.73	73	L shape	L shape
4	C1	CFRP	1.2	80		
5	C4	CFRP	1.2	80	L shape	L shape

**RESULTS AND DISCUSSION**

**Mode of Failure:**

Plate 1 shows the failure modes of control beam (A1), unanchored CFRP laminate strengthened beam (C1), unanchored steel plate strengthened beam (B1), end with intermediate anchored CFRP laminate strengthened beam (C4) and end with intermediate anchored steel plate strengthened beam (B4). It was seen that the control beam without strengthening plates (A1) showed the traditional flexural and ductile failure. Further, unanchored CFRP laminate and steel plate strengthened beams (C1 and B1) failed by plate debonding with brittle manner. Whereas, L shape end and intermediate anchored CFRP laminate and steel plate strengthened beams (C4 and B4) failed by concrete compression and flexure respectively. It was also observed that both of these beams (C4 and B4) had shown the ductile failure mode.

**Failure Load:**

The experimental failure loads recorded by all the beams are shown in Table 2. The results exhibited that the failure loads of all strengthened beams were higher compared to that of the control beam.

However, the failure loads of beam B4 and C4 was 20% and 25% higher than that of beams B1 and C1 respectively. These might be because of using anchorages which prevented premature failure. Amongst all beams, beam C4 showed the highest failure load. It is also seen in the table that all strengthened beams showed higher cracking load compared to control beam due to stiffer behaviour of strengthened beams. Further, beam B1 and B4 showed higher cracking load compared to beam C1 and C4 because of the higher stiffness of the steel plates.

**Table 2:** Test results

Specimen	1 <sup>st</sup> Crack Load in kN (% Increase over control)	Failure Load in kN (% Increase over control)	Failure mode
A1	14	80.59	<i>Flexural</i>
B1	35 (150)	104.3 (29)	<i>Debonding</i>
B4	35 (150)	125.4 (56)	<i>Flexural</i>
C1	27 (93)	123.9 (54)	<i>Debonding</i>
C4	25 (79)	157.8 (96)	<i>Concrete compression</i>



**Plate 1:** Failure mode of tested specimens

**Conclusions:**

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

1. the control beam failed in a ductile flexural manner. Unanchored strengthened beams of steel plate and CFRP laminate showed premature debonding failure in a brittle manner. End and intermediate anchored CFRP laminate and steel plate strengthened beams failed in a ductile manner with concrete compression failure and flexural failure respectively.

2. end and intermediate anchors prevented premature failure.
3. all strengthened beams were found to have higher failure loads compared to the control beam. The end and intermediate anchored strengthened beams showed higher failure load compared to unanchored strengthened beams. L-shape end with intermediate anchored CFRP laminate flexurally strengthened beams gave highest failure loads.
4. all strengthened beams sustained higher cracking loads compared to the control beam. Steel plate strengthened beams gave higher cracking load compared to the CFRP laminate strengthened beams.

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