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Full Length Research Paper

Optimization of intermediate anchors to eliminate premature shear failure of CFRP laminate flexurally strengthened R.C beams

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Flexurally strengthened RC beams usually fail by means of premature shear due to low shear as compared to flexure. Intermediate anchors in the length of shear span of those beams would successfully eliminate this problem. This paper presents the experimental studies on the effects of intermediate anchors in preventing premature shear failure of CFRP laminate flexurally strengthened RC beams. Design guidelines to optimize the intermediate anchors for eliminating premature shear failure are proposed. In the experimental programme, four RC beams were cast. One beam was tested in the un-strengthened condition to act as the control beam. The remaining beams were strengthened with CFRP laminates. Among the strengthened beams, one beam was prepared without intermediate anchors, one was intermediate anchored based on the proposed design method, and the last one was intermediate anchored using arbitrary anchor plates. Results showed that strengthened beam with having optimal intermediate anchors had higher ultimate strength as compared to that of the control beam. The optimal anchors significantly increased both the ultimate load as well as ductility of the said beams as compared to the beam without intermediate anchors. Moreover, the optimal intermediate anchors also reduced the number of cracks and crack widths in the shear span region. In conclusion, the beam with optimal intermediate anchors had identical failure load, crack widths, deflections and strain characteristics as that of arbitrarily anchored strengthened beam.

Key words: Premature shear, CFRP laminate, intermediate anchors, RC beam.

INTRODUCTION

Strengthening of reinforced concrete beams using CFRP laminate is the most popular and effective method. However, premature failures of end peeling, intermediate crack (IC) debonding and shear are evident weaknesses of this method. Significant amounts of research were conducted over the last years to investigate the mechanisms behind these premature failures (El-Mihilmy and Tedesco, 2001; Smith and Teng, 2001; Tounsi et al., 2009). In the case of CFRP laminate strengthened beams, premature shear failure was common due to high strength and linear elastic properties of CFRP laminate (El-Mihilmy and Tedesco, 2001; Tounsi et al., 2009). Moreover, flexurally strengthened RC beams would more often fail by premature shear when the flexural capacities of those beams are shown to be higher as compared to shear capacities (Jumaat and Alam, 2009). Thus, eliminating premature shear failure is crucial so as to obtain maximal flexural beam strength.

A number of research works were carried out recently in an attempt to eliminate premature end peeling and IC debonding (Jumaat and Alam, 2008, 2010; Kim et al., 2008; Bahn and Harichandran, 2008; Aram et al., 2008). U and L shaped end anchor plates had offered significant effects in eliminating premature end peeling (Jumaat and Alam, 2010; Kim et al., 2008). Although research works to prevent end and IC debondings were obtained, works on eliminating premature shear failure of CFRP laminate

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flexurally strengthened RC beams were limited. In general, the intermediate anchors in shear span of strengthened beams would have considerable effects in overcoming this problem.

Shear strengthening of normal RC beams using external pre-stressing, steel plates, straps, CFRP strip and CFRP wrap were studied by a number of researchers (Malek and Saadatmanesh, 1998; Nabil and Grace, 2001; Adhikary et al., 2004; Teng et al., 2002). And as a result, strengthening using steel anchor plates and CFRP strips were found to be more effective. Although, CFRP has excellent strength and durability properties, its unavailability and high costs limit their use in this field. Thus, steel plate has obtained greater popularity to be used as anchor plates for shear strengthening. Despite the effects of steel anchor plates for shear strengthening of normal RC beams are well known, not so much the works on the effects of these anchor plates in preventing premature shear failure of flexurally strengthened beams are found.

Swamy and Mukhopadhaya (1999) first examined the effects of U-shaped steel plate intermediate anchors on CFRP laminate flexurally strengthened RC beams. This was in an attempt to eliminate premature shear failure. In their research the dimensions of intermediate anchors were arbitrarily chosen which prevented the premature shear failure of beams. Bencardino et al. (2007) experimentally investigated the effects of intermediate anchors in shear span of CFRP laminate strengthened beams. To prevent premature failures, arbitrarily U-shaped steel plates end and intermediate anchors had been used. These anchors showed satisfactorily results in preventing premature shear failure. Jumaat and Alam (2009) investigated the effects of L-shaped steel plate intermediate anchors on CFRP laminate flexurally strengthened RC beams. The dimensions of all anchors were arbitrarily chosen. It was investigated that the L-shaped anchor plates completely prevented the premature shear. However, findings of the existing researches demonstrated that the anchors in shear span of flexurally strengthened beams had significant effects in improving the ultimate strength of beams and eliminating premature shear failure, although guidelines to optimize the anchor plates were absent.

In this research, a design guideline is proposed with the intent on obtaining optimal dimensions of steel plate intermediate anchors for preventing premature shear failure of CFRP laminate flexurally strengthened RC beams. Also, the effects of the optimal intermediate anchors on CFRP laminate flexurally strengthened RC beams are experimentally investigated.

DESIGN OF INTERMEDIATE ANCHORS TO ELIMINATE PREMATURE SHEAR FAILURE

Flexurally strengthened RC beams normally fail by premature shear when the flexural capacities of those beams are shown to be higher as compared to shear capacities. Thus, intermediate anchors have to be designed in such a way that before crushing of concrete, strengthened beams will not fail by shear. The design procedure of this anchor plate is shown below;

The maximum shear force of strengthened beams for point load is,

$$V_{ext} = \frac{M_{rc}}{\text{Shear span}} \qquad (1)$$

Maximum shear resisting capacity of beam,

$$V_{max} = V_c + V_s \qquad (2)$$

in which, M_{rc} is the maximum moment resisting capacity of strengthened beam, V_c is shear resisting capacity of concrete and V_s is shear resisting capacity of shear link.

The shear force resisted by concrete is,

$$V_c = v_c bd \qquad (3)$$

Where,

$$v_c = \frac{0.79 \times \left({}^{100A_s}/_{bd}\right)^{0.33} \times \left({}^{400}/_{d}\right)^{0.25} \times M.F}{1.25} \qquad (4)$$

Shear force resisted by shear reinforcement is,

$$V_s = 0.87A_s f_{ys} = 0.87 \times 2 \times A'_s \times N \times f_{ys} = \frac{\pi\varphi_{link}^2}{4} \times 0.87 \times 2 \times N \times f_{ys} \qquad (5)$$

where, φ_{link} is the diameter of shear reinforcement, N is the number of shear reinforcement which crosses the diagonal crack and f_{ys} is the yield strength of shear reinforcement.

The number of shear reinforcement (N) can be obtained from Figure 1 by the equation as follows,

$$N = \frac{d - d'}{s}. \qquad (6)$$

Thus, shear force resisted by shear reinforcement is given as,

$$V_s = \frac{\pi\varphi_{link}^2}{4} \times 0.87 \times 2 \times \frac{d - d'}{s} \times f_y \qquad (7)$$

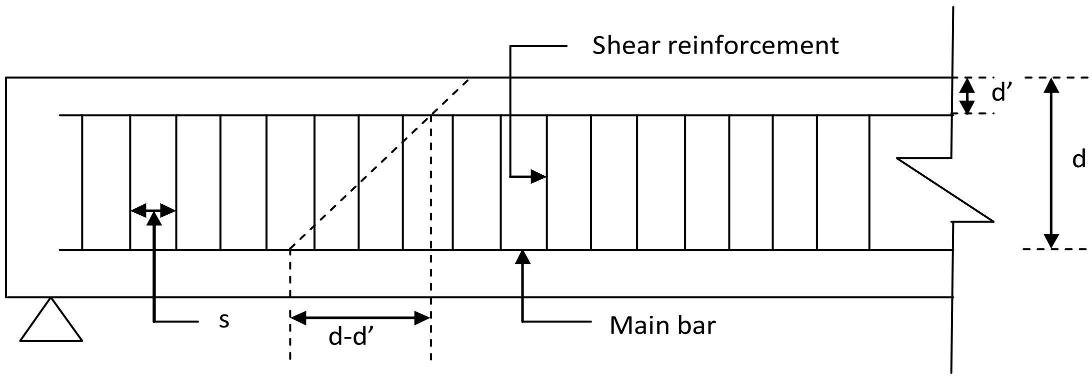


Figure 1. Details of shear reinforcement.

Total shear capacity of beam,

$$V_{max} = v_c bd + \frac{\pi\varphi_{link}^2}{4} \times 0.07 \times 2 \times \frac{d-d'}{s} \times f_y \quad (8)$$

where, f_c' is concrete strength, b is width of beam, d is effective depth of tensile reinforcement, d' is clear cover of compression reinforcement, φ_{link} is diameter of shear reinforcement and f_y is the yield strength of shear reinforcement.

Shear force resisted by external plate,

$$V_p = V_{ext} - V_{max} \quad (9)$$

Shear resisting capacity of anchor plate,

$$V_p = A_p \times 0.87 \times f_{yp} \times 2 \quad (10)$$

Thus,

$$A_p \times 0.87 \times f_{yp} \times 2 = V_{ext} - V_{max} \quad (11)$$

$$A_p = \frac{V_{ext} - V_{max}}{2 \times 0.87 \times f_{yp}} \quad (12)$$

From the area of intermediate anchor plate (A_p), thickness (t_p) and width of plate (w_p) could be attained. Spacing of plate is given by: $S = d/2$, so that all shear cracks cross the intermediate anchors.

EXPERIMENTAL INVESTIGATION

Description of specimens

Four RC beams were prepared and tested in this study. The details of those beams are shown in Table 1. Beam A1 was prepared as a control specimen whereas B1, B2 and B3 were flexurally strengthened using CFRP laminates. From strengthened beams, B2 was intermediately anchored using optimal L-shaped steel anchor plates in order to eliminate premature shear failure. The dimensions of optimal anchor plates were obtained from the proposed design theory without considering the safety factors of materials. In comparison, B1 was simply strengthened without intermediate anchors to fail by premature shear and B3 were intermediate anchored based on arbitrarily chosen anchor plates to fail the beam by crushing of concrete. The dimensions of anchor plates for those beams are also shown in Table 1.

Fabrication of specimens

All beam specimens were 2300 mm long, 125 mm wide, and 250 mm deep as shown in Figure 2. These beams were reinforced with two 12 mm diameter steel bars in the tension zone as main reinforcement. The ratio of main reinforcement was 0.0088. Two ten (10) mm steel bars were used as hanger bars in the shear span and were placed at the top of each beam. Six (6) mm bars were used for shear reinforcement and were symmetrically placed. The spacing of the shear reinforcement was 75 mm. The ratio of shear span to effective depth of all the beams was 3.05. The details of all reinforcements are shown in Figure 2.

Strengthening and anchoring

For all beams, the length of bonded plates was 1900 mm, which covered almost the full-span length of the beams (Figure 3). To obtain a perfect bond, the coarse aggregates in the bonding faces of the concrete surfaces were exposed. Dust and loose particles were then blown out using high pressured water jet. Carbon dust was removed from the bonding faces of the CFRP laminates by using colma cleaner. The surface of the steel anchor plate was then sand blasted so as to eliminate rust. In this research, Sikadur adhesive was used as the bonding material needed to fix CFRP laminates and anchor plates with concrete beams. Both hardener and adhesive resin were mixed together. The well mixed adhesives were then placed on the bonding face of concrete and CFRP laminates. The CFRP laminates were then fixed onto the beams and pressed by a roller to remove gaps and air voids from the bonding interface. Same adhesives were also applied in the inner face of the anchor plates (end and intermediate anchors) as well as on the bonding face of concrete. The anchor plates were then placed in the shear span of the said beam with spacing of 106 mm (Figure 3).

Table 1. Test specimens.

Beam ID	Strengthening material (flexure)			Intermediate anchors (shear)			
	Type	Thickness (mm)	Width(mm)	Materials	Width (mm)	Thickness (mm)	Spacing (mm)
A1							
B1	CFRP	1.2	80	------	------		
B2	CFRP	1.2	80	Steel plate	12	2	106
B3	CFRP	1.2	80	Steel plate	40	2	106

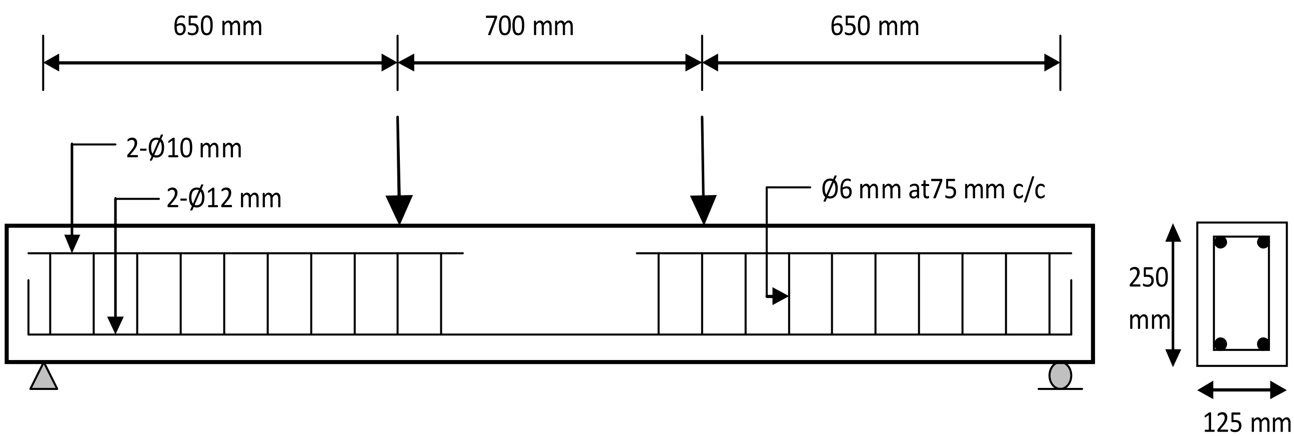


Figure 2. Beam details.

Materials

Ordinary Portland Cement (OPC), 20 mm size aggregates together with mine sand of grading zone 4 were used in casting the beams. The concrete was designed for 30 MPa strength based on DOE method. The compressive strength of the concrete was obtained from three cubes after a 28 day period of curing, in accordance to British Standard (BS 1881). The properties of steel bars, CFRP laminates and anchor plates are shown in Table 2.

Instrumentation and test procedures

Figure 4 shows the location of the different instruments used to record data during testing. Electrical resistance strain gauges measured the strain in the steel bars, CFRP laminate and concrete. The demac gauges were attached along the depth of beams at mid span in order 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 (Figure 4). The load was applied incrementally under load control procedures up to failure using Instron 8505 Universal Testing Machine.

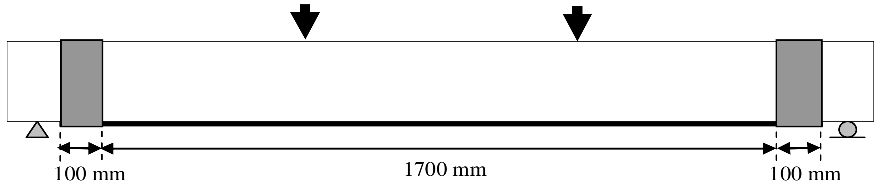
TEST RESULTS

Mode of failure

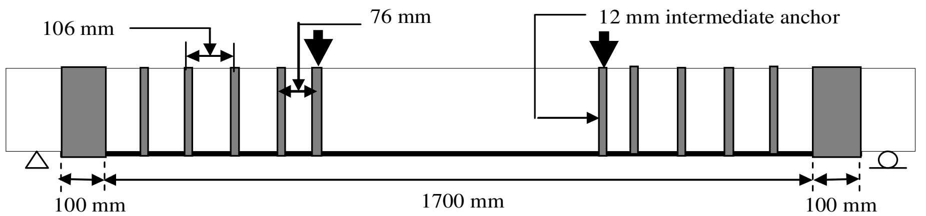
The failure modes of beams A1, B1, B2 and B3 are shown in Plates 1, 2, 3 and 4 respectively. The control beam without strengthening laminate (A1) failed by flexure. Strengthened beam without intermediate anchors (B1) failed by premature shear in the form of critical diagonal crack (CDC) rather than normal trend of shear crack. The failure mode of beam B1 was found to be brittle in nature.

Results showed that strengthened beam with optimal intermediate anchors (B2) failed by debonding of anchor plates. This was then followed by shear failure in the form of normal shear crack rather than CDC. The debonding occurred due to the crushing of concrete from its concrete adhesive interface. Finally, the beam failed as a result of shear immediately after the debonding of anchor plates. Although the anchor plates were designed to eliminate premature shear, bond strength between adhesive and concrete may not have been adequate enough to resist the premature debonding failure of intermediate anchors.

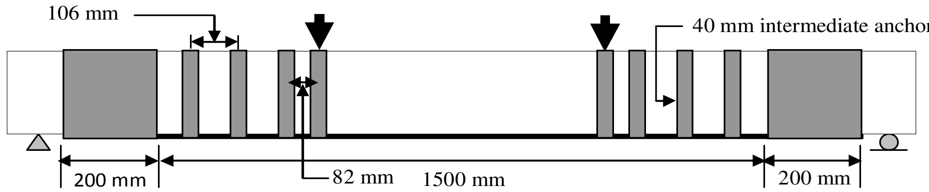
In comparison, the beams with arbitrary anchor plates (B3) failed by crushing of concrete rather than premature debonding or shear failure. In this case, due to the elastic nature of CFRP laminate, the beam tested was able to carry more loads after yielding of bars. Therefore, crushing of concrete only occurred at the failure stage. Furthermore, after the crushing of concrete, uneven displacement of beams were noticed in the crushing



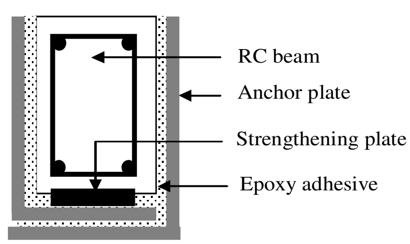
(a) Details of beam B1



(b) Details of beam B2



(c) Details of beam B3



(d) Details of anchors

Figure 3. Strengthening and anchoring details.

Table 2. Material's properties of specimens.

Specimens	Concrete	Flexural reinforcement		Shear reinforcement		CFRP laminate	Anchor plate		
	f_{cu} (MPa)	f_{ys} (MPa)	f_{ts} (MPa)	f_{ys} (MPa)	f_{ts} (MPa)	E_{frp} (GPa)	f_{yp} (MPa)	f_{tp} (MPa)	E_p (GPa)
A1	41.63	551	641	520	570				
B1	40.72	551	641	520	570	165	320	375	180
B2	40.49	551	641	520	570	165	320	375	180
B3	42.46	551	641	520	570	165	320	375	180

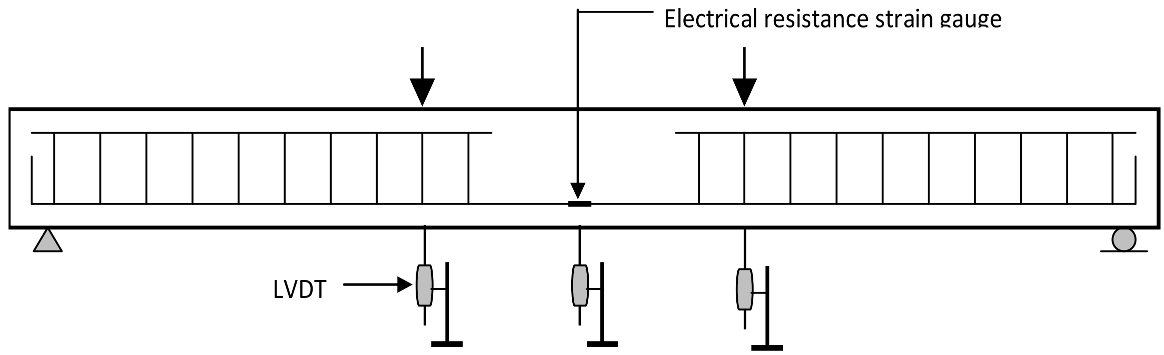


Figure 4. Beam instrumentations.

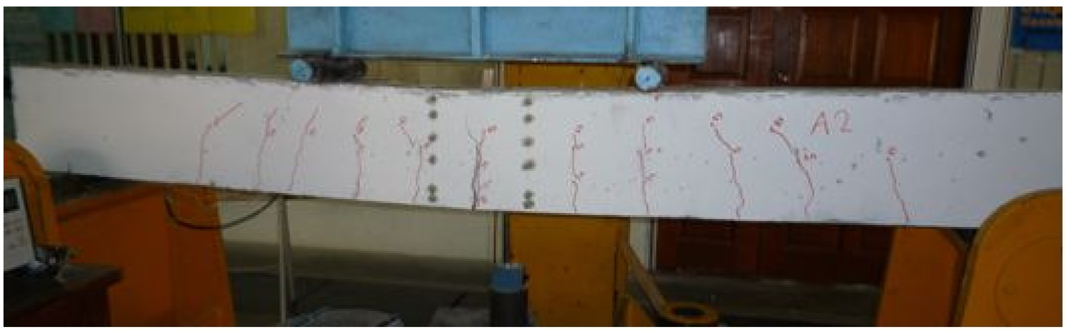


Plate 1. Failure mode of beam A1.

Plate 2. Failure mode of beam B1.

Plate 3. Failure mode of beam B2.

Plate 4. Failure mode of beam B3.

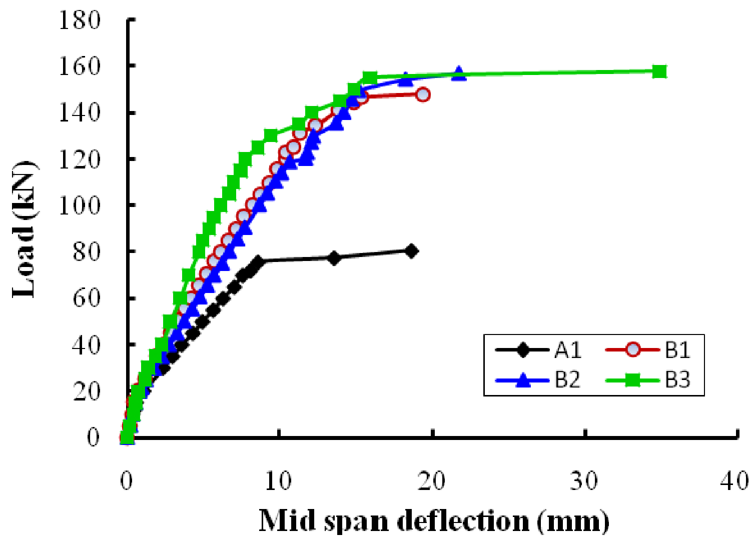


Figure 5. Ductility of beam specimens.

zone. This allowed the beam to form diagonal cracks below the neutral axis. These diagonal cracks debonded the strengthening plate (IC debonding) at mid-span of beam. Results also demonstrated that both optimal and arbitrarily anchored beams failed after yielding of the internal bar which allowed the attainment of sufficient ductility before failure. Furthermore, the optimal anchors of beam B2 were designed without considering the bond strength, thus it showed debonding failure. Since, B2 was intermediate anchored by overdesign, it did not fail by debonding of anchors.

Failure load

The failure loads of all beams are shown in Table 3. It is seen that the optimal intermediate anchored strengthened beams had 89% higher failure load as compared to the control beam. This beam also showed a higher failure load by up to 6% compared to the strengthened beam without intermediate anchors. Optimal intermediate anchors in the shear span of the beam enhanced the ultimate load. The failure loads of both optimal and arbitrarily intermediate anchored strengthened beams were almost identical despite the dimensions of optimal anchor plates being 3.33 times smaller as compared to the arbitrarily anchor plates. The optimal intermediate anchor plates were designed for the excess shear which was obtained from the maximum flexural strength of the strengthened beam. Thus, the beam should fail at its maximum flexural failure load. Since, the arbitrarily anchored beam failed at its maximum flexural failure load, the failure loads of both optimal and arbitrarily anchored beams were found to besimilar. Furthermore, the debonding failure load of the optimally intermediate anchored beam was close to the failure load of arbitrarily anchored beam. Therefore, it could be concluded that anchor plates debonded immediately prior to crushing of concrete.

Ductility

The load vs. deflections of all the beams is shown in Figure 5. Due to the higher stiffness of strengthened

Table 3. Experimental result.

Beam ID	Crack load (kN)	Failure load (kN)	Yield load of flexural bar (kN)	Concrete strain at failure (micro)	Bar strain at failure (micro)	Deflection			Failure mode
						At fail (δ_f) (mm)	At yield (δ_y) (mm)	Ductility factor (δ_f/ δ_y)	
A1	12	83	70		8906	18.58	7.52	2.47	Flexure
B1	25	148	120	2307	3765	19.4	10.4	1.87	Shear
B2	25	157	123	3758	8877	21.74	10.68	2.06	Anchor debonding with shear
B3	25	157.8	125	3607	5770	34.89	8.56	4	Flexure with crushing of concrete

beams, all strengthened beams showed lesser deflections as compared to the control beam. In the elastic zone, strengthened beams with and without intermediate anchors had similar deflections. However, at failure stage, optimal intermediate anchored strengthened beams had higher deflections as compared to that beam without intermediate anchors. Because of intermediate anchors, beams failed at higher load after yielding of the internal bar which aided to deflect the beams more in the failure stage. Thus, strengthened beams with optimal intermediate anchors had higher ductility as compared to strengthened beam without intermediate anchors. Results also showed that the arbitrarily anchored beam had slight lesser deflections as compared to optimal anchored strengthened beam. This could be due to the larger dimensions of anchor plates which enhanced the stiffness of beam. The ductility factor of the arbitrarily anchored beam (B3) was found to be higher as compared to the optimal anchored beam (B2). It happened due to the different failure locations of beams B2 and B3. Beam B2 failed by debonding of anchors followed by shear in shear span rather than mid-span, thus at failure stage maximum deflection occurred at the location of failure. Whereas, beam B3 failed by flexure at mid-span of beam. Since the maximum deflections were recorded from the mid span of beam, B3 showed larger deflections at failure stage.

Cracking patterns

The crack loads of all the beams are shown in Table 3. Strengthened beams with and without intermediate anchors had higher cracking loads as compared to the control beam. The crack loads of both intermediate anchored and without intermediate anchored strengthened beams were almost identical. Anchors did not affect the cracking loads. A Cracking load normallydepends on the material's properties of concrete and strengthening plate. Since intermediate anchored and without intermediate anchored CFRP laminate strengthened beams had almost similar properties of concrete, all beams showed identical cracking loads.

The total number of cracks in beams A1, B1, B2 and B3 were 11, 21, 17 and 18 respectively. The average crack spacings of those beams were 181 mm, 95 mm, 117 mm and 111 mm respectively. The optimal intermediate anchored strengthened beam had lesser number of cracks and higher crack spacing as compared to strengthened beams without intermediate anchors. In this beam, most of the cracks in shear span occurred between adjacent anchor plates. Intermediate anchors in the shear span had increased the stiffness of beams which in turn reduced the number of cracks. The average crack spacing was obtained from the ratio of shear span and number of cracks. Thus, the average crack spacings of intermediate anchored strengthened beams were higher as compared to strengthened beam without intermediate anchors. The arbitrarily anchored beam showed identical crack patterns with compared in comparison to optimal anchored strengthened beam. Figure 6 shows the load-crack width (maximum) at maximum moment zone of beams A1, B1, B2 and B3. The strengthened beams had shown a lesser crack width than that of the control beam. Results showed that there was no noticeable difference of maximum crack widths between with and without intermediate anchored strengthened beams. The reason being that, crack widths of all beams were measured from the maximum moment zone, whereby anchor plates were absent. As a result, intermediate anchors did not have effects on maximum crack widths. However, it was observed that during tests, crack widths at shear span of intermediate anchored strengthened beams were very minimal as compared to that beam without intermediate anchors. It happened due to the presence of intermediate anchors. Intermediate

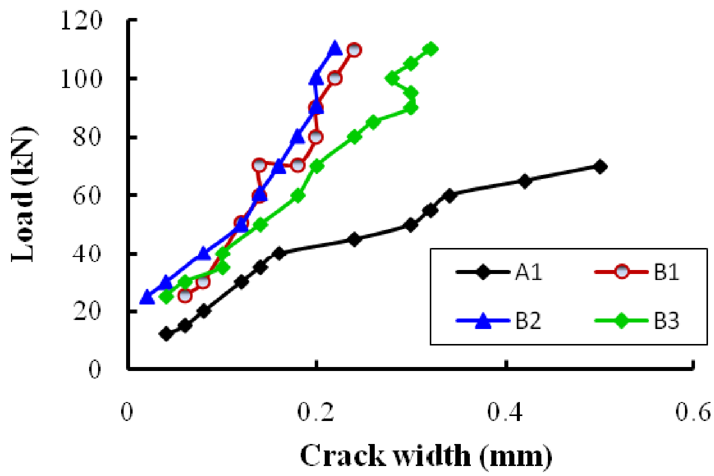


Figure 6. Maximum crack width of beam specimens.

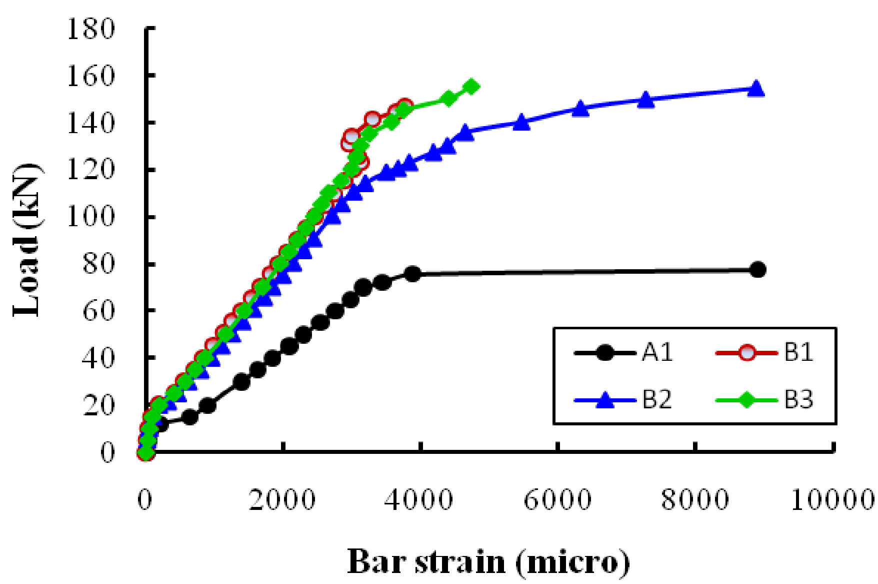


Figure 7. Bar strains of beam specimens.

anchors enhanced the shear capacities of beams which reduced the widths of shear cracks. Furthermore, due to stress concentration near the anchor plates, most of the cracks in the shear span zone occurred from the end of the intermediate anchors.

Strain characteristics

The load vs. rebar strains of all beams are shown in Figure 7. It is seen that both intermediate anchored and without intermediate anchored strengthened beams had identical rebar strains in the elastic zone. It is also seen that the yield loads of all strengthened beams had similar values of 120 kN. However, at failure stage intermediate anchored strengthened beams had more bar strain as compared to beam without intermediate anchors which in turn affected the ductility of the beams. In the elastic region, the bar strains of optimal anchored beam (B2) were found to be almost similar with arbitrary anchored beam (B3). At failure beam B2 showed higher bar strain compared to those of beam B3 though the deflection of beam B2 were found to be less as compared to beam B3. It was happened due to the unavailability of bar strain of beam B3 since the strain gauges were out of service unfortunately at failure stage.

The load-concrete strains at the top part of the beams are shown in Figure 8. All strengthened beams had

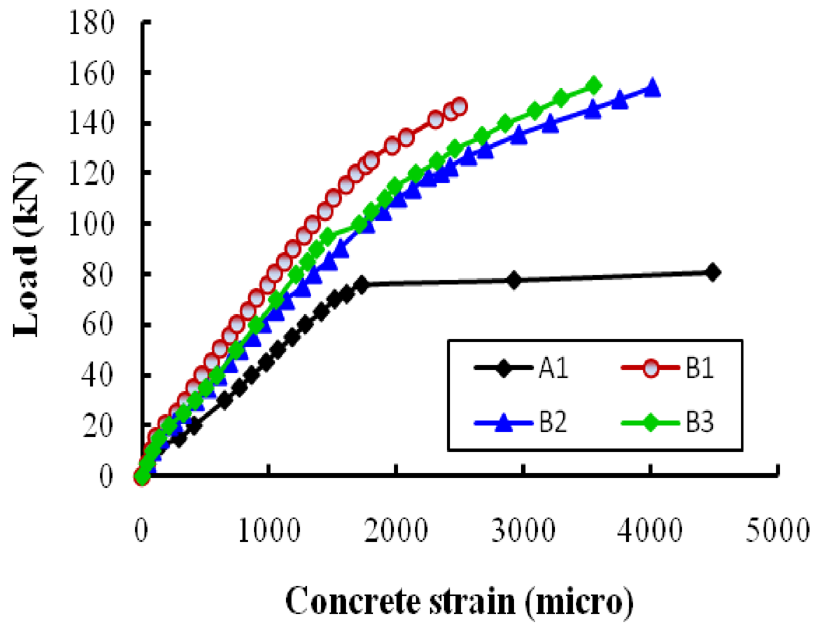


Figure 8. Concrete strains of beam specimens.

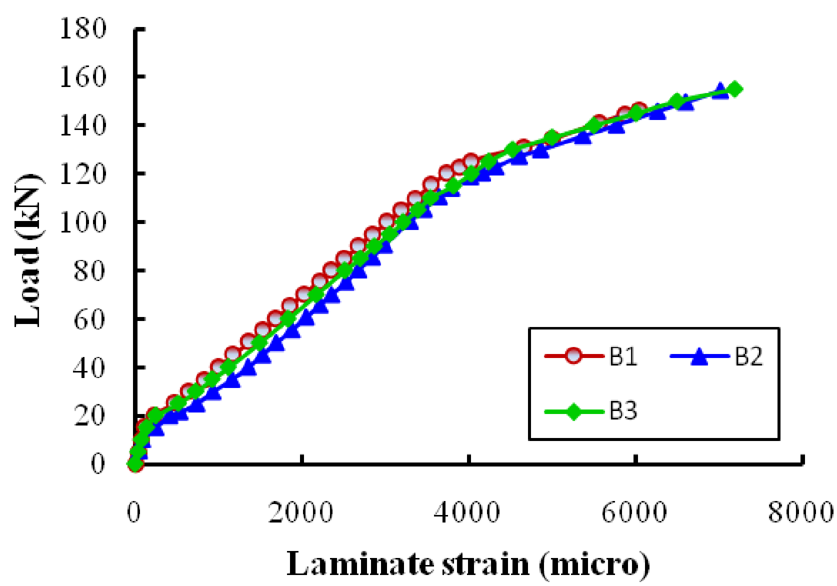


Figure 9. Laminate strains of beam specimens.

similar concrete strains. This is mainly due to the nearly identical stiffness of strengthened beams. After a load of 120 kN, the slope of Figure 8 changed due to the effect of internal rebar yield. Results showed that at failure stage, the concrete strain of optimal intermediate anchored strengthened beam was higher than 0.0035 which confirmed that the anchor plates debonded immediately before the crushing of concrete. However, beam without intermediate anchors exhibited concrete strain lower than 0.0035. This could have happened due to the premature shear failure of the beam. The arbitrarily anchored beam had almost similar concrete strain characteristics compared to optimal anchored beam. Figure 9 shows load vs. laminate strain of all strengthened beams. The optimal anchored strengthened beam had identical laminate strain with comparison to un-anchored and arbitrarily anchored beams. This owes due to similar properties of strengthened beams and laminates.

CONCLUSIONS

The optimal and arbitrarily intermediate anchors in shear span of flexurally strengthened reinforced concrete beams significantly increased the ultimate strength as compared to that of control beam and beam without intermediate anchors. Both intermediate anchored strengthened beams had higher ductility as compared to beam without intermediate anchors. Anchors in the shear span of beams reduced the crack widths therein. Intermediate anchors did not have significant effects on maximum deflections and strain characteristics of beams. The optimal anchored strengthened beams had identical behaviour to that of arbitrarily anchored strengthened beam in terms of failure load, ductility, crack widths and strains of bar and concrete. The design theory of intermediate anchors could enhance the ultimate load capacity of beam. However, future research works need to focus on the elimination of premature debonding failure of intermediate anchors.

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