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Research Article

Anchors for shear strengthening of damaged rc beam using bonded steel plate

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Abstract

Appropriate anchor system has very important role for effective retrofitting of structure specially to prevent debonding of bonded plate for shear strengthening of damaged reinforced concrete beam. The debonding happens at concrete interface of externally bonded (EB) plate due to lower interfacial bond strength. Proper anchor system would enhance interfacial strength to prevent debonding failure. The main aim of the research work was to investigate the effectiveness of various anchor systems for externally bonded steel plate to enhance shear strength of damaged RC beams. A total of five full scale reinforced concrete beam had been fabricated, all beams were fully damaged in shear before strengthening. The damaged beams were then strengthened for shear using steel plates with double connector, multiple connector, welded connector and near surface embedded bar anchor systems. Design guideline had been proposed to obtain dimension of steel plate for shear strengthening of damaged RC beam. Results exhibited that all anchors prevented debonding of steel plate at concrete-adhesive interface. Welded connector (WC) and embedded bar (EB) anchors had completely prevented debonding failures of steel plate at concrete-adhesive and plate-adhesive interfaces. Double and multiple connector anchors failed due to crushing of concrete at anchor zone followed by debonding of plate. Whereas, un-anchored strengthened beam showed premature debonding of plate at concrete-adhesive interface followed by shear failure. The results of the research exhibited that double and welded connector anchors had excellent performance in increasing shear strength to re-store original shear capacities of damaged beams. The theoretical results were comparable with the experimental findings.

1. Introduction

Numerous reinforced concrete infrastructures around the world are considered unsafe due to environmental disasters such as earthquake and tsunami, increased load specification in the design codes, over-loading and also for building degradation due to age. Strengthening of reinforced concrete (RC) structures for those conditions would be the best alternative to enhance the capacities of structure. Because of sudden and catastrophic collapse of shear failure, strengthening of RC beam for shear become one of the most essential parts to ensure ductile failure of structure through enhancement of shear capacity. Researchers proposed various methods of shear strengthening for RC beams such as external pre-stressing [1], externally bonded steel plates [2], near surface mounted (NSM) [3], jacketing of beam [4], and externally bonded reinforcement (EBR) [5]. Strengthening materials include carbon fiber reinforced cementitious matrix (FRCM) composite [6], glass fiber reinforced polymer [7], steel plates [2], cement-based composite [8], highly ductile fibre reinforced concrete [9], CFRP grid [10], CFRP NSM [11], glass fiber textile mesh [12], textile reinforced mortar [13] and ramie fiber reinforced polymer (RFRP) [14] have been used to obtain the expected outcome. As compared to others,

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externally bonded method using steel plate has been widely used for shear strengthening of RC beam.

The major limitation of externally bonded method for shear strengthening of RC beam is premature debonding failure of plate as it prevents the beams to attain its ultimate strength. Recent works investigated the performance of anchors using bolt, fan, spike and embedded connectors to eliminate debonding of plate for shear strengthening of un-cracked RC beams [15-24]. Anchors of bolts, fan and spike require hole on externally bonded plate which reduce the effective cross-sectional area of plate. Moreover, fan and spike anchors are prepared using carbon fibre. In general fibre is unable to resist shear along its cross section, thus, could not be effective as anchor for shear strip. The fan anchor system has mostly been used in FRP wrap to prevent complete separation of wrap [24]. In contrast, embedded connector anchor proposed by Alam et al. [18] had been investigated and was found to be effective in enhancing the bond strength to prevent debonding of plate at concrete-adhesive interface. However, the major limitation of embedded connector anchor was unable to prevent debonding of plate at plate-adhesive interface. Moreover, the effectiveness of existing anchor systems was investigated for shear strengthening of un-cracked RC beams. The presence of cracks in damaged beams might have the effects on anchor system, however, the effectiveness of anchor systems for shear strengthening of damaged RC beams yet to be investigated. The research work aimed to propose welded connector and embedded bar anchor system for shear strengthening of damaged RC beams. The effectiveness of embedded connectors (double and multiple), welded connector and embedded bar anchor systems had been investigated experimentally for shear strengthening of damaged RC beams.

2. Proposed Design Guideline for Shear Strengthening of Damaged Reinforced Concrete Beam Using Steel Plate

2.1 Maximum Design Shear Force for Strengthening of RC Beam

The existing beam may fail by flexure or shear. The beam would fail by flexure once the shear capacity of the beam exceeds its flexural capacity. Hence, the shear enhancement of the existing beam could be possible until the beam fails by flexure. The ultimate flexural capacity of the beam can be calculated in accordance to EC2 [25] as shown below,

$$M = Tz = A_s f_{tk}\left[d - \frac{0.588 A_s f_{tk}}{f_{ck} b}\right] \quad (1)$$

Where,

$$x = \frac{A_s f_{tk}}{0.85 f_{ck}(0.8)b} = \frac{A_s f_{tk}}{0.68 f_{ck} b} \quad (2)$$

$$z = d - 0.4x = \left[d - \frac{0.588 A_s f_{tk}}{f_{ck} b}\right] \quad (3)$$

The beam will fail by flexure once the bending moment exceeds the maximum flexural strength of the beam (as shown in Equation 1). The maximum bending moment could be considered as the maximum flexural strength of the beam. Thus, the design shear force of the beam is,

$$V_{ds} = \frac{M}{L_s} = \frac{A_s f_{tk}}{L_s}\left[d - \frac{0.588 A_s f_{tk}}{f_{ck} b}\right] \quad (4)$$

2.2 Design Shear Force to Re-store Original Capacity of Damaged Beam

The number of shear link to resist shear,

$$N = \frac{[d - d']cot\theta}{s_{link}} \tag{5}$$

Where, θ is the angle of shear crack. The shear crack inclination may vary between 22 degrees to 45 degrees [25]. Crack inclination of 22 degrees could be used for conservative calculation of shear capacity of beam. The shear force resisted by shear link,

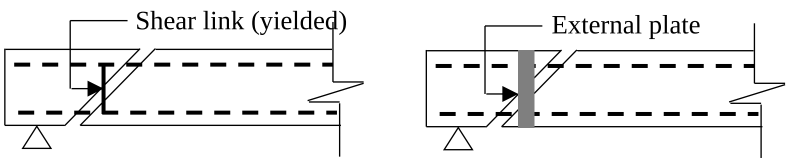
$$V_{y,link} = A_{s,link} f_{y,link} \left[\frac{(d - d')cot\theta}{s_{link}}\right] \tag{6}$$

As per EC2 [24], the shear contribution is only from shear link rather than concrete. Hence, the shear capacity of the un-damaged control beam is,

$$V_{cb} = V_{y,link} = A_{s,link} f_{y,link} \left[\frac{(d - d')cot\theta}{s_{link}}\right] \tag{7}$$

2.3 Cross Sectional Area of Steel Plate to Re-store Original Capacity of Damaged Strengthened Beam

Since the beam is damaged, concrete shows cracks and shear link yields, only externally bonded steel plate will resist shear in strengthened beam as shown in Figure 1. The inclination of shear crack could be considered as 45 degree for conservative design of externally bonded plate.



(a) Beam in damaged condition

(b) Strengthening of damaged beam using EB plate

Fig. 1 Shear strengthening of damaged RC beam

The steel plate (two-sided plate) resists shear force as,

$$V_{sp} = 2A_p f_{yp} N_p = 2A_p f_{yp} \frac{hcot\theta}{s_p} \tag{8}$$

The required optimal shear design of damaged beam to re-store original capacity is,

$$V_{sp} = V_{ds} = V_{y,link}$$

$$\frac{A_p}{s_p} = \frac{V_{y,link}}{2f_{yp} hcot\theta} = \frac{A_{s,link} f_{y,link} \left[\frac{(d-d')cot\theta}{s_{link}}\right]}{2f_{yp} hcot\theta} \tag{9}$$

The damaged shear strengthened beam could fail by flexure rather than shear also. In case, the beam fails in flexure, the maximum design shear could be obtained using Equation 4.

Thus, the required optimal shear design of the damaged beam for the maximum capacity (up to flexural failure of beam) is,

$$V_{sp} = V_{ds} = \frac{A_s f_{tk}}{L_s}\left[d - \frac{0.588 A_s f_{tk}}{f_{ck} b}\right]$$
$$\frac{A_p}{s_p} = \frac{V_{ds}}{2 f_{yp} h cot\theta} = \left\{\frac{A_s f_{tk}}{L_s}\left[d - \frac{0.588 A_s f_{tk}}{f_{ck} b}\right]\right\} / \left(2 f_{yp} h cot\theta\right) \tag{10}$$

2.4 Capacities of Damaged Shear Strengthened RC Beam

2.4.1 Debonding Load of Un-anchored Strengthened Beam

The guideline of Alam et al. [25] (as shown below) can be used to obtain the debonding strain of the plate;

$$\varepsilon_{deb.p} = \frac{F_{bp}\, w_p\, h}{A_p E_p} = \frac{F_{bp}\, w_p\, h}{w_p\, t_p\, E_p} = \frac{F_{bp}\, h}{t_p\, E_p} \tag{11}$$

Thus, $\varepsilon_p = \varepsilon_{deb.p}$

Stress of steel plate, $\sigma_p = E_p \varepsilon_p = \frac{F_{bp}\, h}{t_p}$ (12)

Shear force to cause debonding of plate,

$$V_{deb,p} = 2 A_p \sigma_p N_p = 2 A_p \left\{\frac{F_{bp}\, h}{t_p}\right\}\left\{\frac{h \cot\theta}{s_p}\right\} \tag{13}$$

2.4.2 Shear Capacity by Yielding of External Steel Plate

Based on yielding of externally bonded steel plate, the shear capacity of damaged strengthened beam is,

$$V_{sb} = V_{y,p} = 2 A_p f_{yp}\left[\frac{h cot\theta}{s_p}\right] \tag{14}$$

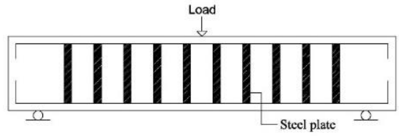
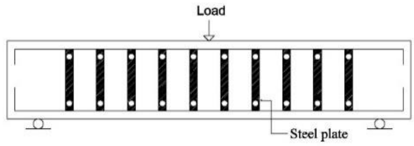
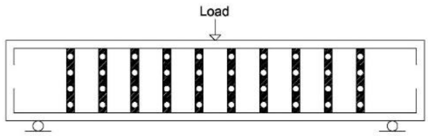
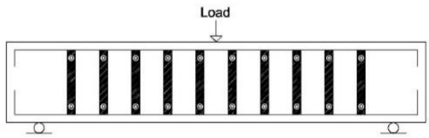
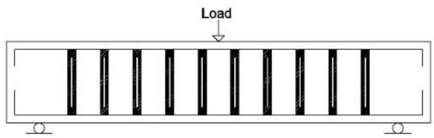
3. Experimental program

3.1 Test Specimens

In the experiment, five full-scale RC beams were fabricated and tested. The dimensions of all beams were 150 mm x 250 mm x 1300 mm. The beams were fully damaged before strengthening. Steel plate having the dimension of 3 mm x 20 mm x 300 mm was used with the spacing of 110 mm for shear strengthening of all damaged beams. The dimension of plate was obtained based on proposed design guideline shown in Equation 10. Double connector (DC), multiple connector (MC), welded connector (WC) and embedded bar (EB) anchor systems were used to eliminate premature debonding failure of EB steel plate. Strengthened beam of SB was left without anchor to compare the results with strengthened beams having anchors. Table 1 presents the details of all specimens.

Table 1. Details of specimens

Beam ID	Details of anchor		Figure of specimens
	Type	Material	

SB	No Anchor		
DC	Double connector	2-16 mm MS bar	
MC	Multi connector	4-16 mm MS bar	
WC	Welded connector.	2-16 mm MS welded bar	
EB	Embedded bar	6 mm MS surface mounted bar	

3.2 Preparation of Beams

The steel case of the beam was fabricated using 2-16 mm flexural reinforcement (at bottom), 2-12 mm hanger bar (at top) and 6 mm shear reinforcement with the spacing of 130 mm c/c. The details of reinforcements are shown in Figure 2. The shear reinforcement (6 mm bar) had yield and tensile strength of 420 MPa and 520 MPa respectively. Whereas, flexural reinforcement of 16 mm bar had 540 MPa and 620 MPa yield and tensile strengths respectively.

DOE method was used to design the concrete mix with the ratio of (cement, sand and stone aggregate) 1:1.96:3.07 for the target strength of 30 MPa. The water cement ratio of the mix was 0.6. The average slump of the concrete mix was found to be 130 mm approximately. All beams were cured under same condition by wet hessian cloth for 28 days after casting.

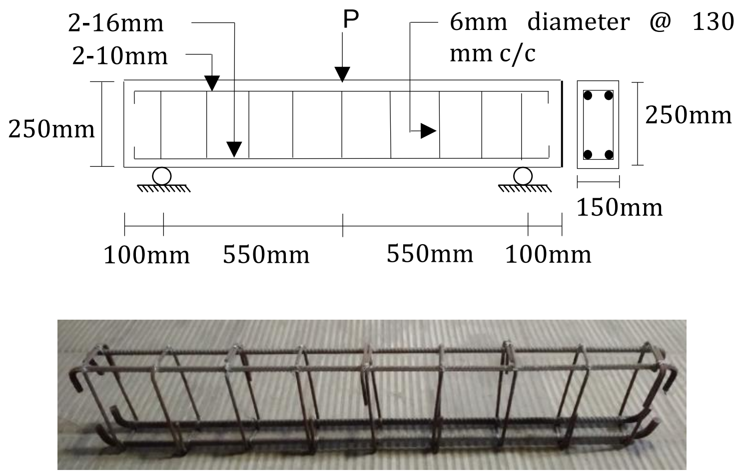


Fig. 2 Details of reinforcements of beam

3.3 Damaging of Beams

After 28 days of curing, all five beams were fully damaged before strengthening as shown in Figure 3. Beams were tested under three points bending. The clear span of the beam was 1100 mm.

Fig. 3 Damaged beam specimens

The test was conducted by applying load with the increments of 5kN. Dial gauge was used to measure the deflection. All beams were fully damaged in shear by applying 136 kN load. The failure modes of all damaged beams are shown in Figure 3.

3.4 Strengthening

3.4.1 Preparation of Concrete Surface and Anchors

The strengthening process were conducted immediately after damaging of beams. The loose particles of concrete had been removed using diamond cutter from bonding face of the concrete beam as shown in Figure 4. The bonding face of steel plates were sand blasted to expose the original texture of the plate and to create a rough surface for ensuring excellent bond with adhesive and steel plate. Thinner was used to clean the prepared surfaces of concrete and steel plate. Two and four holes were made on concrete surfaces at the locations of embedded double and multiple connector anchors respectively. Diameter and depth of the holes were 20 mm and 25 mm respectively.

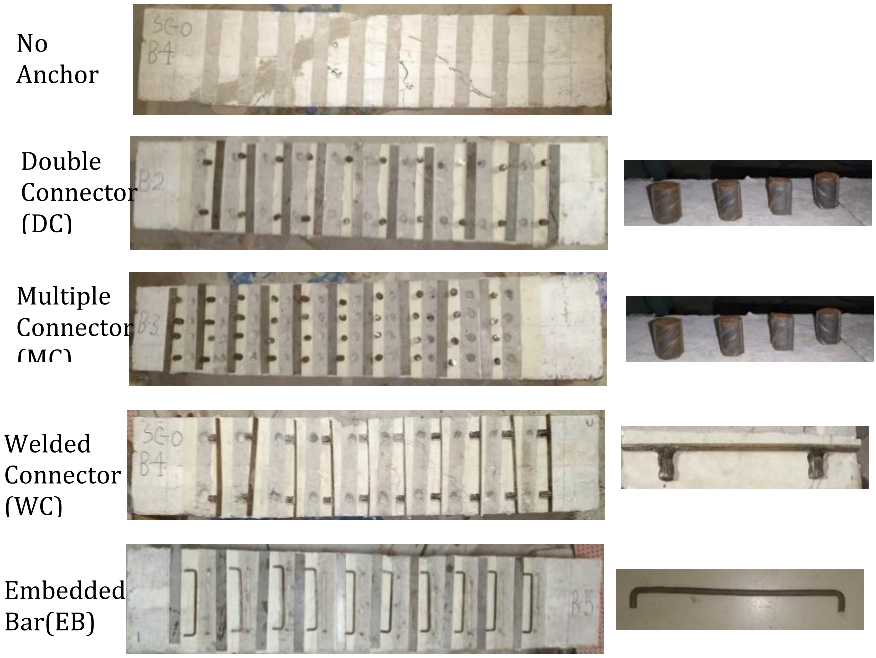


Fig. 4 Preparation of concrete surface and anchors

16 mm bar with 25 mm length was used for double and multiple connectors as shown in Figure 4. Holes were also prepared for welded connector anchor system. Two 16 mm steel bar of 25 mm length were welded near ends of steel plate to prepare welded connector anchor. For embedded bar anchor, 6 mm steel bar as shown in Figure 4 was used. Proper groove was prepared at bonding surface of concrete beam to fix embedded bar. The details of all anchor systems are shown in Figure 4. Before, fixing of plates and anchors, the holes and surrounding area of anchors were properly cleaned from dust using compressed air and thinner.

3.4.2 Fixing of Anchors and Steel Plates

Sikadur 31 epoxy was used to fix anchors and steel plates. Resin and hardener of the epoxy was properly mixed before applied on bonding face of concrete, anchors and plates. The holes of connectors and groove of embedded bar were fully filled with epoxy before placing of anchors. 16 mm steel connectors were then pressed inside epoxy filled holes to avoid air gaps in anchor systems (Figure 5). Embedded bars were also inserted in epoxy filled groove. Once the anchors were fixed properly, epoxy was placed at bonding face of concrete and surface of steel plate. The bonding face of the steel plate was then positioned properly on the beam as shown in Figure 5. The whole strengthening process were conducted in same day to ensure the consistency of the age of strengthening process. After fixing of plates, the strengthened beams were cured by air for seven days before testing.

3.5 Test Set Up and Testing of Beam

All beams were tested under three points bending (single point load) at simply supported condition. The clear and shear spans of the beam were 1100 mm 550 mm respectively as shown in Figure 6. Loading frame was used to test the beams. Mid-span deflection was recoded using dial gauge. The load was applied slowly by controlling the pressure pump. Reading of deflection dial gauge had been recorded at every 5 kN interval. The debonding load, crack load, failure load, crack patterns and failure modes of all beams were also recorded during testing of beams.

Fig. 5 Fixing of anchors and steel plate

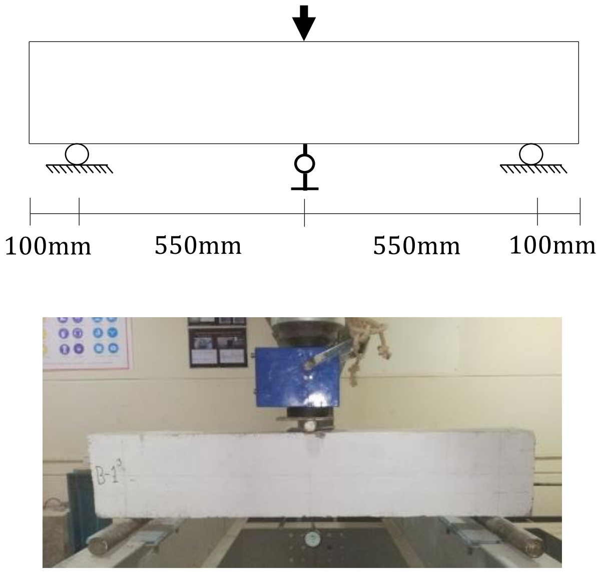


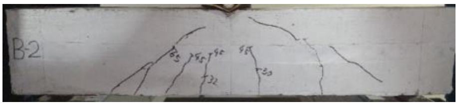
Fig. 6 Test setup and testing of beam

4. Experimental Results

4.1 Effects of Anchors for Shear Strengthening of Damaged RC Beams

4.1.1 Double Connector

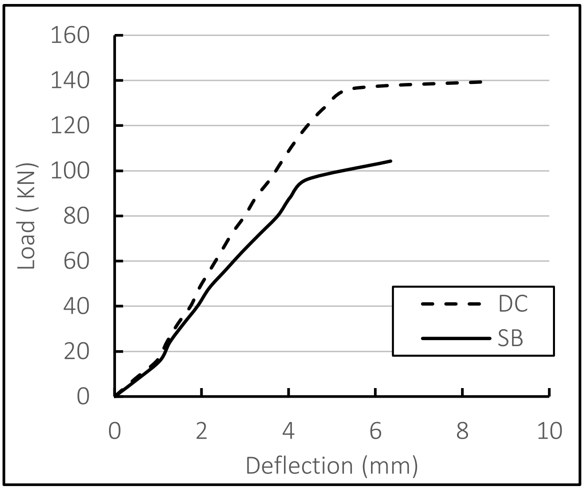
The un-strengthened damaged beam had failed by shear as shown in Figure 7 (a). Shear strengthened damaged beam with double connector anchor system (DC) failed by flexure and flexural-shear followed by crushing of concrete as shown in Figure 7 (b). Double connector prevented debonding of steel plate at concrete-adhesive interface. It was noticed that the plate was partially deboned at plate-adhesive interface near the anchors beside the large cracks. Since, the connector was incapable to prevent debonding of plate at plate-adhesive interface, had shown flexural and flexural-shear failure. Whereas, beam without anchor (SB) failed by premature debonding of steel plate followed by shear as shown in Figure 7 (c), the debonding was noticed at concrete-adhesive interface. Double connector anchor system enhanced interfacial bond strength of plate at concrete-adhesive interface which resulted prevention of debonding failure of plate at concrete-adhesive interface.



(a)

(b)

(c)



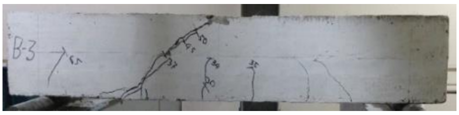
(d)

Fig. 7 (a) Damaged beam for DC, (b) Failure mode of beam DC, (c) Failure mode of beam SB, (d) Deflections of beams DC and SB

Results showed that the ductility performance of strengthened beam with double connector anchor system was better than strengthened beam without anchor system (Figures 7 (d)). Since, the strengthened beam (DC) had failed by partial flexure, the ductility of the beam was higher as compared to beam without anchor (SB). The failure loads of strengthened beams DC and SB were 139 kN and 104 kN respectively, while un-strengthened beam had failed by 136 kN load when it was damaged. The double connector anchor system fully restored the shear capacity of damaged beam and it showed 33.65% higher failure load than those of without anchor (SB). As compared to existing research, the shear capacity enhancement of damaged strengthened beam using hybrid composite plate was found to be maximum of 97% [27]. Existing research also reported that U-shaped cementitious composite material restored the shear capacity of damaged strengthened RC beams by 67% [28].

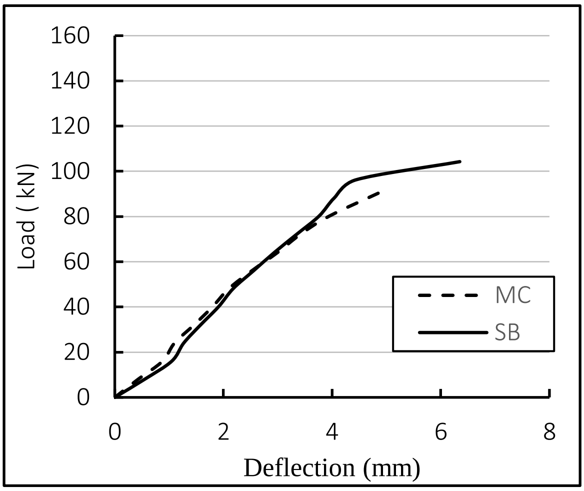
4.1.2 Multi Connector Anchor System

The beam was damaged in shear before strengthening using externally bonded steel plate and multi connector anchor system (Figure 8-a). The shear strengthened damaged beam with multi connector anchor (MC) failed by flexural-shear with crushing of concrete as shown in Figure 8(b). The connector failed immediately after crushing of concrete, and the plate was debonded at plate-adhesive interface near the location of connector. Since, the beam had failed by flexural-shear rather than premature debonding of plate, the failure mode was bit ductile.



(a)

(b)



(c)

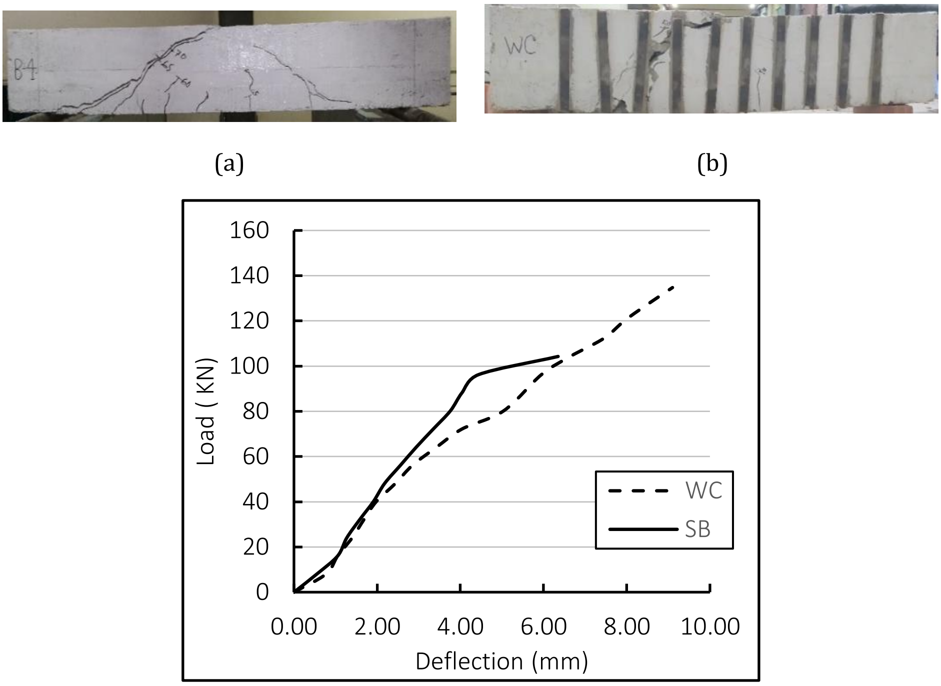
Fig. 8 (a) Damaged beam for MC, (b) Failure mode of beam MC, (c) Deflections of beams MC and SB

The multi connector anchor system prevented premature debonding of steel plate at concrete-adhesive interface. However, once the connector failed, the plate started to debond from plate-adhesive interface. Results also showed that the concrete of beam MC had crushed near the major cracking area of the damaged beam. The multi connector anchor strengthening system had enhanced 91 kN load of damaged beam. Since, the connector of the beam (MC) had failed due to crushing of concrete, the failure load of the strengthened beam was lower than that of without anchor system (Figure 8 (c)).

4.1.3 Welded connector

The beam was damaged in shear (Figure 9(a)) before strengthening. The strengthened beam with welded connector (WC) had failed by flexural-shear followed by crushing of concrete at top compression zone of the beam as shown in Figure 9(b). The welded connector anchor system completely prevented premature debonding of externally bonded steel plate from concrete-adhesive and plate-adhesive interfaces.

The concrete near the major cracking zone of the beam had crushed, once the concrete crushed, the connector had failed. Results also showed that the welded connector had failed because of concrete cover separation as well. The strengthened beam with welded connector anchor failed by 134 kN load which was higher as compared to strengthened beam without anchor as shown in Figure 9(c). Since, the welded connector was effective to prevent premature debonding of externally bonded steel plate at concrete-adhesive and plate-adhesive interfaces, the failure load of the beam was found to be 28.8% higher as compared to strengthened beam without anchor.



(a) (b)

(c)

Fig. 9 (a) Damaged beam for WC, (b) Failure mode of beam WC, (c) Deflections of beams WC and SB

4.1.4 Embedded Bar

The embedded bar anchor system was excellent in complete prevention of debonding failure as shown in Figure 10(b). The beam did not show any kinds of debonding failure. The embedded bar provided sufficient interfacial bond strength at concrete-adhesive and plate-adhesive interfaces, thus, premature debonding failure of externally bonded steel plate had been prevented. Finally, the beam had shown flexural failure with crushing of concrete. The mode of failure was ductile rather than catastrophic brittle as shown in Figure 10(b,c).

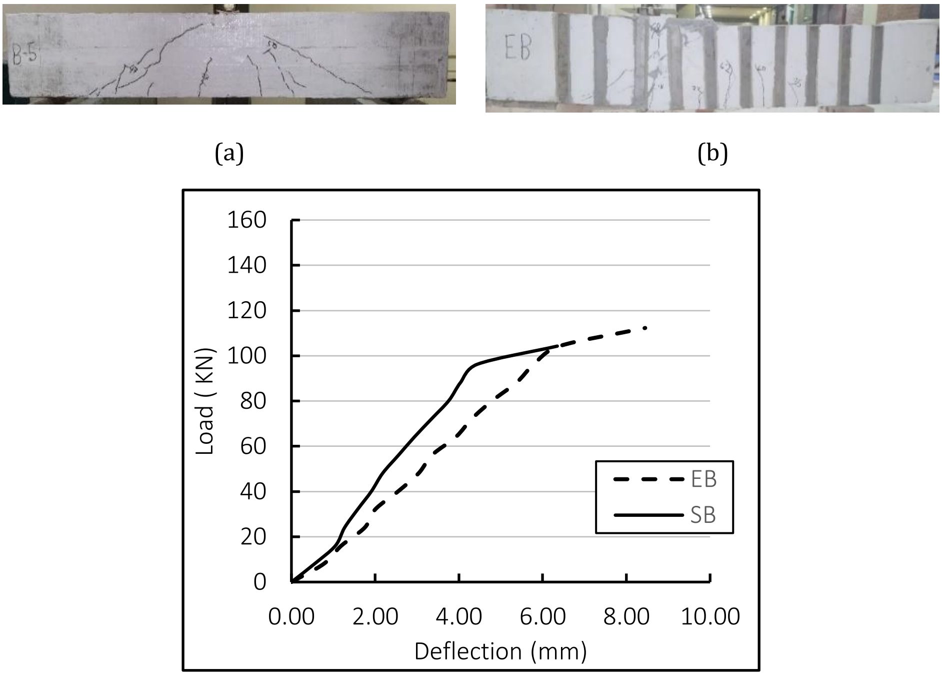
Results showed that shear strengthened beam with embedded bar anchor had failed by 112 kN load. The beam was failed by flexure, the flexural capacity of that particular beam was lower, thus, the shear enhancement of that beam was found to be lower as well. Based on the results of that beam it could be concluded that the shear enhancement capacity of the strengthened beam depends on flexural capacity of that particular beam also.

4.2 Comparative Structural Behavior of Various Anchor Systems

4.2.1 Premature Debonding of Plate and Failure Behaviour of Strengthened Beam

The steel plate of double connector anchor system debonded from plate-adhesive interface near the location of connector. Once the plate detached from the connector, it was progressively deboned from concrete-adhesive interface. Finally, the plate was separated and caused flexural-shear failure of the beam (DC) with brittle mode of failure as shown in

Figure 11(DC). The steel plate of multi-connector anchor did not debond at concrete-adhesive interface, the plate debonded at plate-adhesive interface. In general, the plate had two interfaces i.e. concrete-adhesive interface and plate-adhesive interface, the plate could be debonded from any of the interfaces. The bond strength of plate at concrete-adhesive interface could be sufficiently increased by multi-connector anchor, thus, debonding at concrete-adhesive interface had been prevented. However, connector was unable to prevent debonding of plate at plate-adhesive interface (Figure 11). Results showed that both connectors failed because of crushing of concrete near the large crack of damaged beam.



(c)

Fig. 10 (a) Damaged beam for EB, (b) Failure Mode of beam EB, (c) Deflections of beams EB and SB

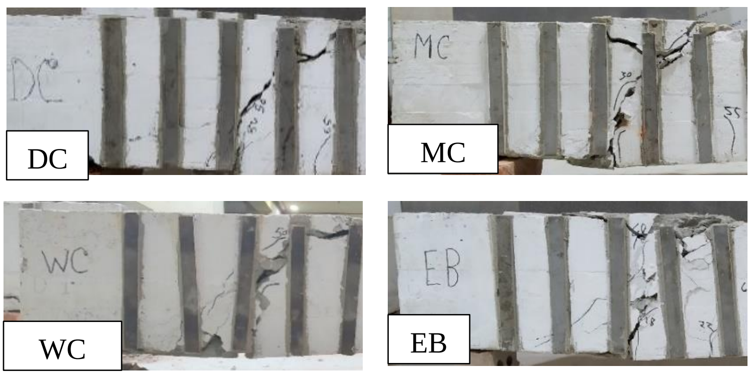


Fig. 11 Failures of shear strengthened beams with various anchors

The debonding of steel plate had been completely prevented by welded connector and embedded bar anchors. In WC, as the connector was welded with steel plate, the plate did not debond at plate-adhesive interface. The anchor of welded connector had failed because of peeling-off concrete cover. Embedded bar anchor was found to be excellent in preventing premature debonding failure, the beam with embedded bar anchor had shown ductile flexural failure as shown in Figure 11 (EB).

4.2.2 Debonding and Failure Loads

Table 2 shows the summary of experimental and theoretical results of all strengthened beams. Shear strengthened beam without anchor (SB) had failed by 104 kN load with debonding of plate at concrete-adhesive interface, the debonding initiated at 80 kN load. Steel plate of double connector strengthened beam (DC) partially debonded at 128 kN load, double connector anchor enhanced interfacial bond strength which resulted higher debonding load of strengthened beam (DC). Multi connector anchor completely prevented debonding of plate at concrete-adhesive interface, however, because of anchor failure due to crushing of concrete, the plate debonded at 90 kN load from plate-adhesive interface. Since, the connector failed, the shear enhancement of that beam was comparatively low.

Table 2. Results of shear strengthened damaged RC beams

Beam ID	Anchor type	Experimental results				Theoretical prediction	
		Debonding load (kN)	Failure load (kN)	Increased shear capacity (%)	Failure mode	Shear capacity (kN)	Flexural capacity (kN)
SB	No anchor	80	104	104	Debonding at concrete interface	135	153
DC	Double connector	128	139.6	139.6	Partial debonding at concrete and plate interface	135	153
MC	Multi connector	91.4	91.4	91.4	Debonding at plate interface	135	153
WC	Welded connector		136.3	136.3	No debonding, cover separation	135	153
EB	Embedded bar		112.3	112.3	No debonding, flexural failure	135	153

Before strengthening, all beams were fully damaged for shear and thus the un-strengthened damaged beams were not able to sustain shear force. Shear strengthened beam with welded connector prevented premature debonding of externally bonded steel plate, and thus, the shear capacity enhancement was 136.3% as compared to damaged beam. Embedded bar anchor prevented premature debonding of steel plate and concrete cover separation failure. The shear capacity enhancement of that beam (EB) was 112.3% as compared to damaged beam. However, the shear capacity of EB was found to be lower as compared to the design shear capacity (136 kN). The shear capacity of that beam even could be higher if the beam had sustained higher flexural capacity. Results showed that the degree of damage and size of cracks influenced the effectiveness of ancho system to enhance the shear capacity of strengthened beams, specially for multi connector anchor system. In terms of capacity enhancement, double connector, welded connector and embedded bar anchor systems were found to be more effective. The concrete of damaged beam near shear cracks was relatively weak, the anchors near the shear crack might not be effective because of weaker concrete. The multi connector supposed to ensure higher bond strength to prevent premature debonding failure of steel plate. However, because of crushing of concrete at the location of connector, the capacity of strengthened beam with multi connector anchors were found to be lower as compared to others.

4.3 Theoretical Predictions

Flexural and shear capacities of all strengthened beams could be calculated based on the Equation of 15 and 16 respectively as shown below.

$$Flexural\ capacity: M = A_s f_{tk}\left[d - \frac{0.588 A_s f_{tk}}{f_{ck} b}\right] \tag{15}$$

$$Shear\ capacity: V_{sb} = 2A_p f_{yp}\left[\frac{h cot\theta}{s_p}\right] \tag{16}$$

Table 3. Parameters and theoretical capacities of strengthened beam

Parameters of strengthened beam (mm, mm^2, N/mm^2)										Flexural capacity (kN)	Shear capacity (kN)
A_s	f_{tk}	d	f_{ck}	b	A_p	f_{yp}	h	θ	S_p		
377	620	211	30	150	54	275	250	45	110	153	135

The particulars and theoretical capacities of beams are shown in Table 3. Results showed that theoretical flexural and shear capacities of strengthened beams were 153 kN and 135 kN respectively. Theoretical shear capacity of un-strengthened control beam was 136 kN, the shear contribution of externally bonded steel plate was almost same with the original shear capacity of damaged beam. All beams were designed for shear strengthening using steel plate to restore the original capacity. Since all beams were fully damaged in shear before shear strengthening, theoretical model considered the shear contribution of externally bonded steel plate only to predict shear capacity of strengthened beam. Results showed that shear strengthened beams DC and WC fully re-stored the shear capacity (139 kN and 136 kN respectively) and had almost similar values of theoretical shear capacities (135 kN) of beams.

5. Conclusions

Externally boded steel plate of shear strengthened damaged RC beam without anchor had debonded from concrete-adhesive interface. Whereas, embedded connector, double connector, welded connector and embedded bar anchor systems were found to be effective in prevention of premature debonding of externally bonded steel plate from concrete-adhesive interfaces of shear strengthened RC beams. The steel plate of double and multi connector anchor systems were debonded at plate-adhesive interface near the connector, the connectors were incapable to prevent debonding of EB steel plate at plate-adhesive interface near the anchors. The anchors could not function once the concrete had crushed or the plate had debonded at plate-adhesive interface. The debonding of plate and failure of anchors caused shear failure of strengthened beams rather than flexural failure. Welded connector and embedded bar anchors were found to be very excellent in preventing premature debonding of externally bonded steel plate both at plate-adhesive and concrete-adhesive interfaces for shear strengthening of damaged RC beams. Strengthened beam with welded connector anchor had failed by separation of concrete cover. In general, all anchors significantly enhanced shear capacities of damaged beams, the anchor system enhanced maximum of 139% shear capacities of damaged beam through strengthening using externally bonded steel plate. Double and welded connector anchors had shown the highest enhancement of shear capacities of strengthened beams and were able to re-store the original capacities of damaged beams. The degree of damage, cracks and flexural capacity influenced the shear enhancement of strengthened beams. Larger crack of damaged beams caused failure of anchor systems which resulted lower enhancement of shear capacities of strengthened beams. The beam with lower flexural capacity caused lower enhancement of shear capacity as well. The dimension of steel plate for shear strengthening of damaged RC beam based on proposed design was sufficient to restore the full shear capacities of damaged beams. The shear capacity of strengthened beam based on the proposed theoretical model considering contribution of externally bonded steel plate was found to be comparable with the experimental results.

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Nomenclature

M	: $Moment\ resisting\ capacity\ of\ beam$
T	: $Tensile\ force\ of\ flexural\ reinforcement$
z	: $Moment\ arm$
A_s	: $Cross\ sectional\ area\ of\ flexural\ reinforcement$
f_{tk}	: $Tensile\ strength\ of\ flexural\ reinforcement$
f_{ck}	: $Concrete\ compressive\ strength\ based\ on\ cylinder\ test$
b	: $Width\ of\ beam$
x	: $Depth\ of\ neutral\ axix$
d	: $Effective\ depth\ of\ beam$
d'	: $Depth\ of\ compression\ reinforcement\ (top\ bar)$
V_{ds}	: $Design\ shear\ force$
L_s	: $Shear\ span$
N	: $Number\ of\ shear\ link$
s_{link}	: $Spacing\ of\ shear\ link$
V_{cb}	: $Shear\ capacity\ of\ un-strengthened\ conctrol\ beam$
V_c	: $Shear\ force\ resisted\ by\ concrete$
$V_{y,link}$	: $Shear\ force\ of\ beam\ due\ to\ yielding\ of\ shear\ reinforcement$
$A_{s,link}$	: $Cross\ sectiona\ area\ of\ shear\ link$
$f_{y,link}$	: $Yield\ strength\ of\ shear\ link$
V_{sp}	: $Shear\ force\ resisted\ by\ steel\ plate$
A_p	: $Cross\ sectional\ area\ of\ single\ steel\ plate$
N_p	: $Number\ of\ steel\ plate\ to\ resist\ shear\ (from\ one\ side\ of\ beam)$
s_p	: $Spacing\ of\ steel\ plate$
f_{yp}	: $Yield\ strength\ of\ steel\ plate$
h	: $Depth\ of\ beam$
$\varepsilon_{deb.p}$	: $Debonding\ strain\ of\ plate$
F_{bp}	: $Bond\ strength\ of\ plate$

w_p : $Width\ of\ plate$
E_p : $Modulus\ of$ elasticity of plate
t_p : $Thickness\ of\ plate$
σ_p : $Stress\ of\ plate$
ε_p : $Strain\ of\ plate$

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