

# Applications of bolted steel plates to shear strengthening of RC beams

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**Abstract.** Many reinforced concrete beams have been found deficiencies in shear due to lack of shear reinforcement. Few researches have been done to investigate shear strengthening of low concrete strength of RC beams using bolted steel plates. This paper presents experimental results on the behaviour of RC beams strengthening using full steel plates along the shear span fixed with bolts. Nine RC beams having dimension of 150x200x1500mm were tested to failure on simply supports with four point loadings setup. The beams were reinforced with tension rebars area of 289.8 mm<sup>2</sup> (2D10+1D13) and transvers reinforcement of Ø6-125. Two dial gauges were installed at the beam middle span to measure beam deflection during the test. The results show that the applications of steel plate and bolts as external reinforcement increase beam shear capacity, stiffness and delay the occurrence of first diagonal cracks. Beams strengthened with U-shape plates gave better performances than the beams with two pieces of L-shape plates due to better anchorages.

## 1 Introduction

Shear failure of RC beams is a brittle failure without significant warning that has to be avoided in RC structural design. Degradation on shear strength of RC beams can be due to various reasons such as changing to service live load as a function of structural change or changing the code requirements, mistakes in design calculations, improper reinforcement details, construction errors or poor construction practices, and reduction of the rebar's area due to corrosion [1]. To improve the shear strength of RC beams, numerous shear strengthening techniques have been studied over decades as reported in [2] such as using prestressing cables, bonded CFRP, additional internal shear reinforcement with concrete jacketing and external bonding of steel plates with epoxy.

Numerous researches have been conducted over a decade to use steel plate in the shear strengthening of RC beams due to its ductile properties with high deformability, wide availability, low price of low-carbon steel and ease application without required skilled labors. Adhikary et al. [3] showed that the increase in beam shear capacity of RC beams with continuous steel plates bonded externally to beam webs is a function of plate thickness and plate depth. Altin et al. [1] showed that using side plates are an effective method to

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strengthen beam in shear, which is decreasing the amount and extent of shear cracking in a beam. Barnes and Mays [5] investigated the shear strength of plated RC beams subject to different shear failure modes, and a design method for RC beams strengthened with continuous external steel side plates was proposed [6]. In the same year, [2,4] also studied various shear strengthening techniques with some parameters of bonded steel plates to RC beam webs and the proposed formula to calculate the shear contribution of the steel plates. In steel plated RC beams, failure of bonded steel plates is controlled by the shear strength of epoxy and concrete [1].

In order to improve the bond strength of steel plates and concrete, bolts or a combination of bolts and epoxy have been studied. Su and Zhu [7] showed that using bolts to anchor the side plates to the beam surfaces contributes to the load-carrying capacity and the energy-absorption capacity of a plated concrete beam. Anchored bolts placed at shear span shorten the steel plates' buckling length and contribute significant effects on ultimate shear strength [2,4]. Aykac et al. [8] studied that using bolts to embed thin steel plates to the soffit of RC beams did not contribute ductility and load capacity. Su et al. [9] and Li et al. [10] studied the shear transfer in bolted side plated RC beams and proposed a new design approach to calculate shear transfer profile and the critical bolts shear force in bolted side-plated RC beams. Most of the previous researches were using two pieces of vertical web plate with anchor bolts. Research on using a piece of U-shape steel plate and two pieces of L-shape steel plate at shear span is still worth to be conducted. Bolts through the beam webs at 2/3 height of steel plate may improve the performance of steel plates due to the clamping effect of the bolts.

The shear capacity of the steel plated RC beams can be calculated as a combination of the contribution from concrete ( $V_c$ ), internal shear reinforcement ( $V_s$ ) and external bolted steel plates ( $V_p$ ). The nominal shear strength is given as the following expression:

$$V_n = V_c + V_s + V_p \quad (1)$$

The contribution of  $V_c$  and  $V_s$  can follow the expression from ACI 318-14 [11], whilst the contribution of  $V_p$  follow the Eq.2 proposed by [4].

$$V_p = \frac{1}{3} \kappa f_{yp} h_p t_p \quad (2)$$

The of  $K$  is based on statistical analysis of 554 data by [4] as follows :

$$\kappa = 0.68 - 0.27\rho_v + 0.28\left(\frac{h_p}{h}\right) - 1.95\left(\frac{t_p}{b_w}\right) - 0.007\left(\frac{f_{yp}}{f'_c}\right) \quad (3)$$

where,  $\rho_v$  is the shear reinforcement ratio,  $t_p$  is the thickness of the plates at both sides of the beam web,  $h_p$  is the depth of the steel plates across the section,  $h$  is the height of the beam,  $b_w$  is the beam's width,  $f_{yp}$  is the uniaxial yield strength of steel plate and  $f'_c$  is the compressive concrete strength.

## 2 Experimental program

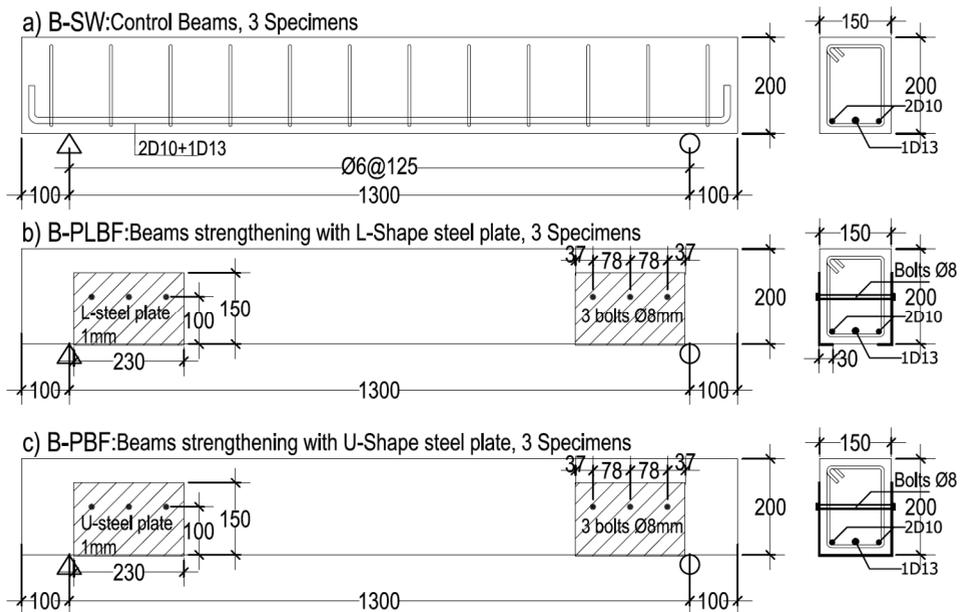
### 2.1 Material properties

The beams were cast using concrete with a mix proportion by weight of 1 cement: 3.2 sand: 3.1 gravels with a maximum diameter of 19 mm. The average concrete compressive strength obtained at 28 days ( $f'_{cr}$ ) was 20.3 MPa. Tension test was conducted to obtain the

properties of the rebars and steel plates. The yield strength ( $f_y$ ) of the rebars D13, D10,  $\text{Ø}6$  was 482 MPa, 457 MPa, and 294 MPa, respectively. The steel plates and bolts as strengthening materials have a yield strength of 178 MPa and 603 MPa, respectively. In order to fill the gap and give adhesive strength between hole and bolts, Sika Anchorfix-2 was used. There were also gaps between the concrete surface and the steel plates since the concrete was not perfectly flat; therefore, Sikagrout 215 was used. The grout was not intended to give bond strength between concrete and steel plates.

## 2.2 RC beam specimens

All RC beams were 150x200x1500mm with longitudinal reinforcement area of 289.8 mm<sup>2</sup> (2D10mm+1D 13mm) and 6 mm for stirrups with a spacing of 125 mm along the beam length. Three beams were controlled specimens (B-SM), three beams were strengthened with L-shape plates (B-PLBF), and the other three beams were using U-shape (B-PBF). Detail geometric properties of all specimens are shown in Fig. 1. After the concrete had been poured, all specimens were moist cured for seven days by covering all beam surfaces with wet burlaps and plastic sheets.

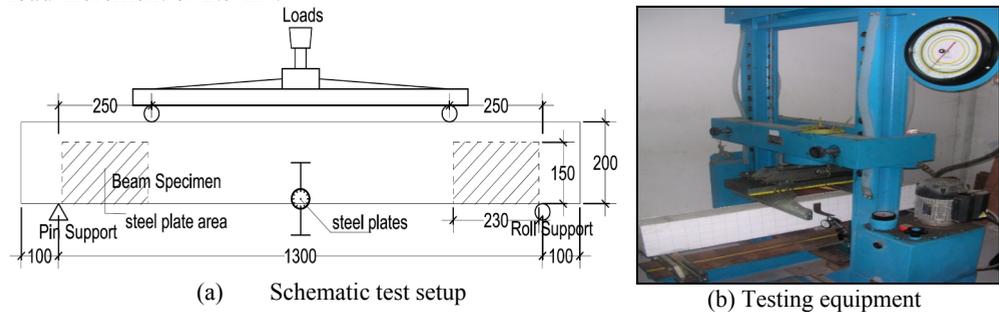


**Fig. 1.** Detail geometry and reinforcement of the specimens.

Installation of steel plates as shear strengthening on specimens B-PLBF and B-PBF after the concrete age of 14 days. The web surface of RC beams was first gridded with sandblasting sheets to flatten the surface, then three holes on each shear zone were drilled through the beam web to install the bolts. The concrete surface and the holes were cleaned and vacuumed to remove all dust and other loose particles. Threaded bolts were installed through the holes and grouted using sika anchor fix-2 until all spaces between the hole and the rod were filled. Then, the steel plates were installed and tightened using anchored nuts on both ends of the threaded rod. The gaps between steel plates and concrete surface were grouted using sika grout 215. The same procedures were applied for both L-shape and U-shape steel plates.

## 2.3 Test setup and instrumentations

Testing of all beams was done after the concrete age of 28 days with four points loading setup as shown in Fig. 3. The beams were merely supported with the load positions were 230 mm from the supports that gave shear span to depth ratio ( $a/d$ ) of 1.7. Two mechanical (or dial) gauges were used to measure mid-span beams deflections during the test at each load increment of 2.5 kN.

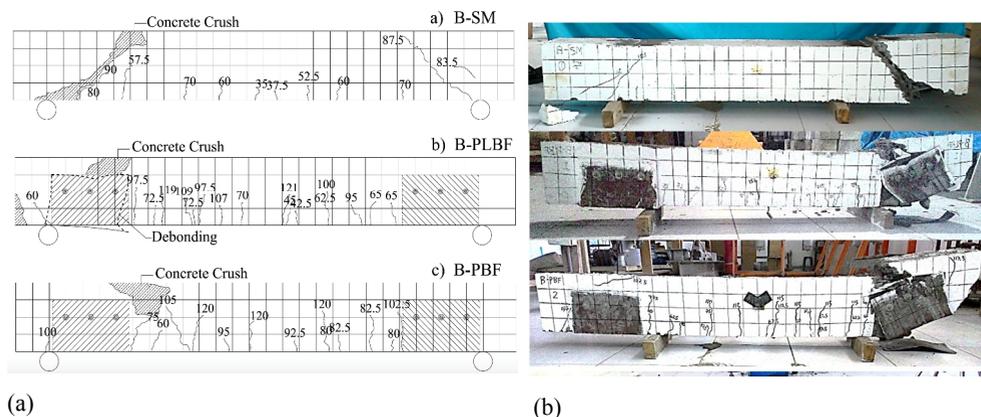


**Fig. 2.** Four points loading test setup (a) schematic test setup; (b) testing equipment.

## 3 Results and discussion

### 3.1 Crack pattern and failure modes

The beams were designed to fail in shear. Flexural cracks were observed first in the region between two applied loads in all tested beams. Fig. 3 shows the examples of crack patterns and condition of beams after testing. The full steel plates along shear zone increase the beam's first crack capacity ( $P_{cr}$ ). The average  $P_{cr}$  for control beams is 31.67 kN, whilst the average  $P_{cr}$  for plated beams B-PLBF and B-PBF is 39.17 kN and 48.33 kN or 23.68% and 52.63% higher than that  $P_{cr}$  of control beams. This indicates that the application of full steel plate as shear strengthening delays the existence of diagonal cracks.



**Fig. 3.** Crack patterns and beam's conditions after testing, (a) example crack pattern of beams, (b) example beam conditions after testing.

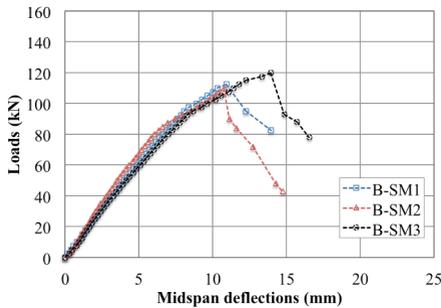
All specimens failed in shear as expected in design whether it followed by concrete crushing at compression zone and the steel plate was debonding or not. All L-shape plates in B-PLBF delaminated from concrete started from the bottom side of beams due to lack of Anchorage. The bolts were provided at 2/3 height of steel plates. Providing plate soffit at

the bottom surface of beams using U-shape plates results in better control of first diagonal cracks due to the better anchorage of bottom steel plates.

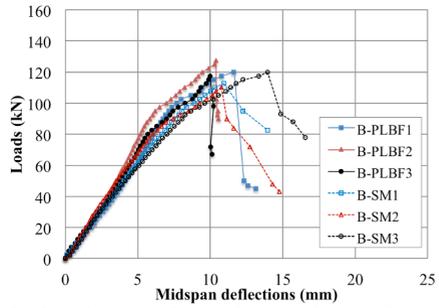
**Table 1.** Failure modes and maximum loads.

Beam ID	Steel plate thickness ( $t_p$ )	$P_{ult}$ (kN)	Mode of Failure	Remarks
B-SM1	-	112.5	Shear	Control Beams
B-SM2		110.0	Shear	
B-SM3		120.0	Shear+concrete crush	
B-PLBF1	1 mm	120.0	Shear, Plate Debonding	Beams strengthened with L-shape plates
B-PLBF2		127.5	Geser + concrete crush + plate debonding	
B-PLBF3		117.5	Shear, plate debonding	
B-PBF1	1 mm	125.0	Shear+ concrete crush	Beams strengthened with U-shape plates
B-PBF2		117.5	Shear + plate debonding	
B-PBF3		122.5	Shear + plate debonding	

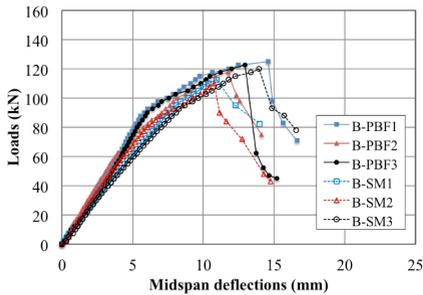
**3.2 Beam deflections**



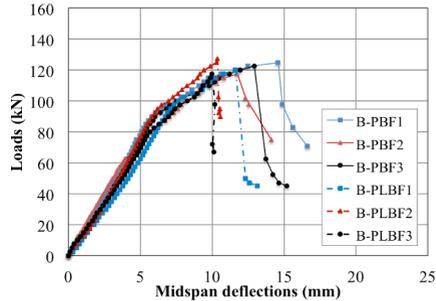
(a) Specimen control (B-SM)



(b) Specimen L-shape plates and control



(c) Specimen U-shape plates and control



(d) Specimen U-shape and L-shape plates

**Fig. 4.** Load-deflection curve of all specimens.

**Table 2.** Elastic and plastic stiffness of all specimens.

Code	Elastic Conditions ( $k_e$ )			Plastic Conditions ( $k_p$ )		
	P/ $\delta$ (kN/mm)	$k_e$ (avg) (kN/mm)	(%)	P/ $\delta$ (kN/mm)	$k_p$ (avg) (kN/mm)	(%)
B-SM1	11.728	11.917	-	10.321	9.713	-
B-SM2	12.879			10.185		
B-SM3	11.145			8.633		
B-PLBF1	12.987	13.826	13.80	11.275	11.669	16.76
B-PLBF2	15.000			12.136		
B-PLBF3	13.492			11.598		
B-PBF1	15.164	14.987	20.48	11.085	11.461	15.25
B-PBF2	14.796			12.346		
B-PBF3	15.000			10.952		

**Table 3.** Capacities of all specimens.

Code	$f'_c$ (MPa)	Maximum Loads		Experimental Max. Shear forces		Avg. $V_{pre}$ (kN)	$V_{n(exp)}/V_{n(teo)}$	
		$P_{ult}$ (kN)	Rata-rata (kN)	$V_{exp}$ (kN)	Average $V_{exp}$ (kN)			
B-SM1	21.9	112.5	114.17	56.25	57.08	-	43.69	1.31
B-SM2		110.0		55.00				
B-SM3		120.0		60.00				
B-PLBF1	19.3	120.0	121.67	60.00	60.83	6.57	55.44	1.10
B-PLBF2		127.5		63.75				
B-PLBF3		117.5		58.75				
B-PBF1	19.7	125.0	121.67	62.50	60.83	6.57	55.62	1.09
B-PBF2		117.5		58.75				
B-PBF3		122.5		61.25				

Middle deflections of all specimens were recorded for every 2.5 kN load increments and plotted as shown in Fig. 4. All data of plotted beams are compared to that of control beams.

The application of full steel plate can also improve beam's stiffness as shown in Table 1. Beam with U-shape plates exhibited higher elastic stiffness than beam with L-shape plate due to the existence of bottom plates. However, when cracks have occurred, the plastic stiffness of the beams with both types of stiffness is not much different.

### 3.2 Beam capacities

The maximum loads can be resisted by all beams are listed in Table 3. The shear capacity of plated beams is 6.57% higher than the control beams. This may be due to the steel plates were not thick enough to prevent out of plane wrapping at high loads result in plate delamination. This is also highlighted by [8] that the minimum thickness of steel plates is 1.5mm. Also, the steel plate bearing capacity at the bolt's hole was not high enough to resist the transverse force in the bolts.

Comparing to experimental shear forces ( $V_{exp}$ ) with the predicted one ( $V_{pre}$ ) using Eq. 1 shows that the ratio of  $V_{exp}/V_{pre}$  is higher than 1.0. This means that all beams are safe and the contribution of steel plate on the shear strength can be well predicted using Eq.2 proposed by [4].

## 4 Conclusions

The test results and discussions drive the following conclusions on the application of steel plates and bolts as a shear strengthening of RC beams. The use of bolted steel plates both L-shape and U-shape can improve shear capacity and delay the occurrence of first diagonal cracks in beams. The performances of beams strengthened with U-shape are better than that of beams strengthened with L-shape plates regarding their crack patterns, shear capacity, and stiffness. Comparing to the capacity of control beams (B-SM), the average first diagonal crack load and ultimate loads of B-PLBF are 23.7%, 6.57%, 52.6% and 6.57% higher.

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