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IMPROVING SHEAR CAPACITY OF RC BEAMS USING EPOXY BONDED CONTINOUS STEEL PLATES

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Abstract— This paper presents the results of experimental program on strengthening of reinforced concrete (RC) beams by external bonding of steel plates. The experimental study is conducted on the strengthening of 26 RC beams divided in two series of beams i.e. without and with internal shear reinforcement. The continuous steel plates of various thickness and depth are centrally bonded with epoxy adhesive to the side of the beam webs. The study has shown that the provision of adhesively bonded external steel plates has the potential to significantly increase shear strength of RC beams. The effects of steel plate thickness and plate depth on ultimate shear strength of the specimens are also investigated. The shear strength of a beam with bonded steel plates increases with increasing plate depth and thickness across the beam section. It is observed from the experimental results and its analysis, that the beams should be reinforced with plates up to the maximum possible section depth to attain the maximum shear contribution from steel plate. Using thicker plates does not increase the strength proportionally, it is better to use deeper rather than thicker plates to achieve the maximum shear contribution for same plate cross-sectional area.

Keywords*-Shear capacity, epoxy adhesive, steel plates.*

I. INTRODUCTION

In recent years, strengthening of existing concrete structures may be required to improve the structural behavior and repair of damaged structures to restore structural performance for economical reasons. Generally, reinforced concrete (RC) beams fail in two modes: flexure and shear. Shear failure of reinforced concrete beam is sudden and brittle in nature and gives no advance warning prior to failure. Shear failure is more dangerous than flexural failure. Hence, reinforced concrete beam must be designed to develop their full flexure capacity. Many reinforced concrete structures have shear problems for various reasons, such as improper detailing of the shear reinforcement, mistakes in design calculations, poor construction practices and reduction of the shear reinforcement steel area due to corrosion in service environment etc. The shear force in reinforced concrete beam is combination of dowel action, aggregate interlock, shear reinforcement and concrete in the compression zone. The shear strength of reinforced concrete beam can be affected by concrete properties, beam size, beam shape and reinforcement details. Nowadays, strengthening of reinforced concrete beam by using steel plates, fiber reinforced polymer (FRP), ferrocement is a common task for concrete structures maintenance.

Sinan Altin et al. investigated the effects of the type and arrangement of steel plates for strengthening on the behavior, strength, stiffness, failure mode and ductility of the reinforced concrete beams [1]. An average of 72% increase in shear strength was obtained for the beam strengthened with epoxy bonded discontinuous steel plates than the used of steel brackets, vertical strips and externally anchored stirrups [2]. The use of epoxy bonded continuous steel plates is provided from the bottom of the soffit in the web portion rather than the vertical strips as strengthening members and these externally bonded steel plates provided good enhancement in shear capacity as that provided by conventional internal shear links [3]. A formula to compute the shear strength of reinforced concrete beams was proposed by adding up the concrete contribution, shear reinforcement contribution and the contribution of steel plates and comparison between the shear strengths computed using the proposed formula and finite element method (FEM) as well as the experimental results is made [4]. G. Arslan et al. concluded that the externally bonded continuous steel plates can improve the ultimate load-carrying capacities of damaged reinforced concrete beams and this study is supported by a three-dimensional nonlinear finite element analysis and an equation for ultimate shear capacity of retrofitted beams is proposed except for beams which have steel plate extended to the supports and/or additional anchorages at the ends of steel plate [5]. Barnes et al. used two methods of plate attachment, namely adhesive bonding and bolting and method of analysis based on the equilibrium of forces along the critical section was proposed. The adhesively bonded plates provide a very high degree of surface crack control but inadequate surface area can lead to interface failure and sudden collapse; additional mechanical anchorage may be required in these circumstances [6].

This paper concentrates on the studies of use of continuous steel plates rather than vertical strips, aligned parallel and symmetrical to beam axis for improving the shear strength of reinforced concrete beams as it is believed that the advantages of improved anchorage, no bolting requirement and ease of installment outweigh the disadvantages of weight and material cost. An experimental study is conducted on the strengthening of 26 reinforced concrete beams divided in two series of beams, viz. without and with internal shear reinforcement. In each series of beams, one of which is control specimen and the remaining twelve of which are shear deficient. In this study, the continuous steel plates are centrally bonded with epoxy adhesive Sikadur-31 along the parallel axis of the beam having various thickness of 2, 2.5 and 3mm with varying depths of 40 mm, 60 mm, 80 mm and 100 mm each. The test results of these beams are compared with the results for the control beam. The effects of steel plate thickness and plate depth on ultimate shear strength of the specimens are investigated.

II. EXPERIMENTAL PROGRAM

In the experimental program carried out, reinforced concrete beam is designed as under reinforced section using M30 grade concrete and Fe 415 grade steel by limit state method. In the experimental investigation, two types of reinforced concrete beams are designed and casted namely series A which do not consists of stirrups and series B which consists stirrups. The series A beams are designed to have two steel bars of 8 mm diameter as reinforcements at tension face as shown in Fig. 1. In series B, the stirrups used are of 6 mm diameter steel bars of Fe 250 grade at the spacing of 85 mm are used along with longitudinal reinforcement of two 8 mm diameter bars as shown in Fig. 2. The beams of both series are designed such that they should behave as shear deficient beams. The dimensions of the beam are 700 mm x 150 mm x 150 mm.

The two steel plates, 700 mm long are bonded to the web of the beams using epoxy adhesive Sikadur 31.The strength of the beams is investigated for the parametric variation of depth and thickness under four point loading. Four different plate depths i.e. 40, 60, 80 and 100 mm are selected each with thickness of 2 mm, 2.5 mm and 3 mm.

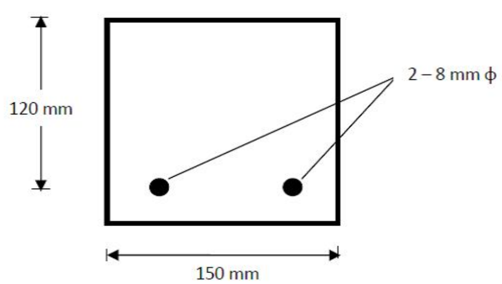

Figure 1 Cross-section of reinforced concrete beam without shear reinforcement (Series A)

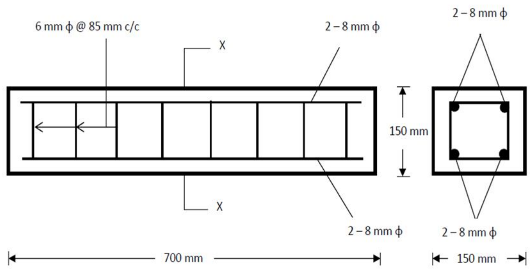

Figure 2 Details of reinforced concrete beam with shear reinforcement (Series B)

A. *Bonding procedure*

Before bonding the steel plates to the concrete surface of reinforced concrete beam, special consideration is given to preparation of the beam's web surface. Both sides of the beam web are roughened by a mechanical grinding, brushed and cleaned with acetone to remove loose particles and dust. The bonding faces of the steel plates are also roughened by a mechanical grinding machine and cleaned thoroughly with acetone. Then epoxy adhesive (Sikadur-31) is mixed in accordance with the manufacturer's instructions. Mixing is carried out in a metal container and is continued until the mixture is a uniform color. The epoxy is uniformly spread all over the roughened web of the beams and the steel plates to a thickness of 1.5 mm and the plates are then bonded to the beams. After bonding operations is completed, specimens are cured for 15 days under laboratory conditions before testing.

B. *Experimental set-up*

The Electronic Universal Testing Machine (UTE-100) with maximum capacity of 1000 kN is used for the shear test of all specimens. A schematic view of the experimental set-up and the arrangement of the measurement devices are shown in Fig. 3. Beams are tested under four-point loading. The load applied to the mid-point of the reaction beam is divided symmetrically into two concentrated loads and applied to the specimens. The ratio of the shear span length (200 mm) to the effective depth of the beam (120 mm) is 1.67 and is the same for all specimens. Specimens are tested under monotonic loading to failure.

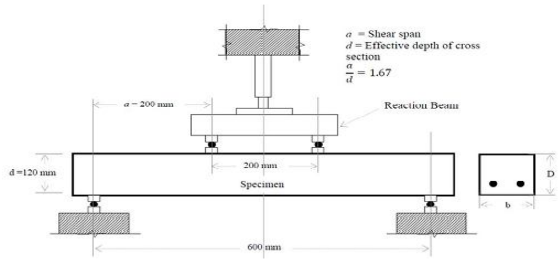

Figure 3 Experimental test set-up

III. ANALYSIS OF PLATED REINFORCED CONCRETE BEAMS

The ultimate shear strength of reinforced concrete beams with web-bonded continuous horizontal steel plates is computed by adding the contributions from concrete, internal shear reinforcement and the external steel plates. Nominal shear strength (V_n) of plate-bonded beam is given as follows:

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

The contribution of concrete (V_c) is computed by following Okamura–Higai formula below

$$V_c = 0.20 f_c'^{\frac{1}{3}} (1 + \beta_p + \beta_d + \beta_n) \left[0.75 + \frac{1.4}{a/d}\right] b_w d \quad (2)$$

where,
$\beta_p = \sqrt{p_w} - 1 \leq 0.732$
$\beta_d = d^{-1/4} - 1$, (d in meters)
$\beta_n = \dfrac{2M_d}{M_u}$
f'_c = Compressive strength of concrete,
a = Shear span,
d = Effective depth of beam,
b_w = Width of beam,
p_w = Longitudinal reinforcement ratio,
M_d = Decompression moment,
M_u = Moment in the section.

As per IS 456-2000 [7], the shear contribution of internal shear reinforcement (V_s) is calculated by,

$$V_s = 0.87 f_y d A_{sv} / S_v \quad (3)$$

where,
f_y = Yield stress of shear reinforcement,
A_{sv} = Area of shear reinforcement,
S_v = Spacing of shear reinforcement.

The expression for shear contribution of web-bonded continuous steel plates to the shear strength of beam (V_p) is given by summing up the shear stresses in steel plates over its depth and thickness

$$V_p = \frac{1}{3} f_{yp} h_p t_p \quad (4)$$

where,
f_{yp} = Yield strength of steel plate,
h_p = Depth of the steel plate,
t_p = Thickness of steel plate.

The values of nominal shear strength has been calculated for all the beams and compared with the experimental values.

IV. RESULTS AND DISCUSSIONS

This section describes the experimental results of series A (without shear reinforcement) and series B (with shear reinforcement) beams. All the beams are designed to fail in shear even after strengthening with steel plates. The ratio of shear span to effective depth (*a/d)* is kept constant throughout the testing of all the beams. The load-deflection behavior and ultimate load capacity for shear is observed throughout the testing to failure of beams. Also the failure mode at ultimate load is observed. Fig. 4 shows typical failure of reinforced concrete beam strengthened with continuous steel plate. The discussion is carried out through comparison between the results determined by the analytical method with those experimentally obtained.

A. Failure modes and ultimate modes

The two set of beams are tested for their ultimate strengths. In series A, 12 beams without internal shear reinforcement and strengthen with steel plates are tested, beam A is taken as control beam i.e. without strengthening with steel plates. In series B, 12 beams with internal shear reinforcement and strengthen with steel plates are tested, beam B is taken as control beam i.e. without strengthening with steel plates. It is observed from Table I and Table II, that the ultimate shear capacity of control beams A and B is less as compared to the other beams (A1 to A12 and B1 to -B12) which are strengthened by external bonding of steel plates. The effect on ultimate shear strengths is studied by variations in

a) Thickness of steel plates (2, 2.5 and 3 mm)
b) Depth of steel plates (40, 60, 80 and 100 mm)

In the case of beams without shear reinforcement, the control beam fails as soon as the first critical shear cracks forms. In the case of plate bonded beams, steel plates solely take up the additional stresses once concrete cracks.

Figure 4 Typical failure of reinforced concrete beam strengthened with continuous steel plate

Steel plates provide very effective bridging across the cracks, leading to relatively higher contribution of plates to shear strength. In the case of beams with internal shear reinforcement, stirrups and steel plates, both shares the additional stresses once the concrete cracks in shear span. Beam with bonded steel plates showed greater stiffness throughout the loading than the control beam. In most cases the addition of externally bonded shear plate reinforcement provided enhancement in shear capacity comparable with that provide by conventional internal shear links. The shear strength of a beam with centrally bonded steel plates increases with increase in plate depth and thickness across the beam section. The maximum increase in ultimate shear strength compared with the control beam is about 86% for beam A12 (plate thickness: 3 mm, depth: 100 mm). Also, for beam B12 with same plate depth and thickness, the increase in ultimate shear strength is about 66% than the control beam.

B. Parametric study

The effect of plate depth and plate thickness on the shear strength for the beams is represented graphically and studied. It is seen that the ultimate shear strength of beam increases with plate depth expect beam B11. The effect of the plate depth on ultimate shear strength for 2 mm plate thickness is shown in Fig. 5.

It is observed that increasing the plate thickness increases the ultimate shear strength of beam except beam B11.The relation between the ultimate shear strength and plate thickness for 100 mm plate depth is shown in Fig. 6. For beam B11, the lower strength beam may be due to the defects in bonding operation, which resulted in not so perfect bond of steel plates to concrete.

C. Specific observations

It is observed that the increase in shear strength with the thickness is less as compared to the increase in the strength with the corresponding increase in the depth.

It is thus clear that the best possible way to enhance the shear strength is to use deeper plates rather than the thicker plates. Table III shows the increase in the percentage of the strength with increase in the thickness, and Table IV shows increase in depth in relation with increase in the percentage of volume of the plate. Here, the values of shear strength have been extrapolated for the thicknesses of the plate from 3.5 to 5 mm for series A beams.

From the analytical formula, the theoretical values for V_c , V_s and V_p have been calculated and they are tabulated with reference to the experimental values as shown in Table V and Table VI

It is observed that the increase in the ultimate load capacity due to addition of plate is greater in series B beams. These values are nearly comparable with the theoretical V_p calculated. The increase in the capacity due to stirrups experimentally is also close to the theoretical value of V_s.

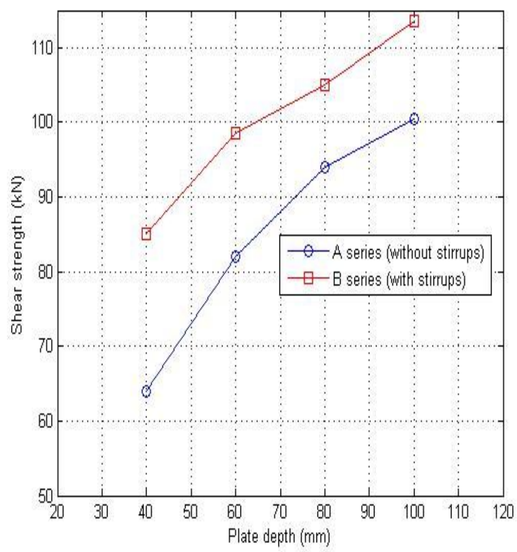

Figure 5 Relation between the shear strength and plate depth for 2 mm thickness of steel plates for beams A1-A4 and B1-B4

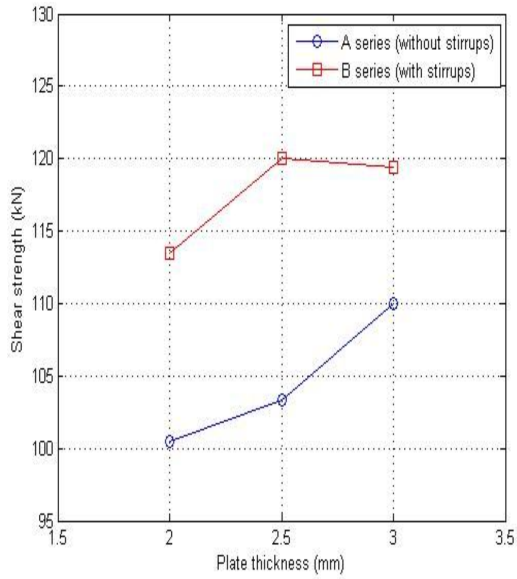

Figure 6 Relation between the shear strength and plate thickness for 100 mm plate depth for beams A4, A8, A12 and B4, B8, B12

V. CONCLUSIONS

The test results confirmed the effectiveness of web bonded continuous steel plates for shear strengthening of reinforced concrete beams. The shear strength of a beam with bonded steel plates increases with increasing plate depth and thickness across the beam section. It is observed from the experimental results and its analysis, that the beams should be reinforced with plates up to the maximum possible section depth to attain the maximum shear contribution from steel plate. Using thicker plates does not increase the strength proportionally, it is better to use deeper rather than thicker plates to achieve the maximum shear contribution for same plate cross-sectional area. The steel plates serve to control the crack opening and catastrophic shear failure up to the load level at which bond failure occurred in the concrete. Externally bonded steel plates increases the shear and flexural capacity, this method can be very well suitably used for retrofitting and increasing the existing capacity of the beams.

TABLE I. TEST RESULTS FOR SERIES A (WITHOUT SHEAR REINFORCEMENT) BEAMS

Specimen	Shear reinforcement	Thickness of steel plate (mm)	Steel plate dimensions (mm)	Cracking loads		Failure load P_u (kN)	Failure mode
				Flexure (kN)	Shear (kN)		
A	None	-	-	30	49.95	59	Diagonal - tension
A1	None	2	700 x 40	35	54	64	Diagonal - tension
A2	None	2	700 x 60	40	76	82	Flexure-shear
A3	None	2	700 x 80	54	89	94	Flexure-shear
A4	None	2	700 x 100	55	95	100.5	Diagonal - tension
A5	None	2.5	700 x 40	43	62	68.85	Flexure-shear
A6	None	2.5	700 x 60	56	76	84.25	Shear-compression
A7	None	2.5	700 x 80	77	85	98.30	Diagonal - tension
A8	None	2.5	700 x 100	90	95	103.35	Diagonal - tension
A9	None	3	700 x 40	58	60	72.90	Flexure-shear
A10	None	3	700 x 60	65.78	81	87	Diagonal - tension
A11	None	3	700 x 80	52	90	102	Flexure-Shear
A12	None	3	700 x 100	60	100	110	Diagonal - tension

TABLE II. TEST RESULTS FOR SERIES B (WITH SHEAR REINFORCEMENT) BEAMS

Specimen	Shear reinforcement	Thickness of steel plate (mm)	Steel plate dimensions (mm)	Cracking loads		Failure load P_u (kN)	Failure mode
				Flexure (kN)	Shear (kN)		
B	Link	-	-	40.20	70	72.10	Flexure-Shear
B1	Link	2	700 x 40	49	80	85	Flexure-Shear
B2	Link	2	700 x 60	60.4	95	98. 60	Flexure-Shear
B3	Link	2	700 x 80	62	87	105	Diagonal - tension
B4	Link	2	700 x 100	60	93	113.5	Diagonal - tension
B5	Link	2.5	700 x 40	37	57	84.75	Flexure-Shear
B6	Link	2.5	700 x 60	35	60	105	Flexure-Shear
B7	Link	2.5	700 x 80	37	65	118	Flexure-Shear
B8	Link	2.5	700 x 100	52.5	105	120	Flexure-Shear
B9	Link	3	700 x 40	30	65	90	Diagonal - tension
B10	Link	3	700 x 60	35	75	103	Flexure-Shear
B11	Link	3	700 x 80	38	65	98.4	Flexure-Shear
B12	Link	3	700 x 100	42	92.4	119.4	Diagonal - tension

TABLE III. PERCENTAGE INCREASE IN PLATE VOLUME AND SHEAR STRENGTH FOR 2.5 MM THICKNESS PLATE

Plate depth (mm)	Plate volume x 10^3 mm^3	Increase in plate volume (%)	A series		B series	
			Ultimate shear strength (kN)	Increase in shear strength (%)	Ultimate shear strength (kN)	Increase in shear strength (%)
40	140	-	68.85	-	84.75	-
60	210	50	84.25	22	105	24
80	280	100	98.30	43	118	39
100	350	150	103.35	50	120	42

TABLE IV. PERCENTAGE INCREASE IN PLATE VOLUME AND SHEAR STRENGTH FOR 80 MM PLATE DEPTH

Plate thickness (mm)	Plate volume x 10^3 mm^3	Increase in plate volume (%)	A series	
			Ultimate shear strength (kN)	Increase in shear strength (%)
2	224	-	94	-
2.5	280	25	98.30	4.57
3	336	50	102	8.51
3.5	392	75	105.1	11.80
4	484	100	107.6	14.46
4.5	504	125	109.5	16.49
5	560	150	110.8	17.87

TABLE V. THEORETICAL AND EXPERIMENTAL SHEAR CONTRIBUTION OF STEEL PLATES FOR SERIES A BEAMS

Beam	Ultimate load P_u (kN)	Increase in capacity due to plate $V_p^{exp} = P_u - P_u^A$ (kN)	Theoretical Shear strength of steel plate V_p^{th} (kN)
A	59 (P_u^A)	-	-
A1	64	5	13.33
A2	82	23	20
A3	94	35	26.66
A4	100.5	41.5	33.33
A5	68.85	9.85	16.66
A6	84.25	25.25	25
A7	98.30	39.30	33.33
A8	103.35	44.35	41.66
A9	72.90	13.9	20
A10	87	28	30
A11	102	43	40
A12	110	51	50

TABLE VI. THEORETICAL AND EXPERIMENTAL SHEAR CONTRIBUTION OF STEEL PLATES FOR SERIES B BEAMS

Beam	Ultimate load P_u (kN)	Increase in capacity due to stirrups $V_s^{exp} = P_u - P_u^A$ (kN)	Increase in capacity due to plate $V_p^{exp} = P_u - P_u^B$ (kN)	Theoretical Shear strength of steel plate V_p^{th} (kN)
B	72.1(P_u^B)	13	-	-
B1	85	21	13	13.33
B2	98. 60	16.6	26.5	20
B3	105	11	32.9	26.66
B4	113.5	13	41.4	33.33
B5	84.75	16.75	12.65	16.66
B6	105	20.75	32.9	25
B7	118	19.7	45.9	33.33
B8	120	16.65	47.9	41.66
B9	90	17.1	17.9	20
B10	103	16	30.9	30
B11	98.4	3.6	26.3	40
B12	119.4	9.4	47.3	50

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