論文 External Shear Reinforcement for Reinforced Concrete Beams by Horizontal Steel Plate Bonding

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ABSTRACT: An experimental study on plate bonding technique for shear reinforcement of RC beams was conducted. Horizontal steel plates of different thickness were bonded to the web of the beams using epoxy adhesive and additionally fastened with anchor bolts. Parameters viz., plate thickness, pitch and penetration of bolts, etc., were considered. It was found that the externally bonded steel plates can be used as shear reinforcement for RC beams and the increment in ultimate shear strength was as high as 84% in comparison with the beam without plate. A formula to compute the shear strength of such beams is presented.
KEYWORDS: anchor bolts, epoxy adhesive, external shear reinforcement, plate bonding, RC beams, shear strength, steel plate

1. INTRODUCTION

Deterioration of existing concrete structures has become a major issue throughout the world in recent time. In Japan, with revised bridge load requirement, several bridges have become deficient. Since demolishing of such structures and constructing the new ones incurs a huge amount of public fund, strengthening has become a matter of choice. Strengthening also becomes necessary when errors are encountered in original design, due to improper concrete mixes and construction errors. With the advent of epoxy adhesives, it has been possible to use plate bonding technique to strengthen the existing concrete structures and repair the damaged ones. So far the researches have been focused mainly on flexural strengthening. However, very few studies have been reported on shear strengthening of reinforced concrete beams.

In this experimental study, several reinforced concrete beams with externally bonded steel plates were tested. The purpose of the external reinforcement was to give the beams the same strengthening characteristics as beams with ordinary shear reinforcement. Therefore no

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stirrups were used in shear failure region. The plates were not extended over the whole height of the beams because due to monolithic casting of beams and slab in practical field, it is not possible to glue the plate to full height of the beam. Moreover anchor bolts were used, in addition to adhesive as fasteners. All the beams were statically loaded to failure under four-point bending. By changing various parameters, the crack pattern, load deflection relationship, diagonal cracking and ultimate shear strengths, strains in the plates, etc., were studied.

2. EXPERIMENTAL PROGRAM

A series of twelve RC beams were tested in this study. All the beams had the same dimensions and reinforcement detail, as shown in **Fig. 1**. The beams were designed according to the specification[4]. A high longitudinal reinforcement ratio ($p_w = 0.0298$) was used, so that the beams were under-designed in shear and desired brittle shear failure could be obtained. Internal stirrups were used at the both ends outside the supports to prevent anchorage failure and mounting the longitudinal reinforcement. No stirrups were provided in the desired shear failure region. The average strength of concrete used was in the range of 27 to 34 MPa. The average yield strength and elastic modulus of the longitudinal reinforcement were 388 MPa and 210 GPa respectively. Horizontal steel plates (2400 mm long and 100 mm deep) were bonded to both sides of the web of the beams with two-part epoxy adhesive. The yield strength of the steel plate was 235 MPa and the elastic modulus was 206 GPa.

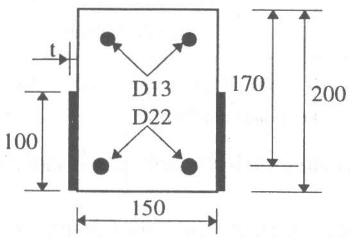
The thickness of epoxy layer was maintained about 2 mm. For different beams, thickness of the steel plates was varied. Furthermore, the plates were fastened with anchor bolts (one set of diameter 14 mm with the length of 40 mm and another set of diameter 17 mm with the length of 50 mm) to the beams. These bolts were installed after hardening of the epoxy adhesive. Different bolt pitch was used for different beams. Epoxy grouting was done for anchor bolts on beam A-8. The parameters considered were plate thickness, anchor bolt pitch, anchor bolt penetration, grouting of anchor bolt, etc. **Table 1** shows the test variables used in the experiment.

Table 1. Test variables in the experimental program

Beam No.	Plate thickness (mm)	Anchor bolt pitch (mm)	Anchor bolt penetration (mm)	Remarks
A-1	-	-	-	control beam
A-2	2.3	740	40	
A-3	2.3	-	-	no anch. bolt
A-4	4.5	370	40	
A-5	4.5	740	40	
A-6	2.3	185	40	
A-7	2.3	370	40	
A-8	2.3	740	40	grouted bolt
A-9	2.3	370	50	
A-10	2.3	740	50	
A-11	2.3	370	through bolt	
A-12	2.3	740	through bolt	

A shear span to depth ratio ($\frac{a}{d}$) of 3 was used for all the beams. The beams were loaded under four-point bending as shown in **Fig. 2** and an incremental monotonic load was applied up to the final failure.

Measurements were taken for mid-span displacement, strains in longitudinal reinforcement and horizontal strains in the steel plates at middle of both the shear spans on both sides of the beams. Each set of three-element-rosette was also attached to the steel plates on mid of both shear spans on both sides of the beams. Further concrete strain gages were attached to measure the concrete strains on the top compression fiber and bottom fiber at the mid span of each beam.



* All dimensions are in mm

Fig. 1. Beam detail

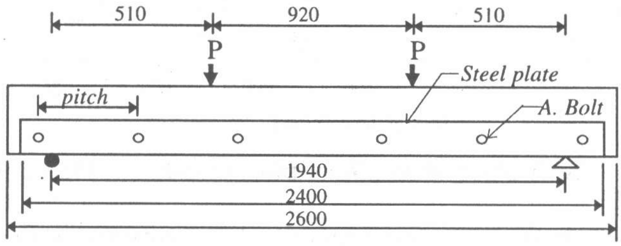


Fig. 2. Beam loading detail

3. RESULTS & DISCUSSIONS

All the tested beams failed in shear. The failure was initiated by the development of several diagonal cracks at either shear span of the beams. The formation of a large diagonal crack led to the ultimate failure accompanied with the yielding of steel plate and subsequent de-bonding. The plates debonded at concrete epoxy interface forming an outward arch. Exception was the beam A-10, which showed failure within the concrete and there was no plate de-bonding. The beams with external reinforcement failed at significantly higher loads in comparison with the control beam A-1. With reference to the control beam (without steel plate), it was seen that the increase in ultimate shear strength was as high as 84% and the average value was about 59% for all the beams. Further it was noticed that for the reinforced beams, initial cracking occurred at a higher load than that of control beam.

It was found that the provision of anchor bolts increased the shear strength of beams. Shear strengths of all the beams with anchor bolts, except the beam A-2, were higher than the strength of the beam without anchor bolt (beam A-3). **Fig. 3** shows the relationship between bolt pitch and ultimate shear strength and **Fig. 4** shows the relationship between shear strength and bolt penetration for some beams. It is evident from the figure that the bolt pitch has inverse relationship with shear strength. Maximum strength was obtained in the case of pitch equal to 185 mm. There exists an optimum depth of penetration of anchor bolt at which the shear strength becomes maximum. Simply increasing the penetration does not necessarily increase the strength. In the test, maximum strength was observed when the penetration depth was 50 mm. It was also seen that grouting the anchor bolt made the beam more stiff, but the increment in shear strength was nominal, so it can be assumed that the grouting is of not much importance as far as shear capacity is concerned. The shear taken by steel increased with the increase in thickness of the plate but providing more thicker plate might result in plate being detached because of its greater stiffness against bending. It implies that there may be a limit thickness of plate beyond which the bonding can not be done effectively.

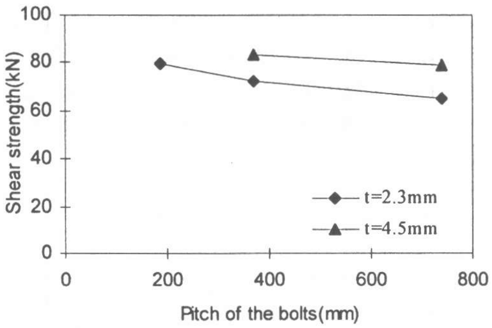


Fig. 3. Shear strength vs. pitch of bolt

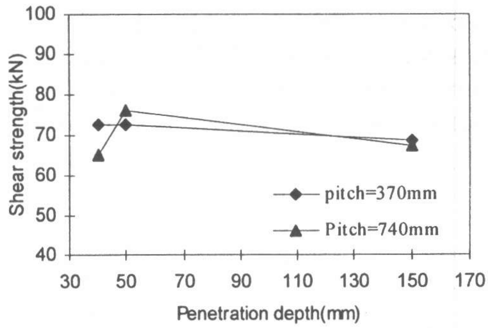


Fig. 4. Shear strength vs. bolt penetration

In the test, it was seen that when increasing the thickness from 2.3 mm to 4.5 mm and keeping all other variables constant, the increment in the ultimate shear strength was about 15% as shown in **Fig. 5**. Results of the tests are presented in **Table 2**.

Table 2. Experimental test results

Beam No.	*Concrete strength (MPa)	Diagonal cracking load (kN)	Ultimate load (kN)	Increase in ultimate load (percent)
A-1	31.3	44.2	45.2	Control beam
A-2	28.3	58.9	63.0	39.4
A-3	27.1	57.5	64.2	42.0
A-4	28.2	66.0	83.4	84.5
A-5	29.2	70.2	79.1	75.0
A-6	29.8	57.5	79.3	75.4
A-7	29.8	61.0	72.6	60.6
A-8	30.3	60.1	65.1	44.0
A-9	31.4	63.7	72.4	60.2
A-10	30.8	61.2	76.2	68.6
A-11	33.8	55.0	68.8	52.2
A-12	33.5	67.0	67.4	49.1

*Concrete strength of each beam was obtained by linear interpolation of the results of the two sets of specimens tested on the first and the last days of the experiment extended over a period of 13 days.

The load-(mid span) displacement curves are shown in **Fig. 6** for the beams with same plate thickness but with varying bolt pitch, where each successive curve is offset by an initial 2 mm displacement to facilitate the comparison. **Fig. 7** shows the load-displacement curves for beams with same bolt pitch but with different thickness of plates. Strains in longitudinal reinforcement were below the yielding point. Strains developed in the steel plates during the experiment showed that, while strain increment was slow till the first diagonal crack, post-crack strain development was rapid. Since concrete could no longer provide the resistance, steel had to contribute the additional shear resistance, resulting in a sharp increase in plate strain. **Fig. 8** shows the relationship between load and strain in steel plate at mid of shear span for some of the beams with 2.3 mm thick plates. Each successive curve in **Fig. 8** is also shifted by an initial 250 Microstrain for easy comparison. **Fig. 9** shows the cracking pattern, plate detachment and failure of the typical beam A-4.

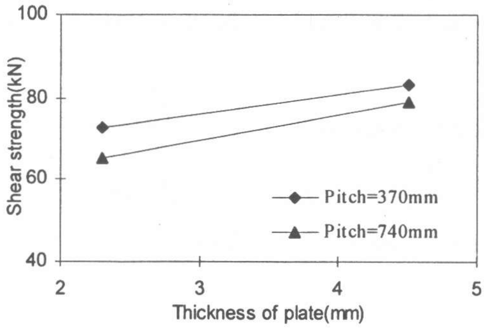


Fig. 5. Shear strength vs. thickness of plate

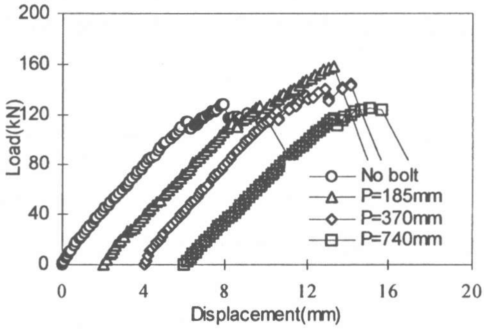


Fig. 6. Load vs. mid-span displacement

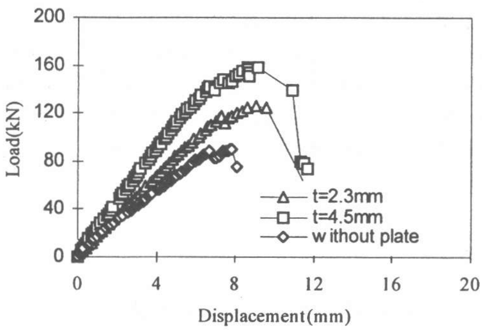


Fig. 7. Load vs. mid-span displacement

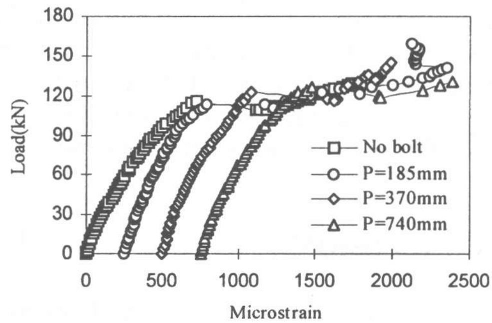


Fig. 8. Load vs. strain in steel plate

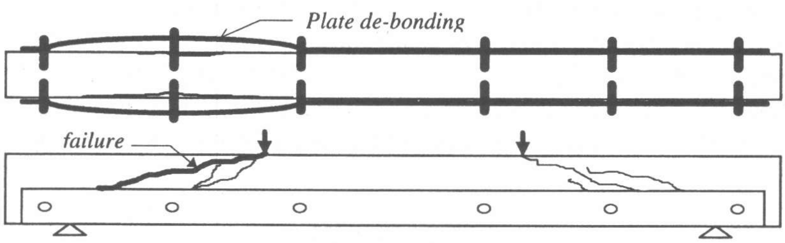


Fig. 9. Cracking and failure of the typical beam A-4

4. PREDICTION OF SHEAR STRENGTH

Shear strength of a beam without the internal shear reinforcement and failing in shear with the yielding of external steel plate, can be computed as the sum of concrete and the steel plate contributions as eq. 1. The concrete contribution (V_c) can be computed as prescribed in the current standard specification for design & construction of JSCE[4].

$$V = V_c + V_s \tag{1}$$

For the contribution of steel plate(V_s), assuming that there is a perfect bond between the concrete and steel plate and normal stress is negligible in comparison with the shear stress; the shear force taken by the steel plate of thickness t and height h at yield is given by

$V_s = \tau_y th$, where τ_y is the maximum shear stress in steel plate at yield

From the yield criterion of maximum shear stress(Tresca) under uniaxial tension, $\tau_y = \frac{f_y}{2}$, where f_y is the yield strength of steel plate. Finally V_s can be written as eq. 2,

$$V_s = 0.5 f_y th \tag{2}$$

However this expression does not take anchor bolt's influence into consideration. In the case of beam without anchor bolt (A-3), the ultimate shear strength computed using above equations is 58.65 kN. Further, the maximum shear stress in steel plate calculated from the strains obtained in the rosette placed at the mid of shear span of this beam on the failed side, is 110 MPa. The ultimate shear strength of the beam calculated using this value is 56.95 kN. Both of these values are in reasonable proximity of the test value of 64.2 kN.

5. CONCLUSIONS

From the results of the tests, it has been confirmed that the epoxy-bonded horizontal steel plates can be used as external shear reinforcement for RC beams. The plated beams showed an enhanced shear capacity as high as 84% in comparison with the beams without plate. Provision of anchor bolts resulted in an increase in the shear strength. The effects of plate thickness, anchor bolt pitch and bolt penetration on shear behavior were significant. A simple expression to estimate the steel contribution on shear strength of such plated beams is presented. However, other parameters like geometry of plating, plate height, plate material, bolt arrangement, etc., should also be covered in further study to reach to the final conclusion.

REFERENCES

1. Swamy, R. N., Jones, R. and Charif, A., "Contribution of externally bonded steel plate reinforcement to the shear resistance of reinforced concrete beams" Repair and Strengthening of Concrete Members with Adhesive Bonded Plates- SP-165 ACI, 1996, pp. 1-24
2. Sharif, A., Al-Sulaimani, G. J. and Hussain, M., "Strengthening of shear damaged RC beams by external plate bonding of steel plates", Magazine of Concrete Research, Vol. 47, No. 173, Dec. 1995, pp. 329-334
3. Mutsuyoshi, H., Aravinthan, T. and Hikimura, T., "Retrofitting of Reinforced Concrete Beams with External Tendons and Plates," Accepted paper, CONSEC'98, Tromso, Norway, June 1998
4. Japan Society of Civil Engineers, "Standard Specifications for Design & Construction of Concrete Structures (Design)," JSCE, 1989, C.L.SP-1, Part 1