論文 Experimental and FEM Study for Shear Strengthening of Reinforced Concrete Beams using Different Techniques

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ABSTRACT: Experiments for shear strengthening of reinforced concrete (RC) beams using epoxy bonded steel plates, CFRP sheets and externally anchored stirrups were carried out to assess the actual shear strength increment with such methods. All the strengthening schemes were found to be effective for shear strengthening of RC beams. An average of 72% increase in shear strength was obtained for steel plate bonded beams and at least 117% increment was obtained for beam with externally anchored stirrups. Further, a numerical analysis using finite element method (FEM) was also conducted to simulate the behavior of these strengthened beams.

KEYWORDS: CFRP sheets, epoxy resins, FEM analysis, reinforced concrete beams, shear strengthening, steel plates.

1. INTRODUCTION

Repair and rehabilitation of existing concrete structures are now one of the major activities of the construction industry. Concrete structures deteriorate due to many reasons such as corrosion of internal reinforcement, chloride attack, freeze-thaw action, etc. Further, poor initial design and construction faults also render existing concrete structure deficient. However, the most important reason for strengthening concrete structures is due to continuous upgrading of design codes. In Japan, for example, the design vehicle load for highway bridges has recently been increased from 196 kN to 245 kN. In order to maintain efficient highway networks and to keep the bridges operational and safe, strengthening and retrofitting of existing structures would be desirable if speedy, reliable, economic and simple strengthening techniques were available. Though the RC beams are generally over-designed against shear type of failure, there are many cases when RC beams have been found to be deficient in shear. Therefore shear strengthening of RC beams becomes necessary and should be considered seriously.

In a past study, Adhikary et al. [1] found that the shear strength of RC beams could be increased and ductile flexural failure could be achieved using epoxy bonded steel plates, vertical strips and externally anchored stirrups. The objective of this paper is to present the results of an experimental study conducted to assess the actual shear strength increment of RC beams with different techniques such as epoxy bonded steel plates, CFRP sheets and externally anchored stirrups. A numerical analysis using finite element method was also performed to simulate the behavior of these strengthened beams. The effectiveness of using such techniques for shear strengthening of RC beams was confirmed through both numerical and experimental results.

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2. EXPERIMENTAL PROGRAM

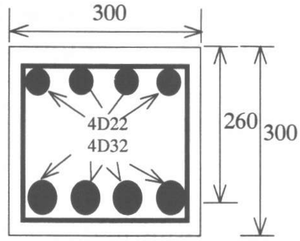

Fig. 1 Details of test beams (mm)

Total six beams were tested in this study. The cross section of all beams was 300 x 300 mm, as shown in **Fig. 1**. The length of the beams was 3500 mm. All the beams were provided with 4-D22 bars (deformed bars with diameter of 22 mm) in compression zone and 4-D32 bars (deformed bars with diameter of 32 mm) in tension zone. In all beams, no shear reinforcements were provided in the desired shear failure zone. However, 2-legged D10 (deformed bars with diameter of 10mm) stirrups were provided for mounting the longitudinal reinforcement and outside the supports to prevent anchorage failures. The average compressive strength of concrete used for tested beams was 36 MPa. **Fig. 2** shows the different shear strengthening schemes used in the experiments. Beam B-1 was kept as a control beam. The steel brackets were installed in beam B-2 to simulate the actual field structure, in RC rigid frames used in some elevated highways in Japan. The purpose of steel brackets in actual field structure is to provide additional support to the longitudinal steel girders in the event of large earthquakes. Beams B-3-1 and B-3-2 were strengthened with steel plates bonded on shear spans. In beam B-3-2, three M12 anchors bolts were used for additional anchorage of steel plates. In beam B-4, 10 mm diameter round bars were anchored at top and bottom using steel angles (L-50x50x8) so as to act as external stirrups. Beam B-5 was strengthened with U-wrapped-epoxy-bonded-single-layer CFRP sheet on shear spans. **Table 1** shows the mechanical properties of reinforcements, steel plates and CFRP sheets used in the experiment. Mechanical properties of the epoxy adhesive used in the

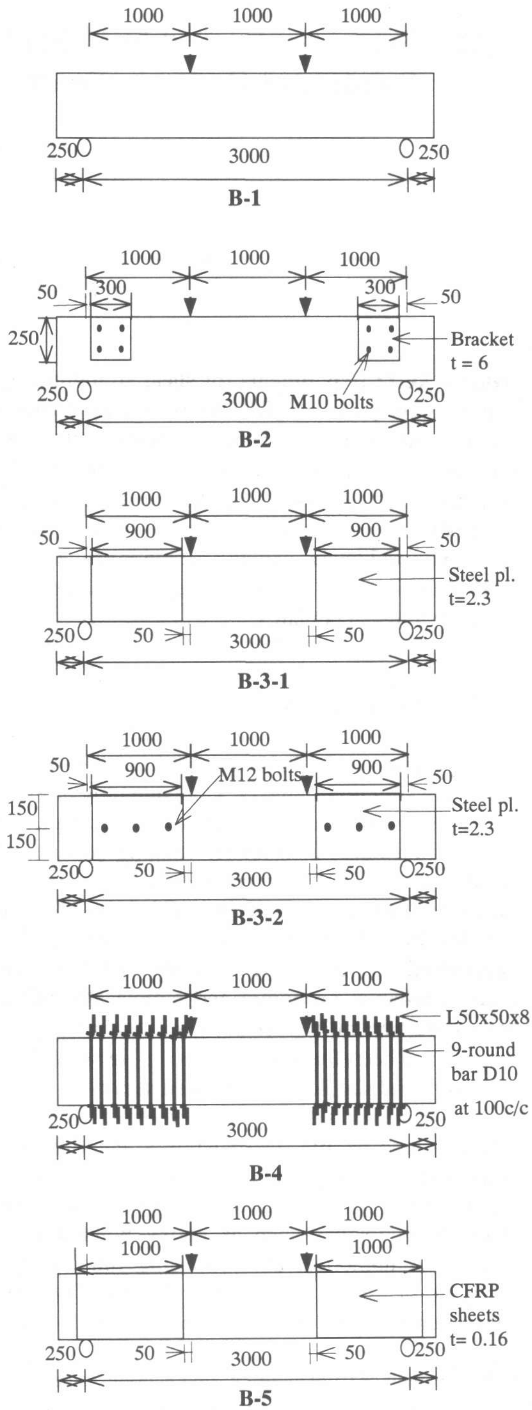

Fig. 2 Different strengthening techniques (mm)

bonding procedure are shown in **Table 2.** The shear span to effective depth ratio was constant 3.85 in all tests. All of the beams were tested under four-point loading over the span of 3000 mm. Load was applied monotonically to the test beams until failure. Crack initiation and propagation were monitored by visual inspection during testing.

Table 1. Properties of reinforcement, steel plates and CFRP sheets

Reinforcement, Steel plates, CFRP sheets	Yield strength (MPa)	Elastic modulus (GPa)
Re-bar D22	391	186
Re-bar D32	398	206
Steel Plate (t = 2.3 mm)	320	199
Steel Plate (t = 6.0 mm)	347	207
D10 round bar	450	206
CFRP sheet (t =0.16 mm)	3400	230

Table 2. Properties of the epoxy resins

Properties of epoxy resin	Value
Pot life (minutes)	60
Tensile strength (MPa)	49
Compressive strength (MPa)	72
Shear strength (MPa)	15.6
Elastic modulus (GPa)	2.13

3. RESULTS OF EXPERIMENTS AND DISCUSSION

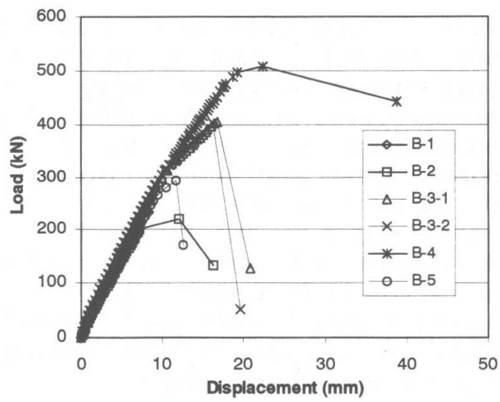

Fig. 3 Load-displacement relationship

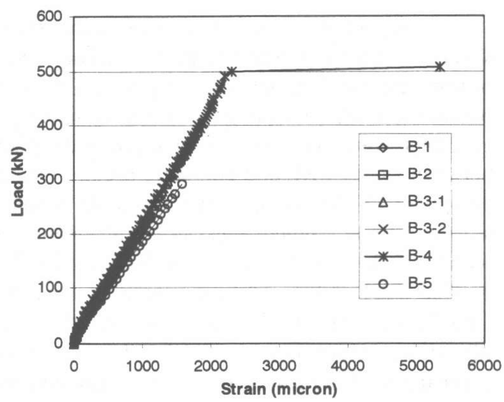

Fig. 4 Strain in longitudinal reinforcement

Fig. 3 and **Fig. 4** show the load versus mid span displacement relationships and load versus strain in longitudinal tensile reinforcement relationships for all tested beams. The control beam B-1 failed in shear due to a critical diagonal shear crack in one of the shear spans at the load of 233.6 kN. The other beams strengthened with different techniques (except beam B4) also failed in shear. The failure load of beam B-2 with steel brackets is a little lower than that of the control beam B-1. It means that the steel bracket has almost no effect in shear strengthening because most of the bracket location was out of the critical shear failure zone. Beams B-3-1 and B-3-2 with epoxy bonded steel plates failed at almost the same load level. It shows that there was no effect of additional anchors provided on beam B-3-2. However, if larger number of anchors is used, they might have significant effect on shear strengthening of RC beams. The shear strength increment was approximately 73% and 71% for beam B-3-1 and B-3-2 respectively compared with beam B-1. Beam B-4 with externally anchored stirrups failed in flexure and crushing of concrete occurred finally in the compression zone. This implies a higher or at least the same shear capacity of the beam B-4 as the observed flexural failure load. With the reference to the control beam B-1, the increase in ultimate shear strength was at least 117 % for this beam. The beam B-5 with epoxy bonded CFRP sheet failed in shear and debonding of CFRP sheet from concrete surface was observed. The increase in shear strength was approximately 26% for beam B-5.

4. FINITE ELEMENT SIMULATION

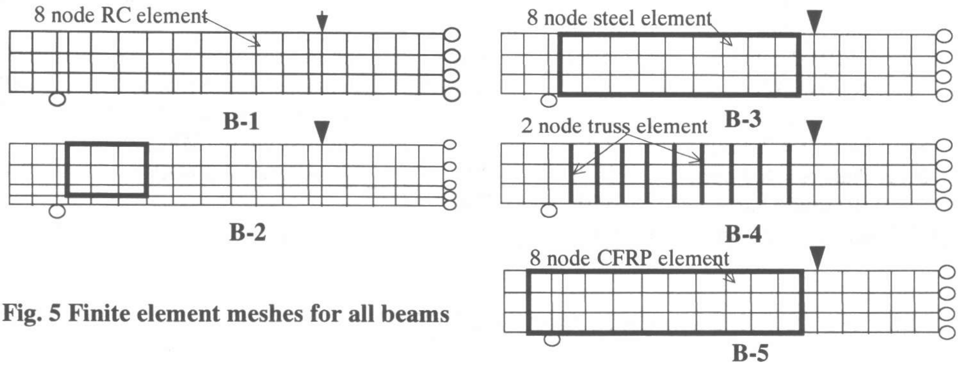

Fig. 5 Finite element meshes for all beams

To simulate the behavior of beams strengthened with epoxy bonded steel plates and CFRP sheets, a nonlinear finite element method was adopted. Due to the symmetry of geometry of the beams and loading pattern, only a half span of each beam was analyzed assuming appropriate boundary conditions along the line of symmetry. The reinforced concrete, steel plate and CFRP sheet elements were modeled using eight-node plane-stress elements. To model the epoxy interface between steel/CFRP and concrete, pseudo two-dimensional 16-node adhesive interface element was employed [2]. Two-node truss elements connected at top and bottom only were used for external stirrups. Finite element meshes for all beams are shown in **Fig. 5.** RC plate element model [3, 4] with the failure criteria following Shawky and Maekawa [5] was used for reinforced concrete. Epoxy bonded steel plates and truss elements were modeled as elasto-perfectly plastic element, whereas CFRP sheet was modeled as linearly elastic. Interface elements were also modeled as linearly elastic till failure, which is governed by the maximum-effective-strength criteria [2]. **Table 3** shows the comparison of the results between the test and the FEM analysis for all the tested beams.

Table 3. Results from experiment and analysis

Beam No.	Strengthening scheme	Exp. failure load (kN) / mode	Ana. failure load (kN) /mode	Ratio Ana./Exp.
B-1	Control beam	233.6 / shear	234.6 / shear	1.0
B-2	Steel brackets	220.5 / shear	274.2 / shear	1.24
B-3-1	Steel plates (without anchors)	405.5 / shear	416.9 / shear	1.03
B-3-2	Steel plates (with anchors)	400.6 / shear	416.9 / shear	1.04
B-4	Externally anchored stirrups	507.6 / flexure	483.5 / shear	0.95
B-5	CFRP sheets	293.2 / shear	341.0 / shear	1.16

Numerical failure modes, ultimate failure loads and the load-displacement relationships obtained from the analysis were compared with the experimental results. In the FEM analysis, all the beams failed in shear and failure elements were located in the center of shear span as the same as observation in the experiment (except beam B4). In the test, beam B4 failed in flexure at a little higher load than that of analysis because some initial pre-stress forces were applied in the external stirrups. In the FEM analysis, however, the initial pre-stress was not considered. The results of ultimate failure load show good agreement between experiment and analysis for most of the beams, especially for the control beam as well as the beams with bonded steel plates and externally anchored stirrups (within the 5% range of test values). The comparison of the load-displacement relationships between experiment and analysis for some selected beams are shown in **Fig. 6** (for the control beam B-1), **Fig. 7** (for beam with epoxy bonded steel plates), **Fig. 8** (for beam with externally anchored stirrups) and **Fig. 9** (for beam with epoxy bonded CFRP sheets). These figures show good agreement between the numerical and experimental curves.

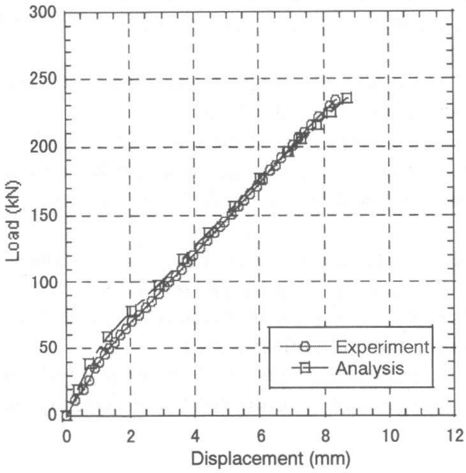

Fig. 6 Load-displacement relationship (Beam B-1)

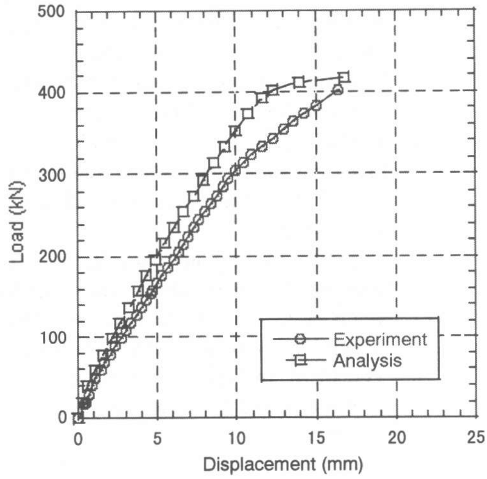

Fig. 7 Load-displacement relationship (Beam B-3-2)

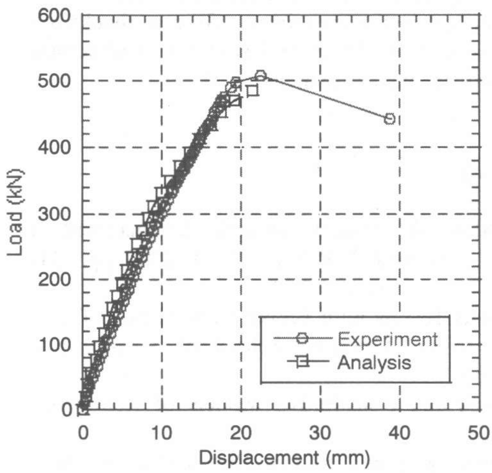

Fig. 8 Load-displacement relationship (Beam B-4)

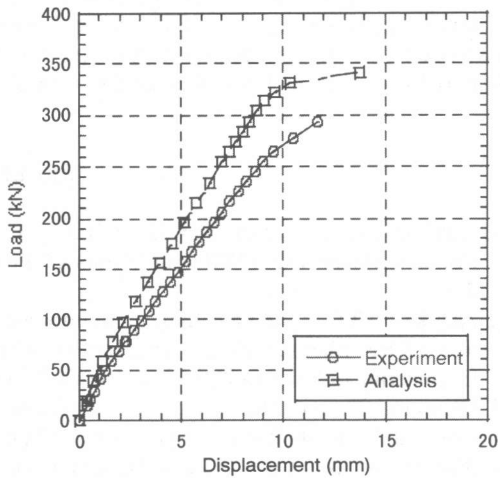

Fig. 9 Load-displacement relationship (Beam B-5)

5. CONCLUSIONS

Experimental and numerical studies were conducted for shear strengthening of RC beams with epoxy bonded steel plates, CFRP sheets and externally anchored stirrups. From the results of experiments and the FEM analysis, the following conclusions can be drawn.

1. It is confirmed that the steel plates and CFRP sheets epoxy bonded on beam's shear spans are effective for shear strength enhancement of RC beams. An average 72% increase in shear strength was obtained for the beam with epoxy bonded steel plates. However, only 26% increase in shear strength was obtained for the beam with U-wrapped-epoxy-bonded CFRP sheets, which might be due to the debonding of CFRP sheets from concrete surface.
2. The steel bracket has almost no effect for shear strengthening of RC beams because much of the bracket location was out of the critical shear failure zone.
3. In shear strengthening technique using steel plates bonded on shear span, if the bonding layer between steel plates and concrete is well prepared, the additional anchors have almost no effect. However, if large number of anchors is used, the effect can be substantial.
4. The maximum load capacity was obtained for beam B-4 with externally anchored stirrups. This particular beam failed at a load almost 117% of the failure load of control beam B-1. Thus, it is confirmed that this method is the most effective one for shear strengthening of RC beams among the methods studied in this research.
5. The FEM analysis presented herein was able to predict the ultimate shear strength as well as overall behavior of the RC beams strengthened with different techniques quite satisfactorily.

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