Strengthening of Deep Beam with Openings Using Steel Plates

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Abstract - *Reinforced concrete deep beams have many useful applications in building structures such as transfer girder, wall footing, foundation pile caps, floor diaphragms etc. For reinforced concrete beams with the same shear and flexural reinforcements, shear failure is most likely to occur in deep beams rather than in regular beam. Thus, retrofitting of deep beams with shear deficiencies is of great importance. This study aimed at examining the potential use of strengthening reinforced concrete (RC) deep beams that had web openings by steel plates. Experiments were conducted to test 8 deep beams under point loading with horizontal rectangular openings. Every tested beam had a cross section of 100 mm x 350 mm and a total length of 700 mm. Two openings, one in each shear span, were placed symmetrically about the midpoint of the inclined compressive strut. Test included using strengthening steel plates of 10 mm. Constructing horizontal rectangular openings led to decrease ultimate shear capacity about 7.68% in comparison with the reference solid beam. While strengthening those openings via steel plates was found very effective in upgrading the RC deep beam shear strength. The strength gained in beams that had strengthened, horizontal rectangular openings was about 9.68% in comparison with the unstrengthened openings. Furthermore, adding studs to the strengthening plates caused a strengthening gain 15% in comparison with the unstrengthened openings.*

***Key Words*: Deep beams, openings, strengthening, steel plate, stud connector.**

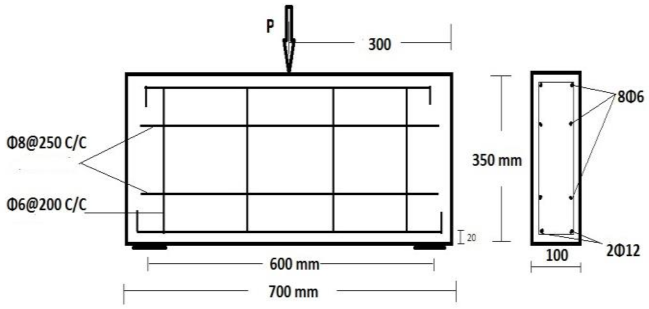
1.INTRODUCTION

According to the Indian Standard Code IS: 456-2000, beam is considered deep, when the ratio of effective span to overall depth (l/D) is less than 2.0 for simply supported members and 2.5 for continuous members. For the previous time, the deep beams have been designed according to the slender beam semi-empirical methods. Nevertheless, some analytical reports and experimental results have specified that internal forces redistribution before failure, internal force mechanisms and shear strength in deep beams are totally different from those occurred in slender beams. Openings are mainly constructed in deep beams to facilitate air conditioning, conduits, computer network cables and electricity. The shear capacity will be reduced If an opening interrupts the natural loading path that joins the loading and supporting points [2, 3]. There is no obvious design procedure for deep beams that have openings regardless of the important effects of these openings on the deep beam structural behavior. Many researchers have studied the different main parameters involved such as cross sectional properties, shear span-to-depth ratio, web reinforcement amount, and opening location, shape and size in addition to concrete strength [4-6]. [7] Tested 32 deep beam specimens that had rectangular openings. The specimens had different sizes of the opening, different concrete strengths, and the shear span-to-depth ratio ranged between 1 and 0.5. The authors concluded that the effect of concrete compressive strength significantly decreased in deep beams with openings in comparison with solid reference beams. [9] Investigated new shear strengthening technique, designated as Embedded through Section (ETS) technique, has been developed to retrofit existing reinforced concrete elements. In this technique the bars of steel or Fibre Reinforced Polymer (FRP) material are introduced into the beam section through the drilled holes and bonded with the adhesive to surrounded concrete. The ETS shear strengthened deep beams have 23.84% to 67.69% increase in load carrying capacity when strengthened with 8mm,10mm and 12mm ETS bars with L/4 and L/6 spacing, compared to the un strengthened deep beam Up to 17.69% increase in ultimate load is found when the diameter of ETS bars increased from 8mm to 12mm. [10] have stated in their research, nine simply supported reinforced concrete deep beams with large web openings strengthened by using external post – tensioning strands have been cast and tested up to failure under one-point load. These beams were divided into three groups according to strengthening schemes by using external strands. Each of these groups consisted of three beams having different opening ratios (0.4, 0.6 and 0.8). The results show that increasing openings ratio caused a decreasing in first cracking and ultimate loads and increasing in mid span deflection for all beams. While, for same openings ratio, the strengthening using horizontal post – tensioning strands scheme was more effective than using vertical strengthening scheme in increasing the first cracking and ultimate load capacities and reducing the deflection [11] have analyzed (RC) deep beams that had web openings by 6mm steel plates. Experiments were conducted to test thirteen deep beams under two point loading with square, circular, horizontal and vertical rectangular openings. Every tested beam had a cross section of 100 mm x 400 mm and a total length of 1000 mm. Constructing square, circular, horizontal and vertical rectangular openings led to decrease ultimate capacity about 20.5 %, 18.3%, 24.7 % and 31.7%, respectively in comparison with the reference solid beam. The strength gained in beams that had strengthened square, circular, horizontal and vertical rectangular openings was about 9.3%, 13.2%, 8.8% & 11.88%, respectively in comparison with the unstrengthened openings. From literature no experimental data exist of use 10 mm steel plate so this experimental study is focuses on the investigation of the effect of 10 mm steel plate in strengthening RC deep beam with 90*70 mm horizontal opening located in shear zone. Its aim is to present experimental evidences that would help researchers and practicing engineers to better understand the interrelationship between the effect of strengthening the openings via steel plates and the strength besides failure mode of RC deep beams.

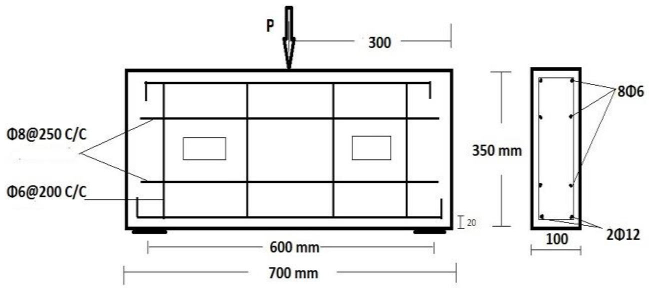
1.1 EXPERIMENTAL WORK

Test Specimen :

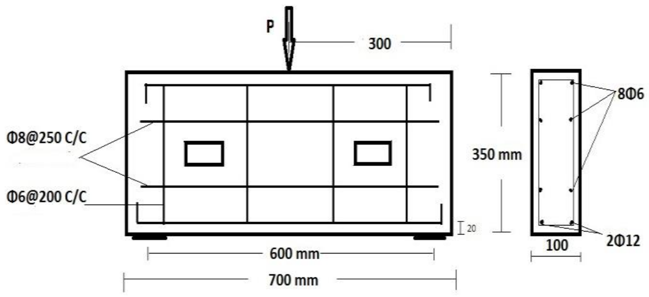
Test specimens are shown in (Figure a) in which all dimensions are in (mm). The specimens had an effective span of 700 mm resulting in an ln/h ratio (span to depth ratio) of 1.71. All beams were tested under a/d of 0.85 in order to ensure that deep beam action will develop. The beams were designed to fail in shear before any flexural distress. Two 12 mm deformed steel bars of fy= 500 MPa were provided as tension reinforcement. Two 6mm deformed steel bars with fy= 500 MPa were provided as compression steel reinforcement. 6mm deformed bars spaced vertically at 200mm and also spaced at 250mm horizontally were provided for the web reinforcement. The horizontal web reinforcement was longitudinal bars at both sides of the beam whereas the vertical web reinforcement was in a form of stirrups. At top and bottom faces of the beam, a clear cover of 20 mm was maintained. Reinforcement cages were first placed in the molds together with plywood boxes that served as the formwork for creating the openings. The beam specimens demolded the next day and cured for 28 days. The 28-day self-compacted concrete compressive strength was 40 MPa. Three 150mm x 300mm concrete cylinders were cast with the beams to determine the compressive strength. The steel plates used to strengthen the openings were 10mm in thickness Steel plates are welded to form steel frame box.



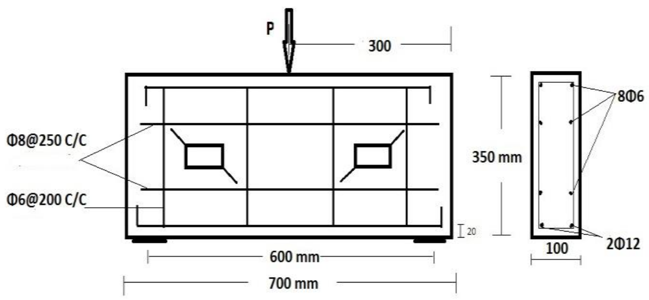
a) REF, solid deep beam (reference, i.e. no openings)



b) HR, beam with unstrengthened horizontal rectangular openings



c) HR.P, beam with horizontal rectangular openings strengthened via steel plates



d) HR.P.N, beam with horizontal rectangular openings strengthened via plates and studs

e) Steel Reinforcement

f) Specimens of Deep beam after 28 days curing

g) Wooden prism used to make openings

h) Welded Steel Frame Box of Steel Plates

i) Steel Frame Box with Welded Steel Bars (Studs)

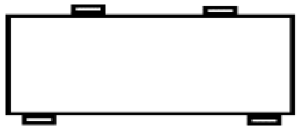
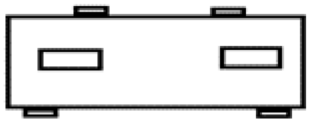
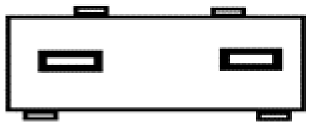
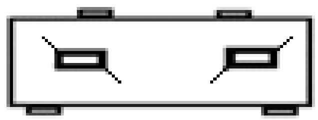
j) Wooden box for casting deep Beam

1.2 Test Set up

The deep beams were tested using an academic testing machine of 400 kN maximum capacity with an effective span of 600 mm. Deep beams with shear span of 300 mm were tested to failure in Three-point loading system. The corresponding beam deflection was measured in UTM using sensors. 100mm x 100mm bearing plates were placed at the supports and under the loading points. In the current study, the loading technique under displacement control has been adopted. 0.1 mm/sec displacement (load increment of 2.5 kN/sec) was applied until failure. The propagation and development of cracks were marked and the mode of failure was recognized.

k) Test set up for deep beam specimens

1Test Matrix

Specimen designation	Number	Shape	Dimensions (mm)	Area (mm2)	ob / a	oh / h	Existing of steel plates	Existing of Stud	Sketch
REF	2								
HR	2	rectangular	90*70	6300	25%	20%			
HR.P	2	rectangular	90*70	6300	25%	20%	Yes		
HR.P.N	2	rectangular	90*70	6300	25%	20%	Yes	Yes	

2. Experimental Results and Discussions

Cracking Behavior and failure mode

The reference beam, unstrengthened and strengthened beam i.e. all tested deep beam specimens failed due to concrete strut failure or due to diagonal cracking. The load was periodically paused in order to observe cracks during the testing. The load at which first cracks appeared was obtained by visual inspection. Generally, at about 46 % of the ultimate load, the first diagonal cracks appeared in the B-region of the solid reference deep beam. The reference solid beam ultimately failed at the concrete compressive struts joining the loading and supporting points. In deep beam specimens with unstrengthened openings, the first diagonal cracks appeared in the range of 31% of the ultimate load near the top and bottom corners of the openings. These diagonal cracks progressively developed towards the loading and supporting points. For deep beams with strengthened openings via steel plates and stud connectors, the first diagonal cracks appeared in the corners of openings at 39% of the ultimate load through incremental loads. These initial cracks extended in both directions towards the support and load regions. It was worth to observe that the cracks were tended around the openings because of steel plate existence. They were many and propagated similar to those of solid reference deep beam. The reference beam REF and other specimens all failed in shear as expected. The beam test results are tabulated in table 2. Result shows that steel plates effective way of strengthening deep beam.

l) REF beam after testing

n) HRP beam after Testing

m) HR Beam after testing

o) HRPN beam after testing

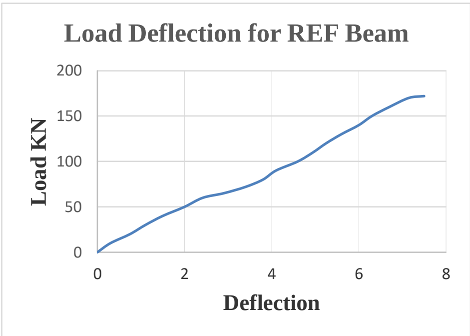
2) Experimental Result and failure mode

Beam designation	First visual shear crack $P_{cr\text{-}diagonal}$ (kN) (kN)	P_{exp} (kN)	$P_{cr\text{-}diagonal} / P_{exp}$	$\Delta_{cr\text{-}diagonal}$ (mm)	Δ_f (mm)	$\Delta_{cr\text{-}diagonal} / \Delta_f$	decrease in P_{exp} (%)*	decrease in Δ_f (%)*	Failure mode
REF	81	172.4	0.46	3.5	7.6	0.33	-	-	Diagonal Splitting
HR	51.2	160.1	0.31	3	6.5	0.29	7.13	15.38	Diagonal Splitting
HR.P	61.4	175.6	0.34	2.8	7.9	0.24	-2	-5.1	Diagonal splitting + Diagonal compression
HR.P.N	71.8	184.2	0.39	2.6	8.5	0.22	-6.4	-11.8	Diagonal splitting+ Diagonal compression

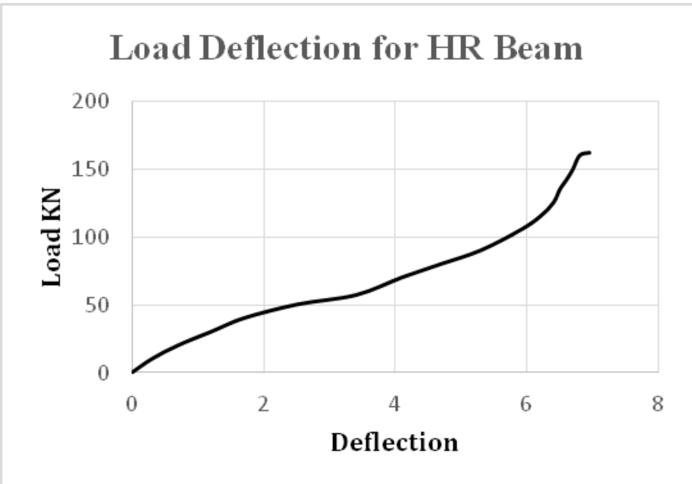
1 Pcr-diagonal =load at first shear crack, Pexp=ultimate shear strength, Δcr- Diagonal crack width, Δf= max midspan deflection, *compared with REF

2.1. Load Deflection Response

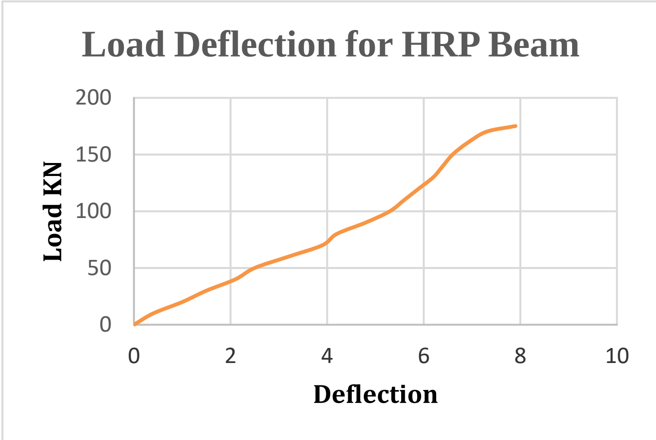
(Figures) shows the load versus midspan deflection curves. In all specimens, the load deflection curve was roughly linear at the first steps of the loading till the appearance of the first diagonal cracks for deep beams with openings. After that, the curves started to bend slightly. The presence of unstrengthened openings decreased the midspan deflection by 14.47 % for HR specimens, as compared with REF beam. When these openings strengthened via 10 mm steel plates, and as compared with the unstrengthened ones, the stiffness of these beams increased. Deflection for HR.P, compared with REF beam is comparable (3.94%). When stud connectors were added to the steel plates, deflection increases 11.84% for HR.P.N specimens as compared with REF beam.



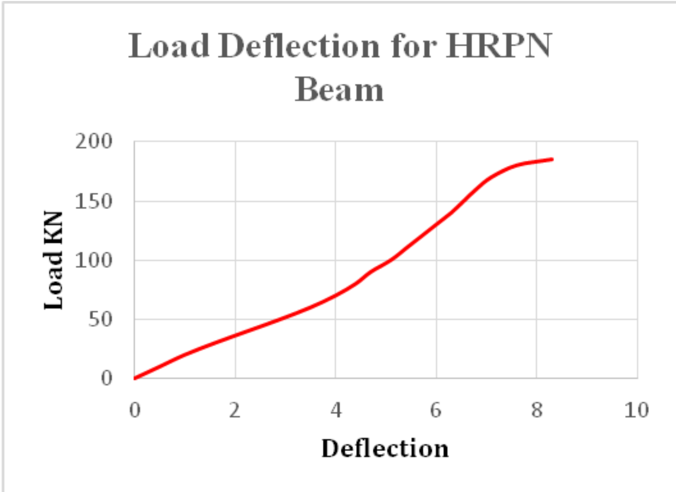
p) Load deflection for REF Beam



q) Load deflection for HR Beam



r) Load deflection for HRP beam



s) Load Deflection for HRPN beam

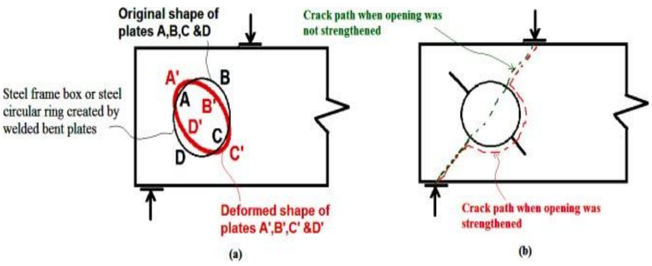
2.2. Shear Strength

The results obtained from the experimental values of load versus deflection response . The presence of openings in this path weakened the ultimate strength of these beams by 7.13% for HR deep beams, as compared with REF beam. This was clear when the main shear crack permeated the openings directly, looked for the shortest and easiest way. Using steel plates inside the openings led to compensate a large part of the removed concrete because of the opening existence on one hand. Steel frame box created by welded bent plates was under compression and confinement of the surrounding concrete. On the other hand, this steel frame box the main shear crack to change its path to make it around the opening (not through the opening) as shown in Figure which elongates its path. That is why; the ultimate strength became comparable for HR.P deep beam as compared with REF beam. In addition to the strengthening of steel plates, studs were added to plates in perpendicular direction to the main shear crack to intercept this shear crack so that they contributed effectively to the beam ultimate shear strength as pure shear reinforcement as shown in Figure. Therefore, the ultimate strength increases 6.84% for HR.P.N beam as compared with REF beam.

The authors believe that the influence of steel plates in improvement in beam ultimate capacity that had strengthened openings was attributed to the following observed facts:

1- Due to the application of load, the points B & D would try to move in the positions B' & D' as shown in Figure. Because of this change of plates shape, points A & C would simply try to move to positions A' & C'. Since the opening was surrounded by concrete, the displacement of A' & C' would be resisted by the concrete which would give much strength to the opening.

2- Contribution to the strength of the beam is due to the length of main inclined shear cracks. It was observed that the length of these cracks had considerably increased in the case of using plates, passing around the plates. Without plates, the crack would propagate through the opening as shown in Figure



3. CONCLUSIONS

1. The failures occur in a brittle manner with a sharp, explosive fracture. Strengths were increased Deflections in the beam were reduced compared to the unstrengthen beam and the beam stiffness was increased. Deep beam behavior depends primarily on the interruption of the inclined compressive strut. Further to that, the four sharp corners in the rectangular opening were subjected to high stress concentration that led to cracking and failure.
2. Strengthening the openings by steel plates gave increase in ultimate shear strength of the beams that have openings by 9.68% as compared with the unstrengthened beam. In strengthened beams, the sudden failure also took place by a development of two main diagonal shear cracks in the regions below and above the openings. In this case the main diagonal shear cracks have not passed through the openings, but around them. Furthermore, the steel frame box formed by steel welded bent plates was under compression and confinement of the surrounding concrete that compensated a large part of the removed concrete caused by the opening existence in additional to elongating the main inclined shear crack.
3. Steel plates with welded bars (stud connectors) gave an increase in the deep beams shear strength by 15% compared with the unstrengthened beam. This increase in ultimate shear strength caused by studs that intercepted the path of the inclined main shear crack. Due to increase in length of studs in addition to the steel frame box which provide wider interception, the shear strength increases.

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