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Shear Behaviour of RC Deep Beams with Openings Strengthened with Carbon Fiber Reinforced Polymer

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***Abstract*—**Construction industry is making progress at a high pace. The trend of the world is getting more biased towards the high rise buildings. Deep beams are one of the most common elements in modern construction having small span to depth ratio. Deep beams are mostly used as transfer girders. This experimental study consists of 16 reinforced concrete (RC) deep beams. These beams were divided into two groups; A and B. Groups A and B consist of eight beams each, having 381 mm (15 in) and 457 mm (18 in) depth respectively. Each group was further subdivided into four sub groups each consisting of two identical beams. Each subgroup was comprised of solid/control beam (without opening), opening above neutral axis (NA), at NA and below NA. Except for control beams, all beams with openings were strengthened with carbon fibre reinforced polymer (CFRP) vertical strips. These eight groups differ from each other based on depth and location of openings. For testing sake, all beams have been loaded with two symmetrical point loads. All beams have been designed based on strut and tie model concept. The outcome of experimental investigation elaborates the difference in the shear behaviour of deep beams based on depth and location of circular openings variation. 457 mm (18 in) deep beam with openings above NA show the highest strength and 381 mm (15 in) deep beam with openings below NA show the least strength. CFRP sheets played a vital role in increasing the shear capacity of beams.

***Keywords*—**CFRP, deep beams, openings in deep beams, strut and tie model, shear behaviour.

I. Introduction

In the construction of high rise buildings, provision of utilities e.g. water, gas and electricity requires a significant number of pipes. These pipes obviously need space to pass through. Hence, these pipes usually pass below the soffit of beams which creates a "dead space". In the case of low rise building, this space may not have substantial effects. On the other hand in case of high rise buildings number of storeys times the height of dead space will increase the height of the building. Consequently, this unused space has an impact on overall cost of the structure. To overcome this problem, engineers have to introduce openings within the beam cross-section. These openings vary in size and shape depending upon the utility ducts [1]

In the modern world most of the high rise buildings have complex architectural requirements such as column free atriums which are quite common these days, require alternative methods to achieve such huge spans. When beam spans more than 9m, deflection of the beam becomes the controlling parameter for its design. Alternative options for such beams are composite beams, plate girders, steel trusses, post-tensioning, prestressing, deep beams, etc.

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Deep beams are structural members which transfer the loads to supports as simply supported beams and the load is transferred through the compression action [2]. ACI 318-14 states two definitions of the deep beam. i) Clear span to depth ratio is less than or equal to four times of beam depth, ii) regions with concentrated loads lies within twice the member depth from the face of the support [2], [3]. Numerous experimental studies have been carried out to analyse the behaviour of the deep beam. Most of which concludes that in deep beams, failure is mostly controlled by its sheer capacity [1], [4]. Hence, shear strength has an ample importance in deep beams. Shear behaviour of deep beams is still considered as very complex phenomena. The opinion of researchers regarding the relation between deep beam size and its shear behaviour is still inconsistent [4]. Therefore, the existing theories, which address the behaviour of slender beams, are not applicable to the deep beams. Hence deep beam is considered as non-flexural region comprises of nonlinear deformation strains [4]. In the case of deep beams, plane sections do not remain plane after concrete cracks. Hence elastic bending moment theory does not remain applicable. A nonlinear approach should be used to understand the behaviour of deep beams after it cracks completely. In deep beams load has been transferred to the supports through the concrete struts due to the formation of arch action, hence, results in high shear strength. The reinforcement acts as a tie. Hence deep beams are analogous to steel trusses. In strut and tie model elements with complex geometries are replaced by suitable simple truss model [4]

Several types of research have been carried out to understand the actual behaviour of deep beams and size effect [4]. Due to complex behaviour and deformed geometry of deep beams, still the existing information is considered as insufficient, and doors to the further unknown behaviour are required to be open.

In deep beams, the shear action is the cause which generates a disturbance in internal stresses. During the shear action, compression is generated in one direction and tension in the perpendicular direction. As the beam depth increases, the shear action phenomena result in the sudden shear failure [3]. The propagation of cracks in large size deep beams is much fast than the small deep beams, and they show a brittle failure [5].

Several modifications have been introduced in the design guidance stated in ACI 318-14 and IS 456-2000 by considering the contribution of concrete strength, the percentage of transverse and longitudinal reinforcement, span to depth for calculating the shear behaviour of deep beams. Contrary to American and Indian codes, British standard does not give any guidance regarding the design of deep beams. However, it explicitly states that for the design of deep beams specialist literature should be referred [4].

Failure of the deep beam is generally due to the crushing of concrete in either reduced region of compression near the support or fails directly along the shear crack. Khaldoun and Khaled (2000) has researched deep beams having span to depth ratio 2.5 and concluded that there seems to be some reserve strength in the post-cracking region, results in relatively less brittle behaviour [6]. Ashour and Morley (1996) carried out extensive research on continuous RC deep beams to understand their behaviour, based on an upper bound mechanism. Span to depth ratio of the beam has a significant effect on load carrying capacity due to the horizontal and vertical web reinforcement. The effectiveness of horizontal shear reinforcement in deep beams is much higher than vertical shear reinforcement [7]. Ashour(2000) reported an analysis of shear mechanism in simply supported RC deep beams. Concrete and steel reinforcement were modelled as rigid perfectly plastic materials. The failure modes were idealised as an assemblage of rigid blocks separated by failure zones of displacement discontinuity. The shear strength of deep beams was derived as a function of the location of the instantaneous centre of relative rotation of moving blocks [8].

Tang and Tan (2004) has suggested a new approach which accounts for the effect of transverse stress on the load carrying capacity of the diagonal struts based on the lower bound strut and tie model concept. This approach considered the interaction of two failure modes first diagonal tensile splitting and second diagonal crushing of concrete due to compression [9]. Russo et al. (2005) presented an expression that explains the shear strength of deep beams using strut and tie model. Diagonal concrete strut, longitudinal reinforcement, vertical stirrups and horizontal web reinforcement play their role in the shear strength of the deep beam [10]. Bakir et al. (2004) regarding the design of short deep beams suggested the strut and tie model as a reliable approach. This model well addresses the behaviour of structural elements with discontinuity regions such as concentrated loads, bends, openings, etc. Strut and tie model is based on three separate mechanisms; concrete strut mechanism, truss mechanism which takes into account of stirrups and horizontal shear reinforcement third is nodal zone mechanism [5].

Nair et al. (2015) have researched deep beams with openings (square and circular) designed by following the strut and tie model design. Corresponding beams were modelled in software ANSYS 14 to predict the behaviour of deep beams by using finite element analysis. Experimental results showed that strut and tie model was a conservative approach to design such special geometry beams. Beams with circular openings showed more shear strength as compared to beams with square openings [11].

Transverse openings can be of any shape and size, but most common openings are square and circular [1]. Prentza (1968) has carried out an extensive research by introducing circular, diamond, square, rectangular and even irregular shapes [12].

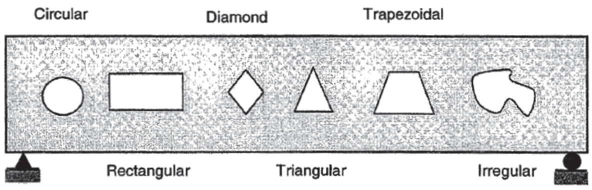

Fig. 1 Opening Shapes considered by Prentzas (1968) [12]

There is no clear definition regarding the size of openings. Many researchers use the term small and large openings without any demarcation. Mansur and Hasnat(1979) have defined circular, square or nearly square as small openings [13]. Somes and Corley (1974) defined if the circular opening has diameter exceeds 0.25 times the depth of deep beams then such openings are considered as large openings [14]. The introduction of transverse openings in deep beams results in further increase in complexity to understand the behaviour of deep beams.

There are two major types of openings which construction industry personnel encounter; pre-planned and post-planned openings [15]. The openings in which parameters such as shape, size, orientation, etc. are well known during design stage are referred to as pre-planned openings. Thus, the design of internal strengthening around the opening is addressed during the design stage [16], [17]. In the case of post-planned openings, existing structural elements such as beams require drilling of openings, to accommodate the new or existing services which are being relocated having clashed with the existing beam. These openings have a significant effect on the structural capacity of existing member. To address such situations, strengthening material such as a fibre reinforced polymer (FRP) is used to strengthen the beams externally. This method can be utilised for the strengthening of deep beams and other such structural members which are affected during the drilling process. The most commonly used strengthening material for external treatment, which is highly recommended by industry personnel and research community due to its excellent characteristics such as ultra high tensile strength, light-weightiness, resistance to corrosion and easy application on site with fewer constructability issues is CFRP [18].

Many research studies have been carried out in last five decades to understand the true behaviour of deep beams. Due to its deformed geometry and complex load transfer path behaviour, current information available is still deemed to be insufficient. The results observed by different researchers after varying the parameters of deep beams are still inconsistent. Further, the guidance related to the use of CFRP on deep beams is still quite limited.

To further understand the behaviour of deep beams with opening and strengthening with CFPR, an experimental programme has been carried out on 16 deep beams. The major objective of this experimental study is to investigate the effect of depth variation and openings in the web of deep beams on its shear strength, the effectiveness of strut and tie model in the design of RC beam, the effect of CFRP on shear behaviour of deep beams. In addition to this comparison of experimental and theoretical results has been carried out.

The novelty of this experimental study is to explore the behaviour of deep beams with different locations of the circular opening along with the vertical strips of CFRP on both sides of openings and both beam faces. The experimental result shows the most recommended location of the opening is above the NA. Use of vertical CFRP strips shows a drastic increase in strength of the deep beam. CFRP plays its role in prolonging the propagation of crack hence saves the deep beam from sudden shear failure.

II. Experimental Programme

The research programme comprises of sixteen deep beams which were divided into two main groups, **Group A** and **B**. Depth of Group A and B beams were **381mm (15in)** and **457mm (18in)** respectively. These two major groups were further divided into eight subgroups G1 to G8 each comprise of two beams for reproducibility. The first subgroup of each major group consists of control beams without any opening to compare results. Circular opening of 76mm (3in) diameter was introduced in remaining six groups by varying the location along the height (above, at and below NA). For the sake of strengthening, beams with openings were laminated with 76mm (3in) wide CFRP vertical strips by using epoxy adhesive along both sides of the openings shown in Fig. 3. The size of beams, span lengths and loading patterns has been selected to fulfil the requirements of deep beams.

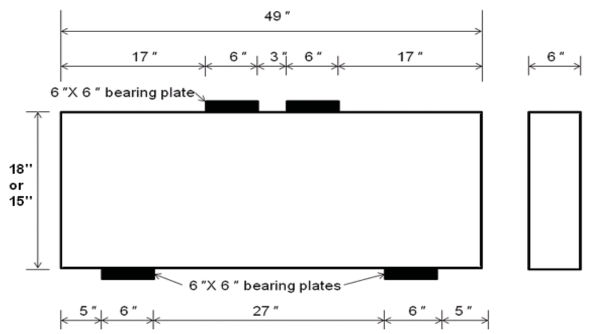

Fig. 2 Details of the sizes of beam specimens, bearing plates, loading pattern and span lengths for the test

The beams were analysed and designed for the assumed load value of 133kN (30kips) (factored load) for each point load. The compressive strength of concrete was 20MPa (3000psi), and tensile strength of reinforcement was 415MPa (60000psi). For the sake of reinforcement 2H20 (2#6) and 2H16 (2#5) diameter steel bars were provided as tension reinforcement for 381mm (15in) and 457mm (18in) deep beams respectively. 2H10 (2#3) steel bars were acting as compression reinforcement in all beams as shown in Fig. 5 and 6 respectively. To keep the horizontal bars in position three vertical stirrups were provided for beams of each group. Longitudinal reinforcement was hooked to 90 degrees after passing through the support region to provide sufficient anchorage. The thickness of clear cover to steel reinforcement was kept not less than 38mm (1.5in) at the top and bottom and 25mm (1in) on both sides in the 152mm (6in) width of all beams. For the sake of openings PVC pipes having diameter 76mm (3in) were placed in reinforcement cage before concrete casting.

Fig. 3 Steel skeletons for beam specimens

Normal strength concrete was produced by using cement, sand and aggregates with a mix ratio of 1:2:4. The electric vibrator was used during the casting of beams to avoid the defects of concrete such as honey combing. Sixteen cylinders were also prepared for testing the compressive strength of concrete after 7 and 28days of curing. For the sake of concrete batch mixing and curing potable water was used, to meet quality control criteria. As the testing was carried out in the laboratory, instead of using conventional wooden formwork, steel moulds shown in Fig. 4 were utilized for the casting of beams. Steel moulds were removed after 24 hours. Beams were cured for 28days to achieve full strength. Beams were dumped into the clean sand for the curing after 24 hours. To avoid excessive evaporation of moisture from the beam surface water was sprinkled after every 3 hours interval. For the sake of deep observation of crack pattern and crack width measurement, all the beams were white washed with the square grid was drawn on their front and back face as shown in Fig. 5.

Fig. 4 Compaction of concrete in moulds with vibrator

The beam specimens were tested under the application of symmetric point loads acting at the centre line of two bearing plates using the hydraulic load cell system. The loads were gradually increased, and cracks developed in the beams were closely observed. Beam deflections were also recorded against the corresponding load. All beams were considered as simply supported and each beam was assumed to carry, two point loads acting at a distance of 305mm (12in) from the centre of either supports.

Fig. 5 Loading arrangement for beam testing

III. Results and Discussions

All beam specimens were tested by the application of static monotonic loads and their responses noted in the form of development of cracks, beam deflection at midspan, strains at failure, shear and ultimate capacities were monitored and carefully recorded at the concrete laboratory of Civil and Environmental engineering department University of Engineering and Technology Taxila Pakistan. Beams having CFRP on them have strain gauges at the surface of CFRP, and one beam of each group has embedded strain gauge to measure the strains inside the beam. These strains were measured by two instruments P3 strain measurement device and Micro Measurement strain measuring device.

It was observed that depth of the deep beam has a significant effect on its shear behaviour. As the depth of beam increases its shear strength also increases and its failure becomes more brittle. Beam type failure and frame type failures were observed during testing.

Both control beams of G-A1 and G-B1 (without openings) each failed in the shear mode as was designed. Minor crack lines started to appear in the tension zone of deep beam soon after the increment of load using a load cell. These minor cracks changed into significant flexural cracks and penetrated up-to the NA of the beam. Following the formation of diagonal tension cracks increase in flexural cracks were also observed.

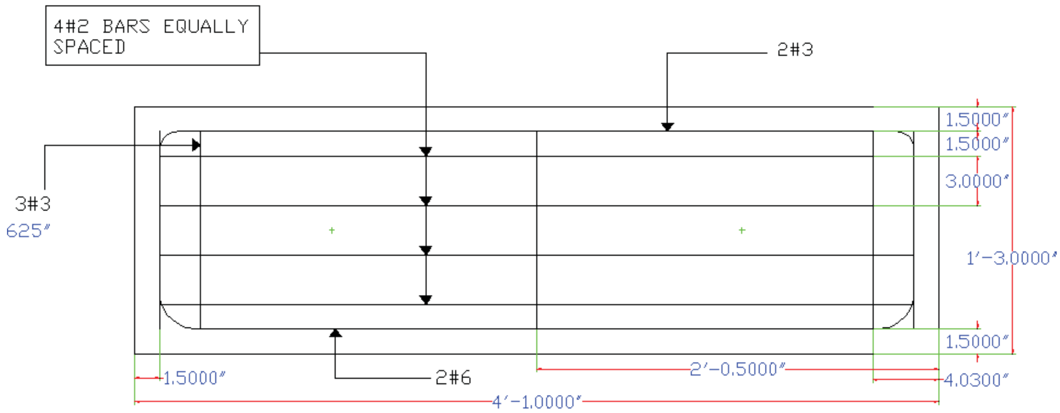

Fig. 6 Reinforcement details of 381mm (15in) deep beam

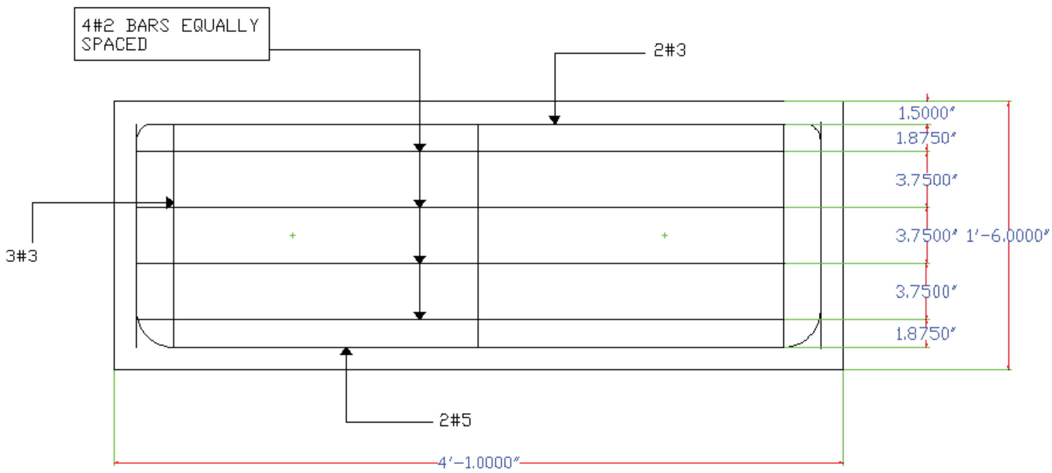

Fig. 7 Reinforcement details of 457mm (18in) deep beam

The continuous increase in crack width resulted in the sudden shear failure of the deep beams in the shear zone. Large diagonal cracks formed from the point of the applied load to the support. Fig. 8 shows the final crack pattern of 381mm (15in) deep beam at failure.

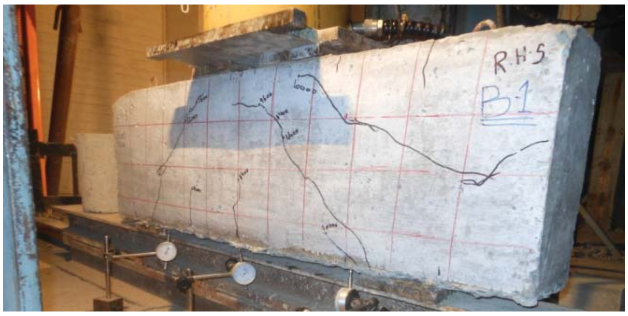

Fig. 8 381mm (15in) deep beam crack pattern

As discussed earlier the behaviour of the deep beam becomes brittle by increasing its depth. Failure pattern of solid 457mm (18in) deep beam in Fig. 9 shows the crushing of concrete near the right-hand side support and shear cracks became wide suddenly leading to the brittle failure.

Fig. 9 457mm (18in) deep beam crack pattern

During the experiment of beams with openings, flexural cracks appeared at the tension zone away from the area restricted by CFRP laminates. All beams were failed with sudden shear failure, the formation of diagonal tension cracks with yielding the bottom reinforcement and concrete crushing near support were observed. The diagonal crack propagated from the point of load application and support towards the circular openings. In some beams pealing of concrete cover along with CFRP laminate was also observed. It was also noted that all beams with an opening above NA the shear cracks did not pass through the openings. As openings were not located in the path of compressive strut hence showed the maximum shear strength. Fig. 10 shows the crack pattern of beams with holes above NA. The increase in ultimate capacity of the strengthened beams is apparently caused by the presence of vertical CFRP laminates near the opening that interrupt the natural path of crack propagation, thus requiring a higher energy to redirect the path to crack through un-reinforced space. CFRP has a marginal effect on the shear strength of deep beams.

Beams having openings below NA showed the least shear strength. The peeling of CFRP laminates was observed. Cracks which originate near the support propagate directly to the openings. The presence of opening near the support resulted in the formation of deformed geometry, and a complex load path hence caused the reduction in shear strength. Supports and loading points are those areas where the size of the compressive struts becomes narrow and hence resulted in high compressive stress concentration which leads to the early formation of cracks or the crushing on concrete. Fig. 11 shows the crack pattern of the deep beam with an opening below NA.

Fig. 10 Crack pattern of beams with opening above NA

Fig. 11 Crack pattern of beams with opening below NA

At last beams with openings at NA showed the shear behaviour in between the two discussed earlier. Fig. 12 shows the crack pattern of the deep beam with an opening at NA.

Fig. 12 Crack pattern of beams with opening at NA

Table I illustrates the comparison of results obtained from this experimental activity. It can be easily concluded from the results that the solid beams even without the CFRP strips have shown the maximum strength. Among the other sub groups beams with openings above NA shown maximum strength and beams with openings below NA has shown least strength.

TABLE I
COMPARISON OF DESIGN LOADS WITH ACTUAL LOADS AT WHICH FLEXURAL AND DIAGONAL SHEAR CRACKS WERE FORMED ON BEAMS

Beam Type	Group ID	Subgroup ID	Opening Location w.r.t NA	Design Loads (P_u) Strut and Tie Modal kN (kips)	Load at 1st Shear Crack (V_{cr}) kN (kips)	Load at Test Failure (V_f) (kips)	% Age Increase/ Decrease w.r.t. Theoretical Capacity
381mm (15in) deep beams	Group A	G1	Control Beam	133 (30)	275 (61.79)	530 (119.10)	297%
		G2	Above NA	133 (30)	230 (51.68)	512 (115.16)	283.87%
		G3	At NA	133 (30)	210 (47.19)	477 (107.30)	257.67%
		G4	Below NA	133 (30)	187 (42.13)	417 (93.82)	212.73%
457mm (18in) deep beams	Group B	G5	Control Beam	133 (30)	290 (65.17)	560 (125.84)	319.47%
		G6	Above NA	133 (30)	244 (54.94)	537 (120.80)	302.67%
		G7	At NA	133 (30)	243 (54.8)	514 (115.55)	285.16%
		G8	Below NA	133 (30)	227 (50.94)	465 (104.50)	248.33%

IV. CONCLUSION

1) Strut & Tie Model (STM) found to be a much conservative approach for the design of the deep beams with a good safety margin.
2) Shear capacity of 457mm (18in) deep was more than the 381mm (15in) because of increase in depth.
3) Control beams of Group A and Group B showed the maximum bearing strength.
4) The beam having holes above N.A shows the maximum strength and beams having holes below N.A shows the lowest strength.
5) In beams with openings above N.A crack did not pass through the opening, so it is the most suitable location for opening with the application of CFRP.
6) Beams with openings below NA showed the least strength.
7) The vertical orientation of CFRP strips on beams provided sufficient resistance to the propagation of cracks through openings.
8) Shear capacity of beams with 381mm (15in) and 457mm (18in) depth was approximately 10% reduced by the intrusion of the opening along the depth comparing with control beam i.e. solid beam.

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