

Finite Element Analysis of Reinforced Concrete Deep Beams with Large Openings

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ABSTRACT: In the construction of modern building structures, reinforced concrete (RC) deep beams are often used as primary load transferring elements, such as transfer girders in offshore structures and foundation. Transverse openings in reinforced concrete deep beam are provided for the purpose to accommodate ducts and pipes. The existence of web opening interrupts the natural load path and reduces the stiffness and load carrying capacity of structural element. The objective of this study is to find critical location and shape of opening. In this paper three-dimensional linear finite element model is used for reinforced concrete deep beam without shear reinforcement is analysed using finite element program ABAQUS. Test specimen has cross-section of 150 x 460mm and total length of 1200mm. Two different shapes of opening with varying locations are adopted. A total five finite element models are analysed. The strength reduction of deep beam with opening due to presence of opening is in range of 57 to 66 %.

KEYWORDS: FEM, deep beams (reinforced concrete), openings, location effect, shape effect.

I. INTRODUCTION

Beam with large depth in relation to spans are called deep beams. In the construction of modern building structures, reinforced concrete (RC) deep beams are often used as primary load transferring elements, such as transfer girders in offshore structures and foundation, wall of bunkers, load bearing walls in building, plate elements in folded plates, pile caps, raft beam wall of rectangular tank, hopper and shear wall etc. Nowadays, the use of deep beam has increased rapidly especially at the lower level in tall buildings for both residential and commercial purpose due to their convenience and economical efficiency. In buildings, a network of pipes and ducts is necessary to accommodate essential services like water supply, sewage, air-conditioning, electricity, telephone and computer network. Usually, these pipes and ducts are placed underneath the beam soffit and aesthetic reasons, are covered by a suspended ceiling thus creating a dead space. The creation of transverse web opening in the beam passing these ducts through this openings in the floor beams lead to reduction in the dead space and results in more compact design. For small building saving thus achieved may not be significant, but for multistorey buildings any reduction in the storey height multiplied by the number of stories represents a substantial saving in total height of building, reduces the length of air-conditioning and electrical ducts, wall and partition surfaces and overall load on foundation [1].

The existence of opening in beams alters the simple beam behaviour to more complex one due to geometric discontinuity. The current code of practices do not include the provision of design of deep beams with openings [2-3]. The presence of web opening in deep beams leads to early diagonal cracking because of the high stress concentration around corner of openings and also there is significant reduction in shear strength of deep beam. There are two types of openings Pre-planned openings and Post-planned openings [4]. In pre-planned openings, the size and location of opening will be known during the design stage itself. In this case adequate internal strengthening of opening is already done during design. But in case of post-planned openings internal strengthening of opening is not possible. The only possible criteria externally strengthen the structural element using external reinforcement in the form of jacketing of steel plate or composite material like fibre-reinforced polymer.

Transverse opening in beam may be of different shapes and size. Experimental work for study effect of various shapes of opening such as circular, rectangular, diamond, triangular, trapezoidal and even irregular shapes has been done [5].

However, circular and rectangular openings have been commonly used in practice [1]. When size of opening is concerned, many researchers use the terms small and large opening without any definition or clear-cut demarcation line. Openings of circular, square or nearly square in shape have been defined as small openings [6]. Circular opening may be considered as large when its diameter exceeds 0.25 times the depth of beam web [7]. Classification of opening is based on the structural response of beam. When opening is small enough to maintain the beam type behaviour or in other words the usual beam theory applies. In opposite to this, large opening are those prevent beam type behaviour to develop [8].

Web opening in deep beam significantly affect its structural behaviour described in previous studies [Kong & Sharp 1977, Kong et. al. 1978, Ray 1966, Ashour & Rishi 2000, Maxwell & Breen 2000, Tan et. al. 2003]. Design formulae have been developed to calculate ultimate strength of deep beam using modified Mohr-coulomb's criterion and the shear friction theory. An experimental work has done to investigate the effect of web reinforcement and the test results were compared to the design formulae. The study showed that the experimental ultimate strength of the beams were very much higher than the predicted values [9]. Experimental work for derived design equation for normal and lightweight concrete deep beam with web opening has been done [9-10]. Experimental program and numerical analysis have been done to investigate the effect of high strength concrete, shear span to depth ratio and web reinforcement ratios of beams [14].

II. SPECIMEN DETAILS AND MATERIAL PROPERTIES

Simply supported deep beam is considered having an overall length of 1200 mm with effective length of 900 mm. cross-section of the beam is 150 x 460 mm. Span to depth ratio (l/h) is 1.95 (less than 2). To ensure that deep beam action will develop in all beams with shear span to ratio of 0.86. Single point loading is applied at the midpoint of the beam. High-Yield Strength Deformed bars of 12 mm and 8 mm diameter are used for the longitudinal reinforcement and 6 mm diameter bars are used as stirrups. The tension reinforcement consists of 2 no's 12 mm diameter HYSD bars each having nominal cross-sectional area of $A_b=113.09 \text{ mm}^2$. Two bars of 8 mm of HYSD bars are also provided as hang up bars each having nominal cross-sectional area of $A_b=50.26 \text{ mm}^2$. Stirrups of 6 mm diameter bar provided at end of deep beam only having nominal cross-sectional area of $A_b=28.27 \text{ mm}^2$. Clear cover of 30 mm was maintained top and bottom of deep beam where as Clear cover of 25 mm was maintained on the beam's vertical side. Reinforcement detailing of reinforced concrete deep beam without shear reinforcement are shown in Fig. 1. This study includes analysis of one control beam (without opening) and three beams with square opening (with different position of opening) and one beam with circular opening. Thus total five such beams are analysed. Two square and circular openings, one in each shear span, are placed symmetrically about the midpoint of reinforced concrete deep beam without shear reinforcement. Large square opening dimensions 200 x 200 mm created at distance 350mm, 375mm and 400mm from centreline of the opening to the edge of the reinforced concrete deep beam. The large circular opening of diameter 226 mm created at distance of 375 mm from centreline of the opening to the edge of the reinforced concrete deep beam in such way that area of circular opening equal to area of square opening. Details of size and location of opening in specimens given in Table 1 and material linear properties used in analysis given in Table 2.

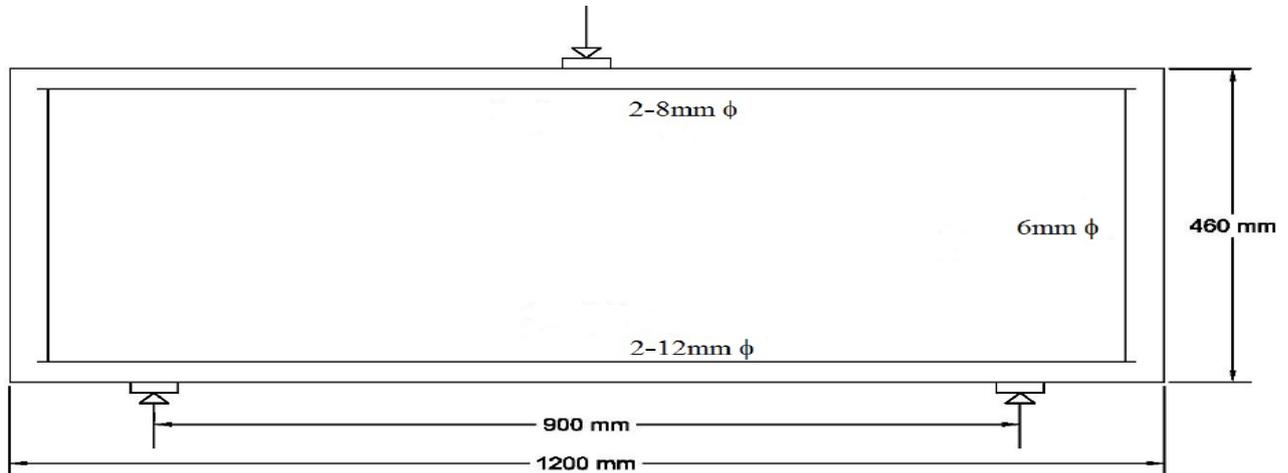


Fig.1 Details of Beam Reinforcement

Table 1: Size and Location of opening in specimens

Sr No.	Beam No	Shape of Opening	Size of Opening	Location of opening from edge
1	B1(Control Beam)	-	-	-
2	B2	Square	200 X 200 mm	350 mm
3	B3	Square	200 X 200mm	375 mm
4	B4	Square	200 X 200mm	400 mm
5	B5	Circular	Diameter=226mm	375 mm

Table 2: Material Properties

Materials	Density (kg/m ³)	Elastic Modulus (MPa)	Poisson's Ratio	F _c (Mpa)	F _y (Mpa)
Concrete	2400	22360	0.17	20	-
Reinforcing Steel	7850	210000	0.27	-	415
Steel Plate	7850	210000	0.27	-	415

III. NUMERICAL ANALYSIS

A three dimensional finite element program 'ABAQUS' is used for the numerical analysis of five reinforced concrete deep beams, one of them as control beam and remaining four beams with opening varying location. In the analysis, appropriate materials are employed to represent the behaviour of concrete, steel reinforcement and steel plates. In reinforced concrete deep beam to model the concrete in ABAQUS use solid element, C3D10I (Continuum, 3D, 10-

node, incompatible mode quad/bricks or improved surface stresses formulation). C3D10I are second order tetrahedral element. C3D10I are ‘improved’ formulation element. However, their integration points are at its nodes. Hence, results based on integration points (such as stresses and strains) do not suffer from extrapolation errors. It is for this reason that these elements are said to have ‘improved surface stress visualization’. In this sense, C3D10I is a good choice for fatigue problems where surface stresses are critical. C3D10I automatically invokes internal constraints to handle incompressible (or nearly incompressible) materials, such as hyper elasticity or plasticity. C3D10I elements are suitable for bending dominated problems and works well with contact analysis, although this element more costly. In reinforced concrete deep beam steel plates are placed at support points and loading point. These steel plates are model by using Solid element C3D20 (Continuum, 3D, 20-node). The C3D20 element is a general-purpose quadratic brick element (3x3x3 integration points). This is an excellent element for linear elastic calculations. Due to the location of the integration points, stress concentrations at the surface of a structure are well captured. Longitudinal reinforcement and vertical stirrups in reinforced concrete beam are model by using element T3D2. The main advantage of beams and truss are their geometrical simplicity and efficiency (require a few degrees of freedom).

IV. EFFECT OF WEB OPENING

The behaviour of the deep beams with web openings considered the load carrying capacities could be explained as follows: For solid deep beams and deep beams with web openings, applied load is directly transmitted from loading point to the reaction point along the path. This path is called as "load path". If the opening interrupts this path, the reduction in the load carrying capacity depends upon the whether this load path could be successfully re-routed around the opening or not. Primarily load path along the path 123, along this path most of the load is transmitted shown in Fig.2. Some of the load might be transmitted along a secondary path 143, which, however, is comparatively less effective because a substantial tensile force along 44' would be required except when the angle ϕ between 14 and 43 is small. When the force in 23 of the primary path reaches a sufficiently high value, the critical lower diagonal crack would occur. For a given applied load, the force in 23 depends on the angle which it makes with the horizontal (angle α), which depends on the location of the opening. It is therefore reasonable predicted that the load carrying capacity of the beam would be affected by the location at which the load path is interrupted by the opening. In the absence of the opening, the upper and lower paths become one, which is the natural load path joining the loading point and the reaction point.

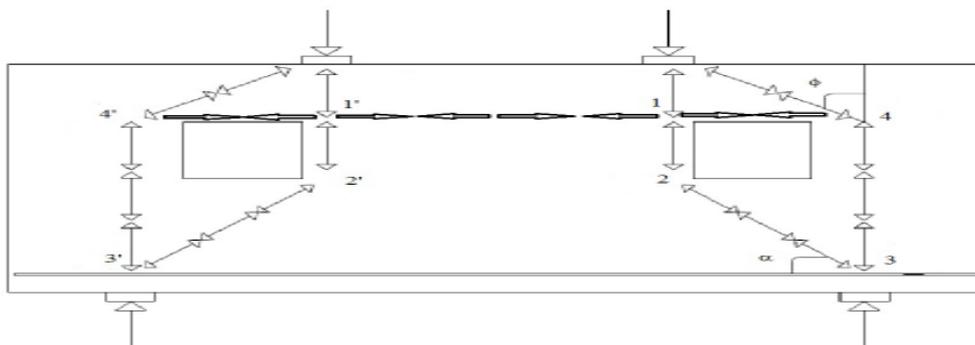


Fig.2. Load – Transmission Paths

Table 3. Shows that the load carrying capacity of deep beams and percentage decrease in load carrying capacity with respect to beam B1.

Table 3: Load Carrying Capacity of Specimens

Beam NO.	Load Carrying Capacity (KN)	Percentage Decrease in Load Carrying Capacity with Respect to B1
B1	210	-
B2	90	57.14
B3	73	65.23
B4	82	60.47
B5	80	61.90

In control beam B1 (without opening) applied load is transmitted directly from loading point to reaction point along load path. Hence, load carrying capacity of control beam is higher than the beam with openings. Opening intercepted path of load from loading point to reaction point, hence reduction in load carrying capacity of beam. From above table observed that beam B3 has minimum load carrying capacity as compare to beams B2 and B4, because opening in B3 interrupted more load path. Beam B2 and Beam B4 are placed equal distance from critical load path but opposite side. From table it is observed that load carrying capacity of beam B4 has less than Beam B2. In other words says, opening located in flexural region of the beam will have large decrease in ultimate load carrying capacity than that of an opening with a similar distance from critical load path outside of flexural. In Beam B3 provided square opening of size 200 x 200 mm at distance of 375 mm from edge of beam. At same distance in beam B5 provide equal area of circular opening, but load carrying capacity of Beam B3 is less than the load carrying capacity of Beam B5. Because in Beam B3 more stress are concentrated at corners of square opening. It is notice that the presence of large square and circular openings significantly caused a huge reduction in beam stiffness and beam capacity.

Based on experimental studies, Kong and Sharp (1977) derived design equations for normal and lightweight concrete deep beams with web openings [9]. The ultimate shear strength equations for reinforced concrete deep beams are,

1) For solid deep beam

$$Q_{ult} = C_1 \left[1 - 0.35 \frac{x}{D} \right] f_t b D + C_2 \sum A \frac{y}{D} \sin^2 \alpha$$

2) For deep beam with opening

$$Q_{ult} = C_1 \left[1 - 0.35 \frac{K_1 x}{K_2 D} \right] f_t B k_2 D + \sum AC_2 \lambda \frac{y_1}{D} \sin^2 \alpha_1$$

$$= W_2/2$$

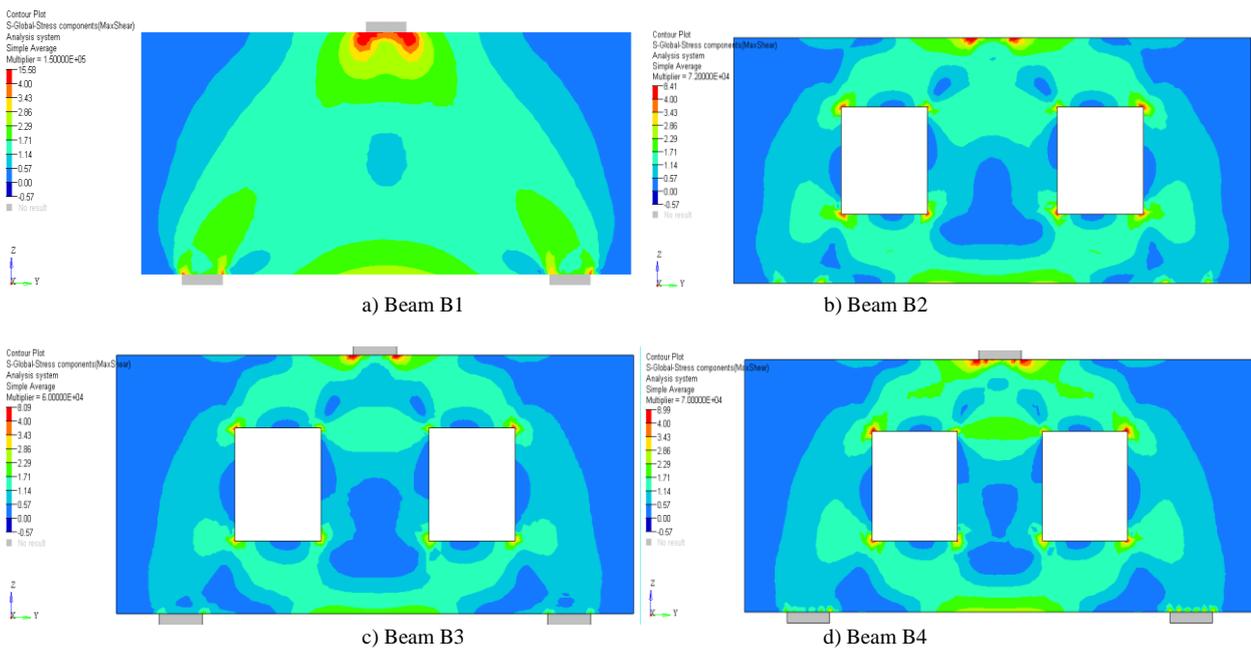
Where, A = Area of individual web bar, C₁ = empirical coefficient (1.40 for normal strength concrete, 1.35 for light weight concrete), b = breadth (thickness) of beam, D = overall depth, f_t = cylinder splitting tensile strength of concrete, x = clear-shear span distance, C₂ = empirical coefficient (300N/mm² for deformed steel bar, 130N/mm² for plain steel bar), y = depth at which a typical bar intersects the potential critical diagonal crack in solid deep beam, which is approximately at the line joining the loading and reaction points, and λ = an empirical coefficient, equal to 1.5 for web bars and 1.0 for main bars.

Table 4: Load carrying capacity by Present Study and Ref. [9]

Beam No.	Load Carrying Capacity (KN) Present Study	Load Carrying Capacity (KN) by Ref. [9]
B1	210	152.27
B2	90	72.07
B3	73	62.35
B4	82	47.05

V. STRESSES IN BEAMS

Deep beams are structural elements loaded as simple beams in which a significant amount of the load is carried to the supports by a compression force combining the load and reaction. As a result, the strain distribution is no longer considered linear, and the shear deformations become significant when compared to pure flexure. Because of their proportions, deep beams are likely to have strength controlled by shear rather than flexure. Fig.3a shows the stress concentration in control deep beam B1 without openings. Hence, in this beam more stresses are concentrated in shear region from loading point to reaction point. Fig 3(b-d) shows the stress concentration in deep beam with square opening. Due to presence of this openings load path is interrupted and corner of openings are subjected to more stresses. Stress concentration in deep beam with circular opening shown in Fig.3e. In circular opening, less stresses developed as compare to square opening.



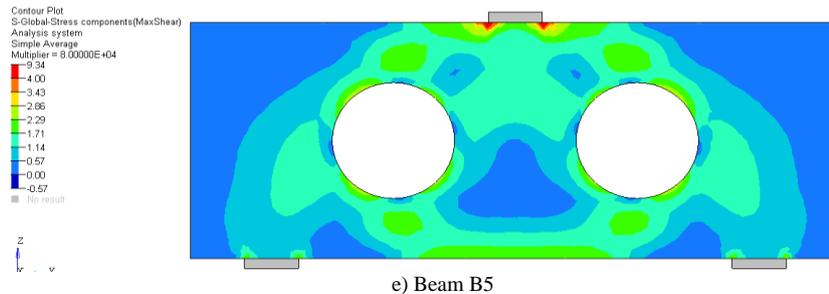


Fig.3 Stress Concentration in Deep beams (a-e)

VI. CONCLUSIONS

This paper presents a numerical analysis of reinforced concrete deep beam with opening without shear reinforcement. Different shape and locations of opening made in web of beams. Based on the numerical results and discussions, the following conclusions are obtained,

- The ultimate load carrying capacity of deep beam without opening beam B1 (control beam) is higher than the deep beams with openings.
- Critical location of large square of size 200 x 200mm found at 375 mm from centreline of opening to edge of beam, at this position of opening ultimate load carrying capacity of beam is significantly reduced.
- The load carrying capacity of the beam B3 opening at critical locations is decreased by 65.23 % as compared to control beam B1.
- At critical location, the load carrying capacity of the large circular opening in deep beam B5 is 8.75 % higher than the load carrying capacity of square opening (Beam B3).
- The load carrying capacities of deep beam without opening (control beam) and varying location of large square opening in deep beams are calculated by using the empirical formulas of Kong and Sharp (1977) within engineering accuracy.
- The large square shape of opening is more critical shape than the large circular opening, because more stresses are concentrated around the corners of square opening.

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International Journal of Innovative Research in Science, Engineering and Technology

An ISO 3297: 2007 Certified Organization

Volume 6, Special Issue 1, January 2017

International Conference on Recent Trends in Engineering and Science (ICRTES 2017)

20th-21st January 2017

Organized by

Research Development Cell, Government College of Engineering, Jalagon (M. S), India

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