Behaviour of RC Beams with Opening in the Flexural Zone at Different Locations strengthened using Steel Plates

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Abstract: Service pipes and ducts used for water supply, wastewater system and computer networks are necessary for multi-storied RC buildings. The utility pipes placed under the floor beams increase the height of the headroom and the opening placed inside the floor beam reduce the beam's strength and causes cracks around the opening. In this case, strengthening the circular openings should be done to improve the beam behaviour by using steel plates in the flexural region. In this study, totally seven beams were cast; one control beam, three beams with unstrengthened circular openings of 150mm diameter in the flexural zone at the top (compression zone), centre and bottom (tension zone) and three beams with circular openings strengthened with steel plate around the opening. Two-point loading was used for testing the beams. The effect of using openings in beams with and without steel plates at different locations along the depth of the beam is investigated. In the beam with opening provided in the compression zone of the beam, the ultimate load decreased by 22% compared to the control beam and sudden failure occurred as the concrete in the compression zone was reduced due to the opening. The ultimate load decreased by 8.7% when the opening was provided in the tension zone of the beam at the midspan. Strengthening the opening with steel plate decreased the ultimate load capacity and the failure mode was shear failure with cracks in the shear zone instead of flexural failure mode. RC beam with circular opening provided in the tension zone is preferred to the beam with opening provided in the compression zone, because reduction in ultimate load capacity is only marginal compared to the control beam.

Keywords: Circular openings; Flexural zone; Strengthening; Steel plate; Ultimate load.

I. INTRODUCTION

In high rise framed structures, service ducts are necessary for various purposes. If the ducts are placed under the bottom of the beam covered by a false ceiling, the floor height increases resulting in the increase of the overall height of the building. The service ducts provided through transverse openings in RC beams reduce the floor height of the building. Due to the provision of openings in beams, the stiffness decreases, which reduces the load carrying capacity and causes excessive deflection under the service load.

Steel plates were used to strengthen openings large and small of various shapes such as square, rectangular and circular in T-beam flange to replace the concrete removed from the flange to form the openings [1]. Size of the opening and the method of strengthening affect the strength of RC beam with opening [2]. Steel plates were also found to be much more effective in reinforcing bars with gaps than CFRP sheets. With steel plates not only the absolute shear strength of the beam was restored but the failure mode was also shifted from the shear to the flexure mode [3]. When multiple openings are provided instead of a single opening, the plastic failure mechanism length increased. [4].

The CFRP layer wrapping used with two layers and three layers, strengthened the shear behaviour of the RC deep beams with openings. [5]. Specifically, RC rectangular beams with circle openings having diameter less than 44% of beam depth had little effect on the peak load size, but circle openings of diameter greater than 44% decreased the peak load by a minimum value of 34.39%[6]. When Aramid fibres are used as reinforcement to strengthen openings of RC beams, the concrete structures can carry heavy loads [7]. When circular openings are located in region of maximum shear of RC beams, it can lead to early collapse of the beam and the shear strength can be predicted using an analytical equation and compared with FE model [8]. Due to the strengthening of multiple openings in the shear span subjected to static load and impact load in RC beams, the strength capacity increased from 27% to 92% varying with the type of opening [9]. Two or three layers of CFRP sheets were essential to restore the original strength for deep beams with opening [10].

The most dangerous position in which to open up to the ultimate strength in the beams was near the support and the easiest spot to open the beams was in the center of the beam (flexure zone). The effect on the load carrying potential for opening at L/2 distance was very limited and thus the central part of the beam should be opened in the beam [11]. The distribution of shear stress in the centre of the upper and lower chords of the opening was null in the area of bending. The highest shear stress occurs in beams with openings at the high shear and high flexure-shearing area on the right lower edge of the corner and on the left upper edge of the corner [12]. In comparison with the equivalent rectangular form, it is demonstrated that the shape of the web opening and the location along the perforated beam length can also influence the structural behaviour of perforated beams in a significant way. [13].

It was found that studies were not conducted in RC beams with circular openings at different locations in the flexural zone strengthened with steel plates and hence such beams were investigated to study their behaviour with respect to the ultimate load capacity, load-deflection behaviour and the pattern of failure

II. Experimental Investigation

A) Materials

Ordinary Portland Cement of 53grade, M-sand passing through 2.36 mm sieve with specific gravity 2.56, crushed granite stone obtained from locally available crushers of sizes 10 – 12mm as fine and coarse aggregate, and potable water with pH range 6 to 7, Fe415 grade Steel reinforcement, mild steel plates of yield stress 250 N/mm2 for strengthening the opening region were used.

B) Test Specimen Details

Totally seven beams were cast;

- One control beam,
- Three RC beams with circular opening of 150mm diameter at the compression zone, tension zone and centre of the beam in the flexural zone.
- Three RC beams with circular opening of 150mm diameter at the compression zone, tension zone and centre of the beam in the flexural zone strengthened with steel plate around the opening.

Test specimens of cross section 150 x 300 mm, length 2000 mm and the same reinforcement were used. The test specimens were made of M20 grade concrete and Fe 415 steel with 2-10 mm φ bars and 3-12mm φ bars at the top and bottom, stirrups of 8 mm φ at 150mmc/c spacing as shear reinforcement. 4mm thick steel plates with shear connectors were used for strengthening the opening region and the effect of providing steel plates around the circular opening on the behaviour and the failure mode of the beam were studied. Fig. 1 shows the typical reinforcement details of the beams with opening (150 mm φ) and Table 1 shows the test specimen details.

Table 1: Details of beam specimens

S. No.	Beam Nomenclature	Beam Description
1	CB	Control Beam (CB)
2	BCOC	Beams with circular opening (150 mm ϕ) at the compression zone
3	BCSPC	Beams with circular opening (150 mm ϕ) at the compression zone strengthened using steel plate
4	BCOM	Beams with circular opening (150 mm ϕ) at the center
5	BCSPM	Beams with circular opening (150 mm ϕ) at the center strengthened using steel plate
6	BCOT	Beams with circular opening (150 mm ϕ) at the tension zone
7	BCSPT	Beams with circular opening (150 mm ϕ) at the tension zone strengthened using steel plate

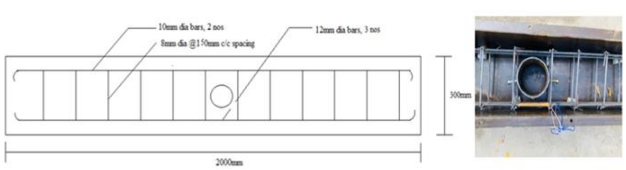
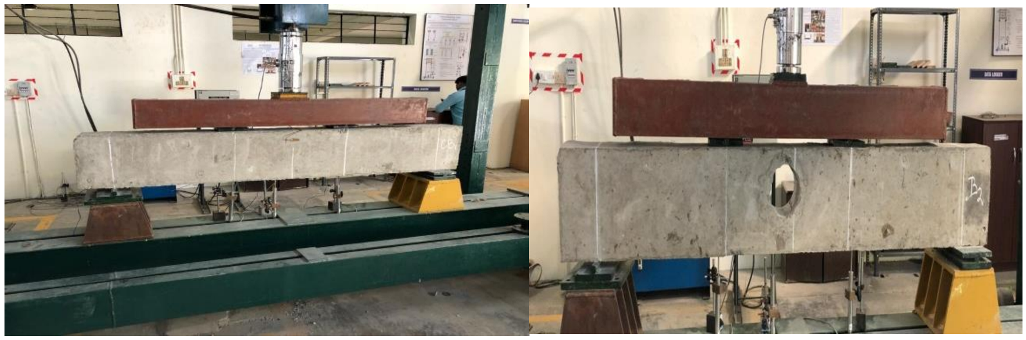


Figure 1: Reinforcement of the Beam with Circular Openings

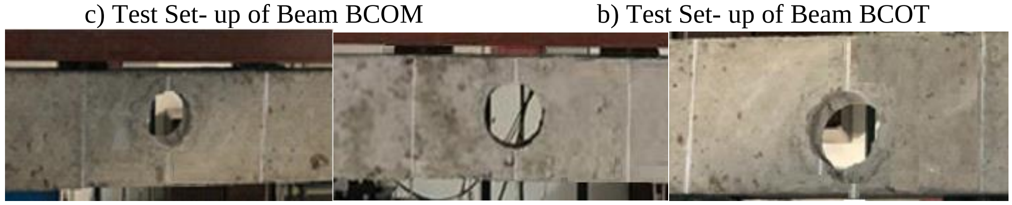
C) Test Set-up

The test set up of the control beam, Beam BCOT and the details of the specimens are shown in Fig. 2. The applied load and deflection of the beam due to two-point loading were measured.



(a) Test Set- up of the control Beam b) Test Set- up of Beam BCOC

c) Test Set- up of Beam BCOM b) Test Set- up of Beam BCOT



a) Opening at the Compression Zone b) Opening at the Centre c) Opening at the Tension Zone

Figure 2: Test Set-up and Details of the Specimens

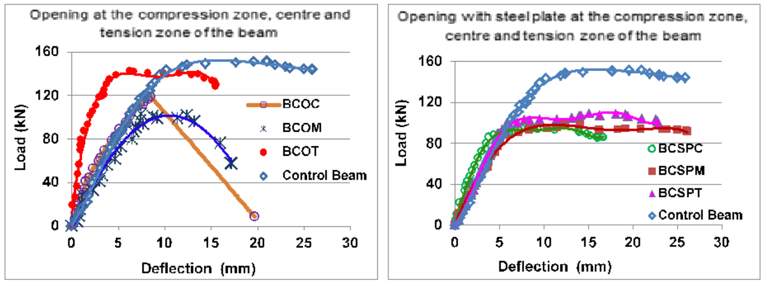
III. Results and Discussion

The first crack load, ultimate load, failure mode and the load-deflection behaviour of the control beam were studied and is shown as Table 2.

Table 2: Load and deflection of the Specimens

S. No.	Beam Description	Crack Load (kN)	Ultimate Load (kN)	Deflection (mm)
1	Control beam (CB)	34.9	151.5	19.6
2	BCOC	26	118.6	8.5
3	BCSPC	22	95.8	12.1
4	BCOM	32.8	102.8	12.4
5	BCSPM	39.3	98.5	12.5
6	BCOT	21.7	142.8	13.4
7	BCSPT	21.6	108.9	15.1

Fig. 3 shows the Load Vs Deflection behaviour of beams with opening (150 mm φ) in the flexural zone with and without steel plate at various positions along the depth of the beam. The ultimate load capacity of beam BCOT was maximum when an opening was provided in the tension zone at the midspan of the beam and when strengthened with steel plate, the beam BCSPT carried an ultimate load 24% lesser than the beam BCOT.



(a) Beams with opening (unstrengthened) at various positions along the depth of the beam
(b) Beams with opening strengthened with steel plate at various positions along the depth of the beam

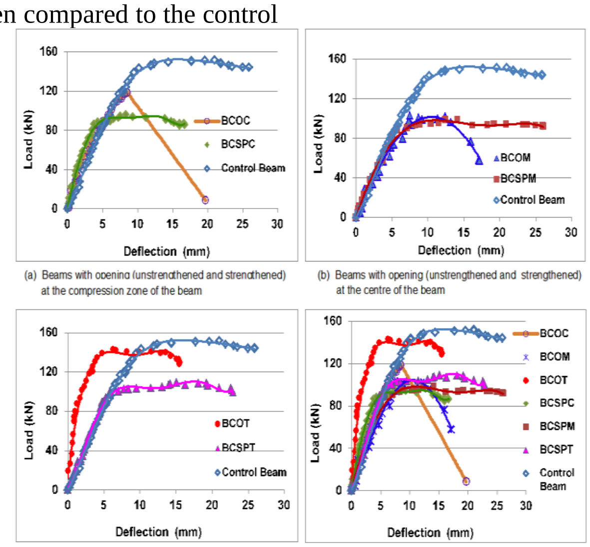
Fig. 3 Load Vs Deflection Behaviour of Beams with Opening (150 mm φ) in the Flexural zone with and without steel plate at various positions along the depth of the beam

The ultimate load of beam BCSPC with opening in the compression zone of the beam at the midspan reinforced utilising steel plate was 13.7 % more than that of the beam BCSPT with strengthened opening in the tension zone. The Load Vs Deflection behaviour of beams with opening (150 mm φ) at the midspan in the compression zone, centre and tension zone is shown in Fig. 4.

Providing a circular opening of 0.5 times the depth of the beam (150mmφ) in the compression zone at midspan considerably reduces the load capacity of the unstrengthened (BCOC) and strengthened beam (BCSPC) by 21.8 % and 37% respectively when compared to the control beam. The ultimate load of beam BCOC was 19.2 % more than that of Beam BCSPC with an ultimate load 95.8 kN. The load versus deflection curves in Figure 4(a) show that the circular opening provided in the compression zone of the RC beam failed suddenly as the concrete in the compression zone is reduced.

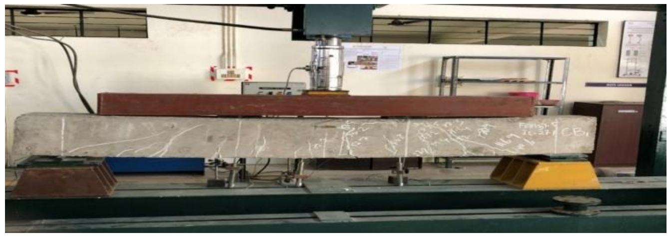
The ultimate load decreased by 32% for beam BCOM with an opening (0.5 times the depth of the beam) at the centre and 35% for the strengthened beam BCSPM when compared to the control beam. The ultimate load of beam BCOM was 4.2 % more than that of Beam BCSPM with an ultimate load of 102.8 kN but strengthening the beam BCSPM with steel plate increased the ductility of the beam when the opening was provided at the centre (Fig. 4(b)). Beams with openings at the flexural zone was subjected to vertical flexural cracks around the opening at the flexural zone.

The opening when provided at the tension zone of the beam at the midspan, the ultimate load decreased by 8.7% and 28% respectively for BCOT and BCSPT, compared to the control beam (Fig. 4(c)). The decrease in the ultimate load was 24% when the opening was strengthened at the tension zone BCSPT when compared with the unstrengthened beam. In beam BCOC, the ultimate load decreased by 22% compared to the control beam and the ultimate load decreased by 8.7% when the opening was provided in the tension zone of the beam at the midspan.

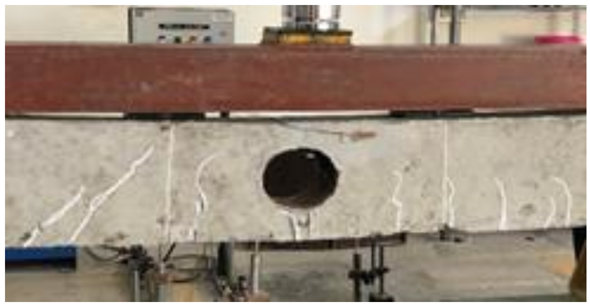


(a) Beams with opening (unstrengthened and strengthened) at the compression zone of the beam
(b) Beams with opening (unstrengthened and strengthened) at the centre of the beam
(c) Beams with opening (unstrengthened and strengthened) at the tension zone of the beam
(d) Beams with opening (unstrengthened and strengthened) at various positions along the depth of the beam

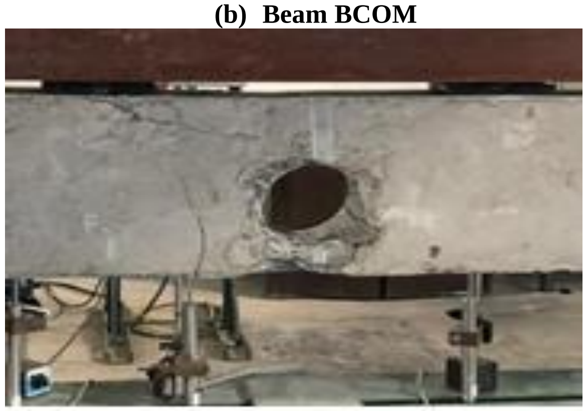
Fig. 4 Load Vs Deflection Behaviour of Beams with Opening (150 mm φ) at the Midspan in the Compression Zone, Centre and Tension Zone



(a) Control Beam



(b) Beam BCOM



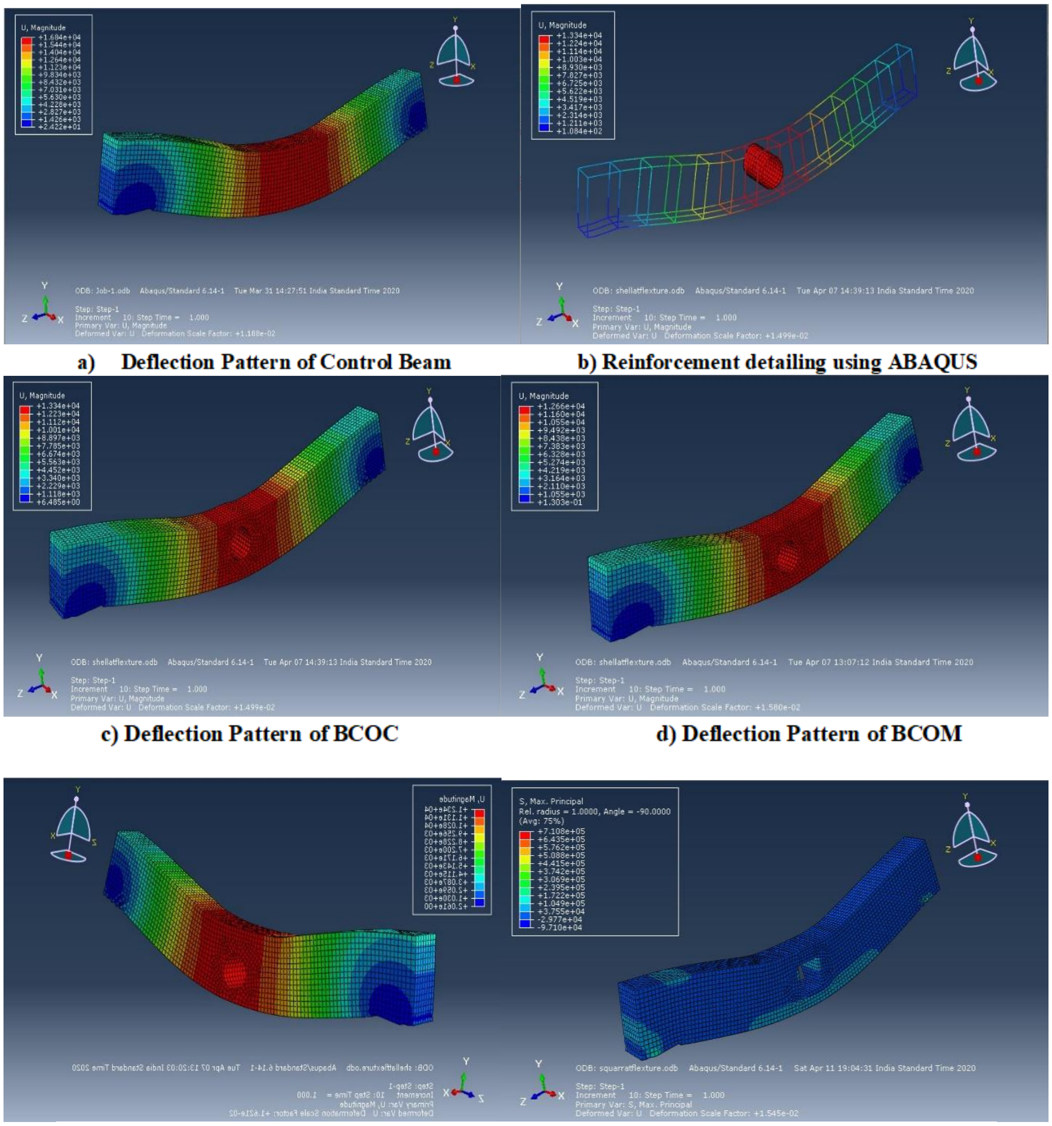
(c) Beam BCOT

Figure 5: Failure Pattern of Beams

The failure pattern of the control beam is shown in Fig. 5 (a). Flexural cracks and diagonal shear cracks were formed in the control beam. Beams with opening at the flexural zone was subjected to vertical flexural cracks around the opening at the mid-span Fig. 5 (b) and Fig. 5 (c). Inclined cracks were formed because of stresses at the point of loading. Crack formation was reduced in the case of beam strengthened using steel plates. This is due to the steel plates provided around the openings which resist the stress concentration at the sides of the openings leading to reduction in crack formation.

IV. ANALYTICAL INVESTIGATIONS

The finite element software ABAQUS had been used to create the models of the tested specimens. Using this model, the load-deflection behaviour and the failure pattern of the RC beam with openings were compared with the experimental results. In the beam models, the material properties were defined and for concrete it was homogeneous and isotropic. Two-noded truss element represented the reinforcement. Eight-noded Iso parametric element was used for idealization of concrete. Tie was used as a contact surface between concrete and steel. Figure 6 shows the deflection pattern and crack pattern of the beam modelled using the finite element software ABAQUS. Table 3 shows the comparison of the experimental and analytical results.



a) Deflection Pattern of Control Beam

b) Reinforcement detailing using ABAQUS

c) Deflection Pattern of BCOC

d) Deflection Pattern of BCOM

e) Deflection Pattern of BCOT

f) Crack Pattern of BCOM

Figure 6: Analytical modeling of Beams with openings using finite element software ABAQUS

Table 3: Comparison of Experimental and Analytical Results

S. No.	Beam Description	Ultimate Load (kN)	Experimental Deflection $\delta_{Exp.}$ (mm).	Analytical Deflection $\delta_{Anal.}$ (mm)	Ratio of $\delta_{Anal.}/\delta_{Exp}$
1	Control beam (CB)	151.5	19.6	17	0.87
2	BCOC	118.6	8.5	9.95	1.17
3	BCSPC	95.8	12.1	13.49	1.11
4	BCOM	102.8	12.4	12.66	1.02
5	BCSPM	98.5	12.5	13.4	1.07
6	BCOT	142.8	13.4	12.34	0.92
7	BCSPT	108.9	15.1	12.3	0.82

The experimental results agreed well with the analytical results. Strengthening the opening with steel plate decreased the load carrying capacity and the failure mode was shear failure with cracks in the shear zone instead of flexural failure mode. RC beam with circular opening provided in the tension zone BCOT is preferred to the beam BCOC with opening provided in the compression zone, because reduction in the ultimate load is marginal compared to the control beam.

V. CONCLUSION

An experimental investigation was carried out to study the effect of openings provided in RC beams at the flexural zone beams with and without steel plates at different locations along the depth of the beam and the following conclusions were made:

- Providing a circular opening of 0.5 times the depth of the beam (150mmφ) in the compression zone at midspan considerably reduces the load capacity of the unstrengthened (BCOC) and strengthened beam (BCSPC) by 21.8 % and 37% respectively when compared to the control beam.

- The ultimate load decreased by 32% for beam BCOM with an opening (0.5 times the depth of the beam) at the centre and 35% for the strengthened beam BCSPM when compared to the control beam and due to strengthening the beam, the ultimate load of the beam BCOM reduced by 4.2 %.
- The decrease in the ultimate load for BCSPT was 24% when the opening was strengthened at the tension zone.
- In beam BCOC, the ultimate load decreased by 22% compared to the control beam and the ultimate load decreased by 8.7% when the opening was provided in the tension zone of the beam at the midspan. The beam with opening provided in the compression zone of the RC beam failed suddenly as the concrete in the compression zone was removed to form the opening.
- The experimental results agreed well with the analytical results.
- Ductility was more for the beams with openings which were strengthened with steel plates.
- RC beam with circular opening provided in the tension zone BCOT is preferred to the beam BCOC with opening provided in the compression zone, because reduction in the load carrying capacity is marginal compared to the control beam.

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