Effect of Large Openings on Bending Strength of Reinforced Concrete Beam

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Original Research Article

ABSTRACT

At the design stage of beams, openings for service ducts are rarely taking into consideration. The introduction of openings for service ducts have negative effects on the strength characteristics of beams, hence the focus of this research is to investigate the effect of large service openings on the ultimate load of reinforced concrete beams produced from locally available materials. A total of ten beams were cast using 20.8 N/mm² concrete grade. The cross-sectional dimensions of the beams were 100mm x 150mm and 1000 mm length, with effective span of 750 mm. The tested beams consisted of two control beams. The experimental beams consisted of eight beams, four of the beams were with 40 mm service openings (with two beams having openings at the centre and two beams having openings at the supports) and the other four beams had 50 mm service holes (with two beams having openings at the centre and two beams having openings at the supports). The reinforced concrete beams were cured by covering it with wet cloths and tested at 28th day. The control beams and experimental beams were subjected to point loads at the beam centre to study the effect of the openings on the ultimate load. The average actual ultimate load for the experimental beams with 40 mm openings at the supports (TII) and centre were (TIII) were 49.48 kN and 63.28 kN respectively, representing 28% increase in the ultimate load when opening is moved from support to the centre of the beam. Also there is 45% increase in the average actual ultimate load for the experimental beams with 50 mm, when the opening is moved from supports (TIV) to the centre (TV). The average actual ultimate load for the control beams (TI) was 63.88 kN, while the estimated ultimate loads for control and the experimental beams was 70.13 kN, which

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shows that the estimated ultimate load is about 10% higher than the actual ultimate load. The openings placed at the supports of beams have more strength reducing effect on the ultimate load, when compared with the openings placed at the centre of the beams.

1. INTRODUCTION

Openings and service ducts are often provided in concrete structural elements to allow access for services, such as pipes for plumbing and electric wiring. The provision of such openings may result in the loss of strength, stiffness, ductility and increase of the deflection [1]. These openings can either be large or small depending on the schematic layout of the building. Mansur and Tan [2], considered circular and square (or rectangular) in shape opening as small if $d \leq 0.25 h$ (where d is depth of square or rectangular openings or the diameter of a circular opening and h is the beam height) and otherwise, it is classified as large opening. When the opening is small enough to maintain the beam-type behaviour, or in other words if the usual beam theory applies, then the opening may be termed as small opening. Those that prevent beam-type behaviour to develop are termed large opening. The presence of large openings in reinforced concrete beams requires special attention in the analysis and design phase because of the reduction in both strength and stiffness of the beam and excessive cracking at the opening due to high stress concentration [3]. Therefore, reinforcement at the opening is needed to ensure the proper strength and stiffness of the beams [1]. Therefore to prevent adverse effects of the provision of openings in beams, these openings must be considered adequately during the design or construction stages.

The passage of ducts through transverse openings in the floor beams leads to a reduction in the dead space and results in a more compact design [2]. For small buildings, the savings thus achieved may not be significant, but for multi-story buildings, any saving in story height multiplied by the number of stories can represent a substantial saving in total height, length of air-conditioning and electrical ducts, plumbing risers, walls and partition surfaces, and overall load on the foundation [2].

British Standard Institution [4] defines a deep beam as a member whose span is less or equal to 3 times the overall section depth. Hence slender beam can be said to be beam whose span is greater than 3 times the overall section depth [5]. Research work into the behaviour of deep beams with ducts has been carried out extensively; however, research into the behaviour of slender beams with big service openings is rare and attracts little or no attention. Hence, the focus of this research is to investigate the effect of big openings on the strength characteristic of slender beams.

In his work, Aziz [6] noted that for beams of 100 mm x 150 mm x 750 mm, with openings when compared with the ones without openings, their the ultimate strengths were decreased by 12%, 22% and 41% for beams containing opening at distance L/2, L/3 and L/6 from the edge respectively. This means that moving of opening locations from the centre towards the supports, lead to decrease in the carrying capacity of the ultimate load.

Lee et al. [7] noted that there was increase in the load carrying capacity of the beam for reinforced concrete T-section deep beams strengthened externally with CFRP sheets. In order to reduce the effects of service openings on the strength characteristics of beams, Suresh and Prabhavathy [8], used steel fibres and steel plates to strengthen the service openings. From the test results, Suresh and Prabhavathy [8] noted that the presence of openings in the shear zone reduces the load carrying capacity by 55% to 70% for the beams with openings.

Olanitori and Tifase [9], noted that the decrease in the flexural strength of the beam with small opening at the centre was between 39.62% and 42.64%, while that of the beam with the small opening at supports is between 6.0% and 14.67%. Olanitori and Tifase [5], investigated the effect of small transverse openings on shear strength of reinforced concrete slender beams. The study shows that the ultimate load of beams with service holes depends on the size of holes, position of holes, and of type loading. Ame, et al, [10] studied the effect of the size of openings and their vertical positions on the ultimate load. The results show that the ultimate load is affected by the size of the holes and their vertical positions.

2. MATERIALS AND METHODS

The materials used this work with their relevant standards are: Portland cement of grade 42 [11], fine aggregate [12], crushed granite [12], water [13], and reinforcing bars [14]. The concrete grade used was determined from the concrete trial mix tests carried out in accordance to the provisions of BS 5328 – 1 [15], BS 5328 – 2 [16], BS 5328 – 3 [17], BS 1881-108 [18] and BS 1881-116 [19], while that of the reinforcing bar was determined from tensile test in accordance to the provision of BS 4449 [14]. All the materials used for the work were sourced locally. After 24 hours of casting, the beams were de-moulded and were cured by covering the with wet nylon materials to prevent evaporation of the water. The beams were subjected to bending test at the 28th day. The concrete cubes were cured by immersion in water in curing tank. The cubes of size 150 mm x 150 mm x 150 mm were removed from the curing tank and put into open space for the water to dry up for 24 hours before subjected to compressive tests at 7th, 14th, 21st and 28th days respectively.

The total number of reinforced concrete slender beams cast was ten, two of which were control beams while the remaining eight were experimental beams. The cross-sectional dimensions of the beams were 100 mm x 150 mm and 1000 mm length, with effective span of 750 mm. All the beams were reinforced with 12 mm main reinforcing bars and with 8 mm bars as stirrups. The two control beams (TI) were without the openings, while the remaining eight experimental beams were with openings. The first two experimental beams (TII) have 40 mm diameter opening at the supports of the beams, while the second pairs of the beams (TIII) were having 40 mm opening at the centre. The third pairs of the beams (TIV) have 50 mm openings at supports, while the forth pair of the beams (TV) were having 50 mm openings at the centre. All the beams were loaded at the centre with a point load until failure occurred. The load at failure for each of the beams were noted and recorded. Table 1 and Fig. 1 show the details of the beams.
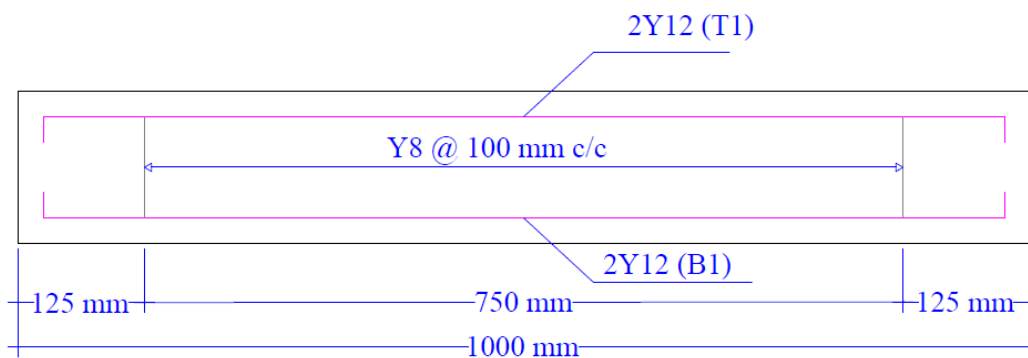

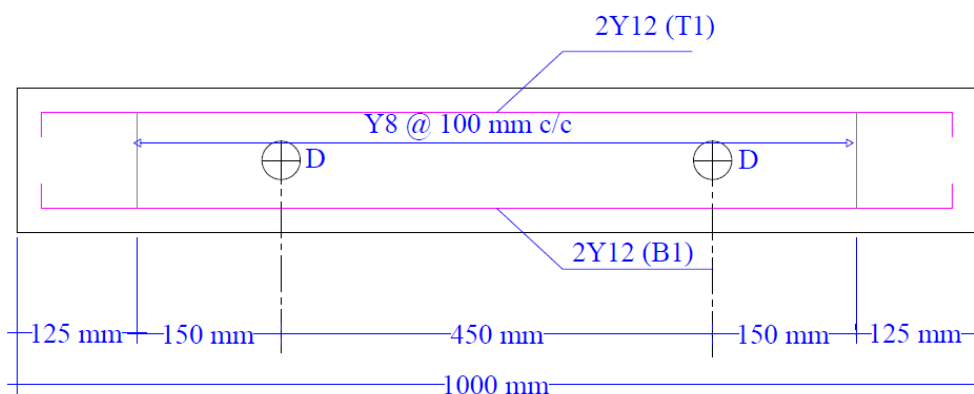**Fig. 1a. Details of control beam TI**

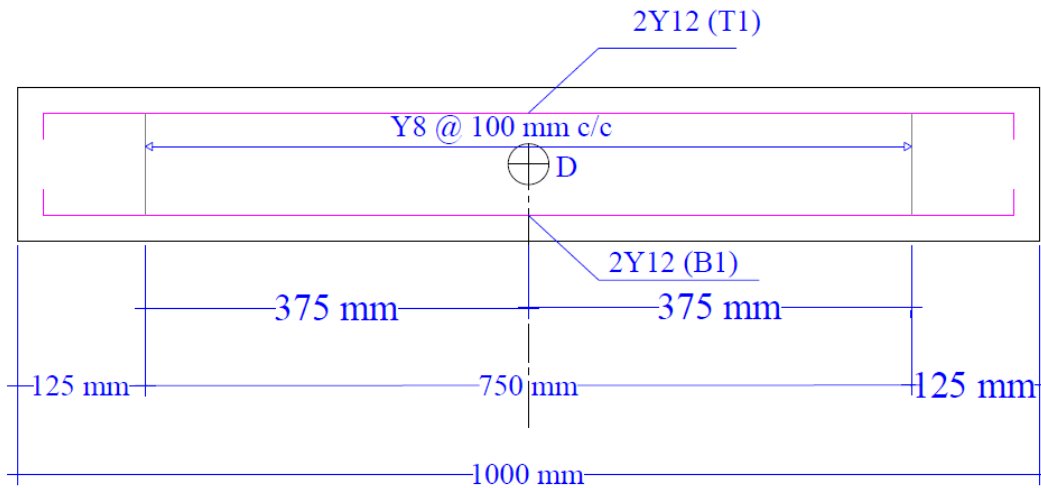**Fig. 1b. Details of experimental beams (Types II & IV) with openings at supports**

Fig. 1c. Details of experimental beams (Types III & V) with openings at the mid-span
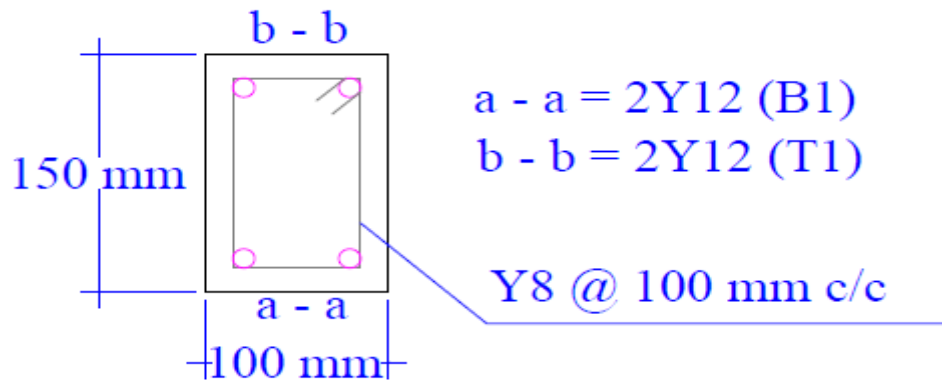

Fig. 1d. Cross-section of the experimental beams

Fig. 1. (a – d): Details of experimental beams

Table 1. Details of the experimental beams

Beam Type	Opening Diameter (mm)	Position of Opening (mm)
I	-	-
II	40	Supports
III	40	Centre
IV	50	Supports
V	50	Centre

3. RESULTS AND DISCUSSION

The results of the compressive tests carried out on the concrete cubes at 7th, 14th, 21st and 28th day are presented in Table 2, and normal distribution statistical method was used to determine the characteristic strength of the concrete mix. The characteristic compressive strength of concrete cubes were determined using Equation (1)

$$f_k = \bar{x} - 1.64\sigma \tag{1}$$

Table 2. Summary of results of concrete compressive tests

Age (Day)	Characteristis strength (N/mm^2)
7TH	10.03
14TH	12.50
21ST	18.60
28TH	20.80

Table 3. Results of tensile tests of high yield reinforcements

Bar Size Ө (mm)	Yield Load (kN)	Yield Stress f$_y$ (N/mm^2)
8	18.60	370.00
12	41.92	370.65

Table 3 shows the result of tensile tests carried out on high yield bars of diameters 8 mm and 12 mm respectively. The yield stress of the reinforcing bars was determined to be 370 N/mm^2 for 8 mm bar and 370.65 N/mm^2 for 12 mm bar size.

Table 4 shows the results of the flexural tests on the control beams and experimental beams. From Table 4, the average load at failure for the control beam TI is 63.88 kN, while the average loads at failure for beams (TII & TIII) with 40 mm diameter of openings at supports and centre are 49.48 kN and 63.28 kN respectively. Also the average loads at failure for beams (TIV &TV) with 50 mm diameter of holes at supports and centre are 42.85 kN and 62.26 kN respectively.

In order to estimate the ultimate load at failure for the control and experimental beams, Eqns. 2, 3 and 4 are used. The moment of resistance M$_R$ of the section was determined using Eq. 2.

$$M = 0.156 f_{cu} bd^2 + 0.87 f_y A_S^1 (d - d^1) \qquad (2).$$

Where fcu – concrete strength, b – beam width, d – beam depth, fy – bar strength, d^1 is the depth of the compression reinforcement and A_S^1 – area of compression reinforcement.

Substitute for the values of f$_{cu}$, b, A_S^1 and f$_y$ in Eq. 2, and this results into:

$$M_R = [0.156 \times 20.8 \times 100 \times 126^2$$
$$+ 0.87 \times x \times 370 \times 226(126 - 16)] \times 10^6$$
$$M_R = 5.15 + 8.0 = 13.15 \text{ kNm}$$

For simply supported beam:

$$M_{max} = \frac{FL}{4} \qquad (3)$$

Equating M$_R$ to M$_{max}$, we have:

$$F = \frac{4M_R}{L} \qquad (4)$$

Where F is the estimated ultimate load F$_{EUL}$.

Substituting for M$_R$ and L, we have:

$$F_{EUL} = \frac{4 \times 13.15}{0.75} = 70.13 \text{ kN}$$

From Table 5, the Estimated Ultimate Load (F$_{EUL}$) is 70.13 kN, while F$_{AUL}$ of the control beams (TI) is 63.88 kN, and this represents a decrease of 8.91% in the ultimate load when compared with the estimated one. Plate 1 shows the failure mode of control beam TI. The beam was with slender shear span of a/d of 2.98 (a = L$_E$/2 = 375mm; d = 126 mm), hence the inclined cracks disrupt the beam section equilibrium to the extent, that the beam failed at the inclined cracking load of 63.88 kN. This failure was largely caused by bound failure.

Also from Table 5, for the beams with 40 mm diameter openings at the supports (beam TII), there was 29.45% decrease in the ultimate load when compared with the estimated one, while there was 9.77% decrease in the ultimate load for beam (beam TIII) with 40 mm diameter openings at the centre when compared with the estimated one. For beams with 50 mm diameter openings at the supports (TIV), there was 38.9% decrease in the ultimate load when compared with the estimated one, while there was 11.22% decrease in the ultimate load for beam (TV) with 50 mm diameter opening at the centre when compared with the estimated one.

Table 4. Results of flexural test beams

Beam No	Weight (kg)	Position of Hole	Position of Load	Load at Failure (kN)	Average load at Failure F_{AUL}
TI_1	43.40	-	At beam centre	63.85	
TI_2	43.50	-	At beam centre	63.74	63.88
TII_1	44.2	Supports	At beam centre	49.28	
TII_2	44.0	Supports	At beam centre	49.67	49.48
$TIII_1$	43.6	Center	At beam centre	63.0	
$TIII_2$	44.1	Centre	At beam centre	63.55	63.28
TIV_1	44.0	Supports	At beam centre	43.52	
TIV_2	43.8	Supports	At beam centre	42.17	42.85
TV_1	43.5	Center	At beam centre	61.52	
TV_2	44.1	Centre	At beam centre	62.99	62.26

Plate 1. Mode of failure of control beam TI

Plate 2 shows the failure pattern of experimental beam TII, which is almost the same as that of the control beam TI in Plate 1, except that the inclined crack passes through the opening at support, which subsequently caused the reduction in inclined failure load of 49.48 kN. The final failure was caused by bond failure.

Plate 2. Mode of failure of experimental beam TII

Plate 3. Mode of failure of experimental beam TIII

Plate 3 shows the failure pattern of experimental beam TIII. There was inclined crack with no opening at the support to cause any disruption to the propagation of the crack and, after a redistribution of internal forces, were able to carry additional load, in part by arch action. The final failure of the beam was caused by bond failure. Hence failure load beam TIII which is 63.28 kN is greater than that of beam TII which is 49.48 kN.

Plate 4 shows the failure pattern of experimental beam TIV. The inclined crack passes through the opening at support, which subsequently caused the reduction in inclined failure load of 42.85 kN due to the bigger size of the opening, when compared with the inclined failure load of beam TII of 49.48 kN, The final failure was caused by bond failure.

Plate 5 shows the failure pattern of experimental beam TV. There was inclined crack with no opening at the support to cause any disruption to the propagation of the crack and, after a redistribution of internal forces, were able to carry limited additional load, in part by arch action. The final failure of the beam was caused by bond failure. Hence failure load beam TV which is 62.25 kN is greater than that of beam TIV which is 42.85 kN.

Table 6 shows the effects of large openings on the ultimate load of the beams when compared with that of the of the control beam. From Table 6, there was 22.54% decrease in the ultimate load for beam with 40 mm diameter openings at the supports (beam TII) when compared with the control beam, while there was 0.94% decrease in the ultimate load for beam (beam TIII) with 40 mm diameter openings at the centre when compared with the control beam. For beams with 50 mm diameter openings at the supports (TIV), there was 32.92% decrease in the ultimate load when compared with the control beam, while there was 2.54% decrease in the ultimate load for beam (TV) with 50 mm diameter openings at the centre when compared with the control beam.

Plate 4. Mode of failure of experimental beam TIV

Plate 5. Mode of failure of experimental beam TV

Table 5. The comparison of estimated ultimate load and actual load of the experimental beams

Beam No	Estimated Ultimate Load (F_{EUL}) kN	Actual Ultimate Load (F_{AUL}) kN	$\dfrac{(F_{EUL} - F_{AUL}) \times 100}{F_{EUL}}$
TI	70.13	63.88	8.91
TII	70.13	49.48	29.45
TIII	70.13	63.28	9.77
TIV	70.13	42.85	38.90
TV	70.13	62.26	11.22

Table 6. Effect of holes on the strength characteristics of slender beams

Control Beam	Experimental Beam							
	40 mm Opening				50 mm Opening			
TI	TII		TIII		TIV		TV	
F_{AUL} (kN)	F_{AUL} (kN)	% Difference	F_{AUL} (kN)	% Difference	F_{AUL} (kN)	% Difference	F_{AUL} (kN)	% Difference
63.88	49.48	22.54	63.28	0.94	42.85	32.92	62.26	2.54

4. CONCLUSIONS

From the discussion of results the following conclusions can be made:

1. Estimated ultimate load is higher than the actual ultimate load.

2. For beam (TII) with 40mm openings at the supports, there were decreases of 29.45% and 22.54% of actual ultimate load when compared with the estimated ultimate load and the actual ultimate load of the control beam respectively, while for beam (TIV) with 50 mm openings at the supports, there were decreases of 38.9% and 32.92% of actual ultimate load when compared with the estimated load and the actual ultimate load of the control beam respectively.

3. For beam (TIII) with 40 mm openings near the centre, there were decreases of 9.77% and 0.94% of actual ultimate load when compared with the estimated ultimate load and the actual ultimate load of the control beam respectively, while for beam (TV) with 50 mm openings at the centre, there were decreases of 11.22% and 2.54% of actual ultimate load when compared with the estimated load and the actual ultimate load of the control beam respectively.

4. Increasing the size of openings at the supports from 40 mm to 50 mm, the ultimate load reduces from 49.48 kN to 42.85 kN, which represents a 13.4% reduction, while increasing the size of opening at the centre from 40 mm to 50 mm, the ultimate load reduces from 63.28 kN to 62.26 kN, which represents a 1.61% reduction.

5. The ultimate load of beam (TIII) with 40mm openings at the centre was 63.28 kN, while the ultimate load of beam (TII) with 40 mm openings at supports was 49.48 kN, hence there was decrease of 21.81% of the actual ultimate load, when the opening was moved from centre to the supports.

6. The ultimate load of beam (TV) with 50mm ducts at the centre was 62.26 kN, while the ultimate load of beam (TIV) with 50 mm ducts at supports was 42.85 kN, hence there was decrease of 31.18% of the actual ultimate load, when the duct was moved from centre to the supports.

7. Introduction of service openings resulted in the decrease of the ultimate load of beams, and increasing the diameter of the service openings increases the decreasing effect of openings on the ultimate load.

8. Openings placed at the supports have more decreasing effect on the ultimate load of beams when compared with that at the centre.

Based on the above conclusions, the following recommendations can be made.

1. Since there is decrease in the ultimate load of beams with service holes, loaded at the centre with a concentrated load, when compared with the estimated one, there is need to modify the existing design equations of beam for flexure when designing beams with service ducts to take care of the decreasing effect of service ducts on the ultimate load.
2. For beams loaded at the centre with a concentrated load, service ducts must be located near the centre of beams, since the effect of openings located at the centre on strength characteristics of beam is reduced when compared with openings located at the supports.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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