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Effect of Small Transverse Service Holes on Shear Strength of Reinforced Concrete Slender Beams

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ABSTRACT: This paper presents the results of a study conducted to investigate the effect of small transverse hole on the shear capacity of slender beams. A total number of ten beams were cast, with concrete grade of C13.02. The cross -sectional dimensions of the beams were 100mm x 150mm, with an effective span of 560mm. The tested beams consisted of two control beams. The experimental beams consisted of eight beams, four of the beams were with 20mm service hole (two beams with holes at the centre and two beams with holes at 220mm from both ends), while the other four had 25mm service holes, with two of beams had holes at the centre, while the other two beams had holes at 220mm from both ends. The beams were subjected to both point load and load at third points. 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.

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From a practical point of view, openings in concrete members are means of accommodating utility services in building structure. Usually, these pipes and ducts are placed underneath the beam soffit and, for aesthetic reasons, are covered by a suspended ceiling, thus creating a dead space. Passing these ducts through transverse openings in the floor beams instead of below or above the member leads to a reduction in the dead space and results in a more compact design (Mansur *et al.,* 1985). For small buildings, the savings thus achieved may not be significant. But for multi-storey buildings, any saving in storey height multiplied by the number of stories can represent a substantial saving in materials and man hour. All these translate to reduction in the sizes of structural members of reinforced concrete structures, which in turn, reduces the amount of cement needed for construction, this is accompanied by reduction in CO_2 emission associated with the production of cement: this will have reduction effect on the greenhouse, a major cause of climate change. The web openings of the beam result in the decrease of flexural stiffness, flexural and shear strengths, increase in the deflection of the beam and may lead to cracking. Therefore the reinforcement at the openings is needed to ensure the proper strength and stiffness of the beams (Mansur *et al*, 2006, Mansur and Tan, 1999a, Vivek, and Madhavi, 2016). Euro Code 2 (BS EN 1992-1-1, 2004) 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. Beams with small and large openings need separate treatments in design (Mansur and Tan, 1999b). Mansur and Tan (1999b), 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 otherwise, it is classified as large opening. Therefore, analysis and design of a beam with small openings may follow the similar course of action as that of a solid beam. Mansur *et al.*, (2006,), noted that the results of the Strut and Tie Model (STM) analysis of reinforced concrete deep beams with transverse circular opening in the web, show good agreement with experimental results. Mohamed *et al* (2014), shows that web openings crossing the expected compression struts should be avoided, and the depth of the opening should not exceed 20% of the beam overall depth and that reinforcement distribution should be in the range of 0.1 – 0.2 beam depth for simply supported deep beams. For deep beams with opening, 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 (Aziz, 2016).

The simplified version of the expression to determine the shear strength of concrete (ACI 318, 2008) is presented as Eq. 1.

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$$V_c = \frac{1}{6}\sqrt{f_c^1}b_w d \qquad (1)$$

Where V_c is the nominal shear strength provided by concrete; f_c^1 is the concrete strength; b_w is the web width; d is the effective depth of section.

To include the effects of loading type and shear span to depth ratio into current code provisions, Brown *et al* (2006), proposes:

$$V_c = \frac{1}{12}\sqrt{f_c^1}b_w d \qquad (2)$$

According to Arslan (2008), the nominal shear strength provided by concrete can be estimated using Eq. 3.

$$V_{cr} = V_{crt} + V_{crd} = 0.15(f_c)^{0.5}b_w d + 0.02(f_c)^{0.65}b_w d \qquad (3)$$

Where: V_{cr} is the cracking shear strength, V_{crt} is the diagonal tension cracking strength, V_{crd} is the dowel strength and f_c the concrete strength.

Shear strength models for diagonal cracking strength of RC slender beams without stirrups were by proposed by Kim and Park (1996), Rebeiz (1999) Khuntia and Stojadinovic (2001) Arslan (2012). Also in their work, Arslan and Polat (2013), showed that there exists a significant amount of contribution of concrete to the shear strength (18 - 69%), however, noted further experiments should be conducted with a wider range of shear reinforcement ratio, shear span-to-depth ratio, concrete strength and various loading schemes in order to obtain more reliable assessments.

Since the mid-1980s, there is an increasing amount of experimental evidence showing that the underlying concepts of the provisions of current codes (for example, BS EN 1992-1-1, (2004) and ACI 318, (2008)) for the shear in particular and, to a certain extent for the flexural design of reinforced concrete (RC) structures are in conflict with fundamental properties of concrete at both the material and the structural levels (Kotsovs, 2007). Olanitori and Tifase (2017), noted that the decreasing effect of size of hole at the centre on the ultimate load of slender beam loaded at centre is 39.62% to 42.64%, while that loaded at third points is 9.0% to 14.67%. The tension reinforcements in reinforced concrete sections did not contribute as much to shear resistance of reinforced concrete sections as predicted by BS EN 1992-1-1 (2004), thereby confirming the assertion of Kotsovos (2007), that dowel action of the reinforcing steel has little part to play in the shear resistance (Olanitori *at el*, 2014, Olanitori and Afolayan, 2014).

Based on the results of their research work Olanitori *at el* (2014), suggested that in order to reduce the failure of reinforced concrete space framed structures with beam-column joints hinged, that Eq. (4) can be used in the prediction of the shear capacity.

$$V = \lambda_c V_c \qquad (4)$$

Where: λ_c is the concrete shear capacity factor, V is the shear capacity of the space frame and, V_c is the shear capacity due to concrete.

From ACI 318-08 (2008), design shear strength is calculated using Eq. (5).

$$V_n = V_c + V_s = \frac{\sqrt{f_c}}{6}b_w d + \frac{A_w f_y d}{s} \qquad (5)$$

Olanitori *at el* (2016), suggested that for reinforced concrete space framed structures with beam-column joints rigid, that Eq. (6) can be used in the prediction of the shear capacity.

$$V = \lambda_s V_s + \lambda_c V_c = 0.23V_s + 0.7V_c \qquad (6)$$

Where: λ_s is the tension reinforcement and stirrups shear capacity factor.

MATERIALS AND METHODS

The materials used for this research work were Portland cement, sand (4.75mm), crushed granite (12mm), clean water and reinforcing bars. The concrete grade to be used was 13.02 N/mm^2, while that of reinforcing bar was 410 N/mm^2. Two numbers of beams were used as control beam (beam without holes), while the total number of experimental beams (beams with service holes) were eight. Four of these beams had 25mm service holes (two of the beams have holes at the centre, while the other two had holes at 220mm from both ends), while the other four had 20mm service holes (with two of the beams have holes at the centre and the other two had holes at 220mm from both ends). The beams specifications and materials strength characteristics are as given below:

Beam: 100mm x 150mm x 1000mm;
effective span $l_e = 560mm$; $f_{cu} = 13.02$ N/mm^2; $f_y = 410$ N/mm^2; $d = 130\ mm$;
Reinforcing bar = 2Y10; As = 157 mm^2.

The beams were given two types of loadings: point loading and loading at third point. The point load was applied at the centre of the beam, while the second loading was a two symmetrical point load applied at 200mm apart, and at a distance of 180 mm from the supports. The flexural tests carried out on the beams were in accordance with BS EN 12390-5 (2009).

RESULTS AND DISCUSSION

The estimated ultimate load was determined using the rectangular stress block of doubly reinforced rectangular section, while the shear capacity was determined using the equations of the BS EN 1992-1-1 (2004). These values are presented in Table 1.

Table 1: Estimated and actual strength characteristics of the control beams

Beam No`	Load Position	M_R (kNm)			P_{UL} (kN)	V_{SC} (kN)	
		M_{ER}	M_{AR}	P_{EUL}	P_{AUL}	V_{ESC}	V_{ASC}
B1	beam Centre	10.15		72.5	68.00	91.33	34.00
B2	third points	10.15		113.28	75.00	91.33	37.50

The results of the tests carried out on the beams are presented in Tables 1 to 5. Table 1 shows the estimated values of the moment and shear capacities of the control beams, as well as the results of the flexural tests carried out on them. From Table 1, the ultimate load was 68.0 kN for the control beam loaded with point load at the centre, while the ultimate load for the one loaded at third points was 75.0 kN. This shows that the ultimate load of control beam loaded at third points is 10.29% greater than that loaded at centre. From Table 2, the ultimate load of experimental beam (B3) with 20 mm diameter holes at the centre and loaded at the centre was 42.1 kN, while the one loaded at the third points (B4) was 47.15 kN. This shows that the ultimate load of the experimental beam loaded at the third points is 12% greater than one loaded with point load at the centre. Also for experimental beams B5 and B6, with 20 mm holes at the supports, but loaded at the centre and at point thirds, had ultimate loads of 62.5 kN and 73.0 kN respectively. This shows an increase of the ultimate load of beam loaded at third points over the loaded at the centre by 16.8%.

Where: M_R is the moment of resistance, M_{ER} is the estimated moment of resistance, M_{AR} – actual moment of resistance, P_{UL} – ultimate load, P_{EUL} is the estimated ultimate load, P_{AUL} – actual ultimate load, V_{SC} – shear capacity, V_{ESC} is the estimated shear capacity, V_{ASC} – actual shear capacity, B1 is the control beam loaded at centre and B2 is the control beam loaded at third points.

Table 2: Results of flexural test on Experimental Beams.

Beam No	Weight (kg)	Position Of Hole	Position Of Load	Load At Failure (kN)	Shear Force V(kN)
Beams with 20mm service holes					
B3	43.50	centre	beam centre	42.10	21.05
B4	42.70	centre	third points	47.15	23.58
B5	44.20	supports	beam centre	62.50	31.25
B6	44.00	supports	third points	73.00	36.50
Beams with 25mm service holes					
B7	43.70	centre	beam centre	39.00	19.50
B8	43.50	centre	third points	48.25	24.13
B9	40.60	supports	beam centre	52.00	26.00
B10	41.3	supports	third points	65.00	32.50

Table 3: 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	$\left(\frac{F_{EUL}-F_{AUL}}{F_{AUL}}\right)x100\%$
B_1	72.50	68.00	6.62
B_2	113.28	75.00	51.04
B_3	72.50	42.10	72.21
B_4	113.28	47.15	140.25
B_5	72.50	62.50	16.00
B_6	113.28	73.00	55.18
B_7	72.50	39.00	85.90
B_8	113.28	48.25	134.78
B_9	72.50	52.00	39.42
B_{10}	113.28	65.00	74.28

Table 4: Comparison of estimated shear and actual shear force of the experimental beams

Beam No	Estimated Shear Force (V_{esf}) Kn	Actual Ultimate Shear Force (V_{ausf}) Kn	$\left(\frac{V_{ESF}-V_{AUSF}}{V_{AUSF}}\right)x100\%$
B_1	91.33	34.00	168.62
B_2	91.33	37.50	143.55
B_3	91.33	21.05	333.87
B_4	91.33	23.58	287.32
B_5	91.33	31.25	192.26
B_6	91.33	36.50	150.22
B_7	91.33	19.50	368.36
B_8	91.33	24.13	278.49
B_9	91.33	26.00	251.27
B_{10}	91.33	32.50	181.02

Also in Table 2, there are results of the flexural texts on the experimental beams with service holes of 25 mm diameter. The ultimate load of B7 with 25 mm diameter service holes at the centre and loaded at the centre was 39.0 kN, while that of beam B8 loaded at third points was 48.25 kN. This shows an increment of 23.72% of the ultimate load of B8 over that of B7. Also for beams B9 and B10 with 25 mm diameter service holes at the supports but loaded at the centre and at third points respectively, had their ultimate loads to be 52.0 kN and 65.0 kN respectively. This shows that ultimate load of B10 is 25% greater than that of B9. Table 3 shows the comparative analysis of the estimated load and actual load of the experimental beams. For beams B1 and B2, the estimated ultimate load is greater than the actual ultimate load by 6.62% and 51.04% respectively. For beams B3, B4, B5 and B6, the estimated ultimate load is greater than actual ultimate load by 72.21%, 140.25%, 16.00% and 55.18% respectively. Also for beams B7, B8, B9 and B10, the estimated ultimate load is greater than actual ultimate load by 85.90%, 134.78%, 39.42% and 74.28% respectively. The comparative analysis of the estimated and actual shear capacities of both the control and experimental beams were shown in Table 4. For beams B1 and B2, the percentage increase of the estimated shear capacity over the actual is 168.62 kN and 143.55 kN respectively. For Beams B3, B4, B5 and B6, the percentage increase of the estimated shear capacity over the actual is 333.87 kN, 287.32 kN, 192.26 kN and 150.22 kN respectively. Also for Beams B7, B8, B9 and B10, the percentage increase of the estimated shear capacity over the actual is 368.36 kN, 278.49 kN, 251.27 kN and 181.02 kN respectively.

The effect of size of service holes on the strength characteristics of beam loaded at the centre is presented in Table 5. The ultimate load of the control beam loaded at centre is greater than the ultimate load for beams B3 and B7 by 38.09% and 42.65% respectively. Also, the percentage increase of the ultimate load of B3 over that of B7 is 7.95%. This indicates that for beams with diameter of service holes at the centre, increases from 20 mm to 25 mm, there is 7.95% decrease in ultimate load when loaded at the centre. Also for beams B5 and B9, with 20 mm and 25 mm diameter holes at the supports and loaded at centre, the reducing effect of increasing the diameter of the holes from 20 mm to 25 mm on the ultimate load is 20.19%.

Table 5: Effect of Size of Hole on Strength Characteristics of Beams

Beam No	Ultimate Load F (Kn)	$\left(\frac{F_{CONTB} - F_{EXPB}}{F_{CONTB}}\right) x100\%$	$\left(\frac{V_{CONTB} - V_{EXPB}}{V_{CONTB}}\right) x100\%$
Beams loaded at Centre with Point Load			
Ultimate load of control beam B1 = 68.00 kN			
B3	42.10	38.09	38.09
B5	62.50	8.09	8.09
B7	39.00	42.65	42.65
B9	52.00	23.53	23.53
Beams loaded at Third Points			
Ultimate load of control beam B2 = 75.00 kN			
B4	47.15	37.13	37.13
B6	73.00	2.67	2.67
B8	48.25	35.67	35.67
B10	65.00	13.33	13.33

Table 5 also shows the effect of size of service holes on the strength characteristics of beam loaded at third points. The ultimate load of the control beam loaded at third points is greater than the ultimate load for beams B4 and B8 by 59.07% and 55.44% respectively. Also, the percentage increase of the ultimate load of B4 over that of B8 is 2.33%. This indicates that for beams with diameter of service holes at the centre, increase from 20 mm to 25 mm, there is 2.33% decrease in ultimate load when loaded at third points. The ultimate load of the control beam loaded at third points is greater than the ultimate loads for beams B6 and B10 by 2.74% and 15.38% respectively. Also for beams B6 and B10, with 20 mm and 25 mm diameter holes at the supports and loaded at third points, the reducing effect of increasing the diameter of the holes from 20 mm to 25 mm on the ultimate load is 12.31%.

Using Eq. 5 (ACI 318, 2008) and Eq. 6 (Olanitori and Afolayan, 2016), the estimated shear capacities are 91.5 kN and 26.57 kN respectively, while the shear force at failure was 37.5 kN and 34.0 kN for the control beams loaded at third points and at the centre with a point load respectively. The shear at failure is less than the predicted value of ACI 318 (2008), because the beams failed by bending before the attainment of their ultimate shear capacities. The value of the estimated shear capacity using Eq. 3 (Olanitori and Afolayan, 2016) is less than the shear force at failure, because the equation was derived from beams with fixed ends.

Conclusion: The ultimate load and shear capacity of beams with service holes depends on the size of holes, position of holes and the type loading. The bigger the diameter of the service holes, the more the reducing effect on the ultimate load. Also, the service hole at the centre of the have higher reducing effect on the ultimate load and shear capacity, when compared with the ones near the supports, hence service holes should be located near the supports of beams, as practicable as possible.

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