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Behavior of high strength self compacted concrete deep beams with web openings

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Abstract

Deep beams transfer loads through loading face to supports in an inclined direction and mostly fail in shear. These beams are with a small span-to-depth ratio. Openings are used to facilitate the passage of utility pipes and service ducts. However, it will cause increasing in cracking and deflection and reduction in the ultimate load of the loaded deep beam. This research investigates and analyses the behavior of reinforced high-strength self-compacted concrete deep beams (RHSSCC) with web opening. Sixty-one deep beams were cast to investigate the effect of size (75 mm and 50 mm two opening's size were used), shape (square, circular and relatively new type "rhombus" shape) and location of openings with respect to a neutral axis (upper or lower N.A.) and with respect to the load path (in or out load path) on the behavior of RHSSCC deep beam with three types of web openings (symmetrical, unsymmetrical and centered web openings). Load-deflection curves, crack pattern, absorbed energy and crack pattern for the tested beams is discussed.

Keywords: Civil engineering

1. Introduction

Deep beams are progressively employed in modern construction and have practical applications in wide range of structures. Deep beam is defined by ACI 318-14 [1]; as a structural element with clear span is equal to or less than four times the overall depth, or with applied concentrated loads that are within a distance equal to or less than two times the depth from the face of the support. Load in the deep beam is transferred significantly to supports by compression struts with very little or no flexure. The behavior reinforced concrete deep beams are more complex and differ from that of shallow beams [2, 3, 4]. Also, deep beams strains are not linearly distributed across the beam depth [5].

Creating web opening in reinforced concrete (RC) deep beams is an essential requirement to be suitable for the utility services like electricity and air conditioning conduits. Many researchers have been conducted on RC deep beams with openings [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28].

Due to the reduction of the cross-sectional area of the beam, Opening in the web of a deep beam reduces its shear capacity and stiffness [16, 17, 18, 19]. The shear capacity reduction depends on the interruption degree with the naturalistic load path which is the connecting line between load and support points. The full interruption to the natural load path with an opening leads to more significant shear capacity reduction [11, 12].

Opening Shape is one of the important parameters that affect the shear strength of the deep beam. Circular and square shapes are most common types of openings being provided in deep beams. Many researchers found that, regarding the structural strength of the beam, using circular opening has advantages over using square opening.

The strength of the beam is reduced with the increasing of the opening size. The increase in the opening size dimensions cause changes in the cracks' pattern and failure's type. Failure will change from flexural failure to beam type shear failure. The cracking development increased with the increasing in openings size.

Location of the opening has a considerable effect on the structural strength of the deep beam. If compared with the opening shape, opening location gives more effect than opening shape.

Although there are attempts that have been conducted for evaluation of the ultimate strength of deep beams, there are still limitations and uncertainties on the understanding of the mechanism of the behavior and the failure pattern of high strength

concrete deep beams, especially those with web openings. So, there is a necessity to investigate high strength concrete deep beams with web openings [28].

Experimentally test results of high-strength concrete deep beams conducted by Tan et al. [20] and Yang et al. [21] showed that the effect of concrete strength on the nominal shear strength is more significant in the deep beam than in slender beam because the most loads is transferred by the concrete strut.

Deep beams have a narrow width and contain congested shear reinforcement. Therefore, there is a problem in conventional concrete flow that may be attributed to incomplete filling of the deep beam bottom part. Problems such as voids, segregation, and weak bond with reinforcement bars and holes in the surface have been appeared while casting. So, self-compacting concrete (SCC) is the most suitable type for casting deep beams.

The present work focuses on the investigation of the effect of web openings on the behavior of Reinforced high-strength self-compacted concrete (RHSSCC) deep beam. These openings have different locations and various shapes (circular & square and rhombus) and sizes.

2. Materials and methods

2.1. Experimental program

Sixty one RHSSCC deep beams have been cast as the experimental program was carried out to investigate the effect of shape, size, and location of web openings. Three types of web openings location were used. The first type has two openings in both sides for deep beam named "symmetrical openings", the second has one opening in one side named "unsymmetrical opening" and the third has the opening in the center of deep beam span named "centered opening". As for shape, three different shapes of opening were used (square, circular and rhombus). The square and circular openings are traditionally used in all the previous researches as previously indicated, while rhombus shape was used as a new type of shape. Two opening sizes were used to investigate the effect of opening size on the load-deflection behavior of HSSCRC deep beam (50 mm and 75 mm side length or circular diameter). The chosen dimension was selected to be suitable to the distance between vertical or horizontal steel reinforcement bars. Changing the position of the openings in both horizontal and vertical direction was also introduced in this research. As for horizontal direction symmetrical and un-symmetrical cases of openings only were located on or out of load path. While for the vertical direction, openings were located upper or lower neutral axis (N.A.) (opening located out of the middle third of deep beam depth) for all type of web openings.

2.2. Materials

The density of reinforcing bars in deep beams that made the vibration of concrete is not an easy task. The use of SCC is highly desirable. The workability for HSSCC was known by slump flow and J-Ring tests. The result of tests was accepted according to British standard (BS EN 206-9, 2010) [8] and Egyptian code (E.C.P. 203/2012) [14] as shown in Fig. 1. The HSSCC mix design is given in Table 1. In the mix design, cement used was ordinary Portland cement CEM I 52.5N. Natural and clean sand with a specific gravity 2.71 t/m^3 and fines modulus 2.0. Crushed Dolomite of maximum nominal size 12.5 mm and specific gravity 2.65 t/m^3 was used as coarse aggregate. Sika Viscocrete 3425 is the used Super-plasticizer it is a polycarboxylate based super-plasticizer supplied by Sika Egypt, which meets the requirements of super-plasticizer according to ASTM-C-494 [29], types G and F. The used super-plasticizer has 1.08 Kg/lit density, and 40% solid content (by weight). The density and fineness of the silica fume used were 2210 kg/m^3 and 23.52 m^2/gm respectively. The density of the used silica fume was 300 kg/m^3. The used silica fume met the requirements of ASTM C 1240 [30].

Two types of steel reinforcement were used as shown in Table 2. The first was the mild steel (St.37) which was used as vertical and horizontal shear reinforcement. The second type was the high tensile steel (St.52) which was used for the upper and lower reinforcement.

2.3. Deep beams casting

All Specimens were cast in moulds of dimension of 150 × 300 × 1100mm. All deep beams were of the same dimensions and reinforcement (RFT) as shown in the Fig. 2. The web openings were created using medium density foam for square and rhombus openings and PVC pipe for circular openings as shown in Fig. 3. Beams were cast to be tested and cured with wet canvas till testing as shown in Fig. 4 after 28 days also 6


Fig. 1. Slump flow & J-Ring tests.

Table 1. HSSCC mix design.

Cement (Kg/m^3)	550
Silica fume (Kg/m^3)	27.5
Coarse aggregate (Kg/m^3)	762
Fine aggregate (Kg/m^3)	762
Water (Litre/m^3)	184.8
Super-plasticizer (Litre/m^3)	6.93
Slump of concrete Diam. (Cm)	> 65
Time of slump T_{50cm}(sec)	4.2
Different high of J-ring (Cm)	0.4
Characteristic cube strength (MPa)	73.6

Table 2. Mechanical properties of steel Rft.

Steel Type	Yield Stress (Kg/cm^2)	Tensile Strength (Kg/cm^2)	Elongation (%)
Mild St.	2950	3990	22.2
High Tensile St.	3680	5310	13.2
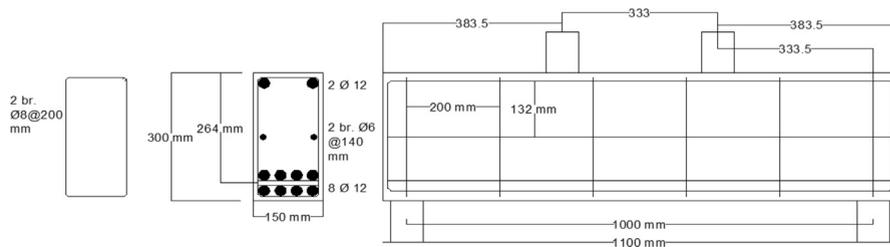
Fig. 2. The RFT details for tested beams.

cubes (150 × 150 × 150mm) for each deep beam were cast to be sure of the compressive strength at the age of 7 and 28 days.

2.4. Nomenclature for specimens

Fig. 5 shows the Nomenclature for deep beam specimens where:

The first letter points to opening type, (S) for symmetrically web openings, (U) for unsymmetrical web opening, and (C) for centered web opening. While for the second letter, it indicates to opening shape, (S) for square, (C) circular, (R) for rhombus opening. Opening's position with respect to (N.A.) denoted with the third letter, (U) upper (N.A.) and (L) lower (N.A.). The number refers to the opening size in millimeter (mm). Finally, letter stands for position's opening (for symmetrically and unsymmetrical cases) with respect to load path, (P) at load path and (O) out of load path. Fig. 6 shows an example for specimens' Nomenclature for unsymmetrical
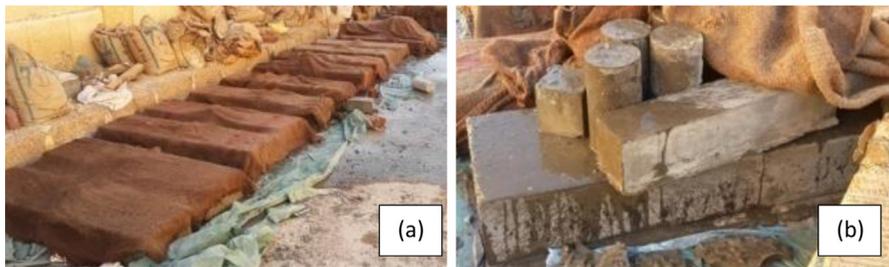
Fig. 3. Casting of deep beam with opening.

Fig. 4. The Beams curing (a) curing with wet canvas (b) cured cubes, cylinders, brism and deep beam.
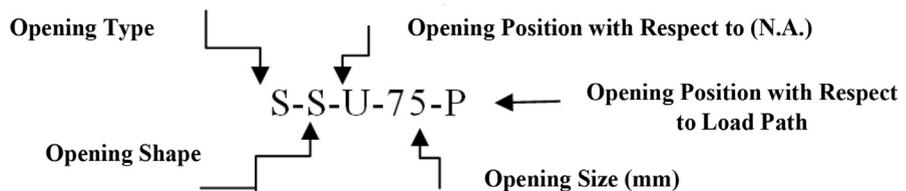

Fig. 5. Nomenclature for specimens.

circular shape with 50 mm diameter and located lower (N.A.) out of the load path (UCL50O).

2.5. Four point load test procedure

A steel frame with two movable I-beam girders were used as a support for beams. The load was applied by a hydraulic cylinder double acting with 150 ton capacity and 150 mm maximum stroke which was connected to a hydraulic pump. The applied load was measured by a load cell of 225 ton capacity. Fig. 7 shows the loading frame and equipments. An LVDT for measuring displacements up to 100 mm was placed under each beam at the center of its span to measure deflections within the region of pure bending between the two load points. The load cell and the LVDT were connected to a data logger that shows a continuous record of the applied load and the corresponding deflection at mid span.
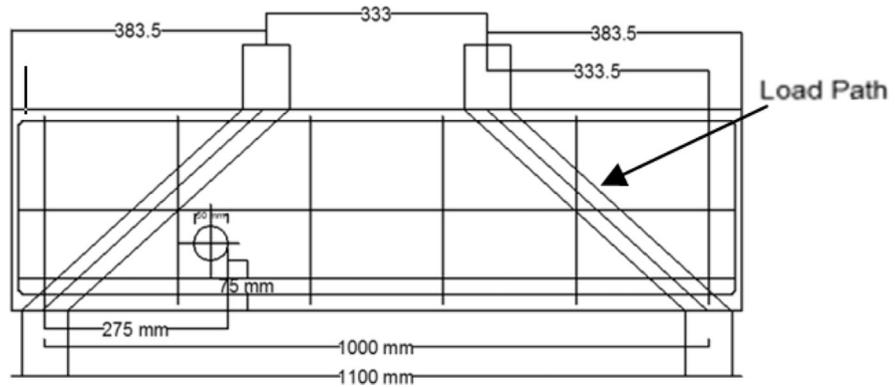
Fig. 6. The beam UCL50O.

2.6. Control beam's strain distribution

Control beam's stress distribution was measured at different loading stages by pre-drilled stainless steel discs (Demec points) which are attached to the structure using a suitable adhesive material. Fig. 8 shows the strain at cracking and ultimate load. From the stress distribution of control beam, it could indicate that (N.A) is at the middle third of the beam depth and it tends slightly to the upper direction.

3. Results and discussion

Table 3 shows the values for cracking, ultimate load and absorbed energy (AE) for sixty-one tested beams. The ultimate and cracking load are indicated from the load deflection curves. The absorbed energy was calculated by measuring the area under load deflection curve for each beam [24]. The absorbed energy (AE) value is an indicator of the degree of ductility for the tested beam [10]. The increase in absorbed energy value refers to more ductile than the low values. Figs. 9, 10, 11, 12 and 13 show the load deflection curves for all the tested beams.
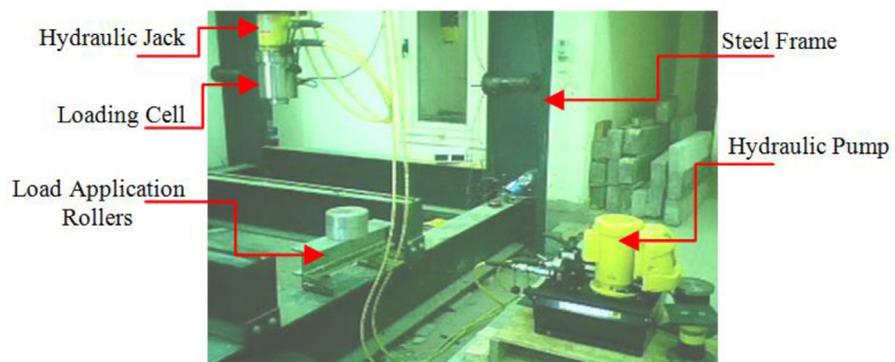

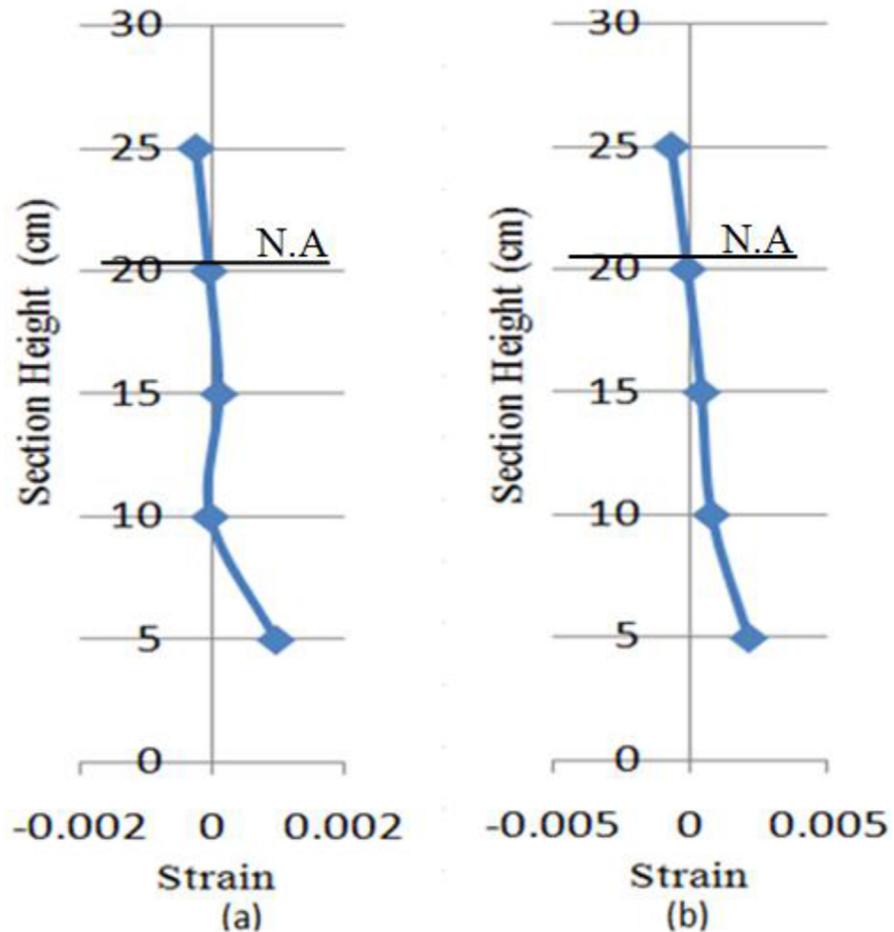**Fig. 7.** Loading frame and equipments.

Fig. 8. Strain distribution for control beam (a) at cracking load (b) at ultimate load.

From the absorbed energy results of symmetrically and unsymmetrical opening in RHSSCC deep beam, the ductility of the opening located out of the load path is more than that of opening met load path. The ductility for the deep beam with opening located lower (N.A.) was more than that of the opening located upper (N.A.). While for beams contain centered opening, the opening was located in the upper of (N.A.) was more ductile than the opening located lower (N.A.).

Deep beams contain centered opening have the highest absorbed energy (highest ductility), followed by that contain unsymmetrical opening and finally that contain symmetrical opening gave the lowest absorbed energy (lowest ductility).

3.1. Ultimate and cracking loads

Size, shape and position of web openings have a considerable effect on the ultimate and cracking loads of RHSSCC deep beams. From Table 3 a reduction in the values of ultimate and cracking load of RHSSCC deep beams with openings compared to

Table 3. Deep beams test results.

T.	MODEL	P_{CR}(KN)	P_U(KN)	AE (KN.mm)	T.	MODEL	P_{CR}(KN)	P_U(KN)	AE (KN.mm)
	CONTROL	326	582.2	1164.4	Unsymmetrical opening	**USU50O**	245.6	473.4	1297.1
Symmetrical openings	**SSU75P**	140.8	269.9	448.034		**USL50P**	266.9	490.7	1216.94
	SSU75O	225	333	559.44		**USL50O**	263	516	1359.66
	SSL75P	205.2	343.2	641.784		**UCU75P**	198.6	313	658.87
	SSL75O	232.3	411.3	826.713		**UCU75O**	265.9	454.3	1347
	SSU50P	156	286.3	475.3078		**UCL75P**	269.1	462.3	1047.1
	SSU50O	195.7	341.4	785.22		**UCL75O**	281.2	499	1449.6
	SSL50P	205.1	351.3	670.983		**UCU50P**	233.6	439.2	1190.2
	SSL50O	243.5	433.8	1043.289		**UCU50O**	267.3	508	1366.52
	SCU75P	175.8	292.8	509.472		**UCL50P**	276.3	510.3	1201.8
	SCU75O	217.1	422.6	849.426		**UCL50O**	275	539.1	1477.9
	SCL75P	249.4	447.1	1059.627		**URU75P**	192.8	299.7	521.48
	SCL75O	239.3	467.2	1179.68		**URU75O**	249.9	481.8	1062.4
	SCU50P	176.2	325.2	710.562		**URL75P**	260.2	481.8	1156.3
	SCU50O	213.5	425.8	1124.112		**URL75O**	249.6	509.4	1269.7
	SCL50P	254.3	463.3	1169.83		**URU50P**	195.4	316.2	717.774
	SCL50O	234.2	492.3	1294.618		**URU50O**	230.1	489.3	1147.409
	SRU75P	179.8	281.6	523.776		**URL50P**	263.6	501.7	1653.102
	SRU75O	225.1	388.4	827.292		**URL50O**	247.2	519.4	1680
	SRL75P	212.2	348.7	737.5005	Centered opening	**CSU75**	310.6	546.2	1695.95
			494.4	1456.008				528	
	SRL75O	278.4	494.4	1456.01		**CSL75**	269.9	528.8	1351.1
	SRU50P	169.2	331.3	722.234		**CSU50**	280.9	556.4	1724.84
	SRU50O	234.3	448	1003.69		**CSL50**	276.8	539.9	1366.1
	SRL50P	235.4	476.8	1082.34		**CCU75**	256.4	546.9	1425.1
	SRU50P	285.9	518.2	1471.7		**CCL75**	265.2	530.8	1374.8

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Table 3. (*Continued*)

T.	MODEL	P_{CR}(KN)	P_U(KN)	*AE* (*KN.mm*)	T.	MODEL	P_{CR}(KN)	P_U(KN)	*AE* (*KN.mm*)
Unsymmetrical	**USU75P**	165.7	279.3	498.551		**CCU50**	267.3	562.2	1774.6
	USU75O	224.1	404.9	803.727		**CCL50**	247.3	548.6	1601.9
	USL75P	225.9	420.9	839.6955		**CRU75**	259.5	549	1701.9
	USL75O	267.4	450.4	894.044		**CRL75**	252.6	530.9	1117.5
	USU50P	178.2	293.4	563.6		**CRU50**	271.5	560.3	1619.3
						CRL50	261.1	539.7	1611
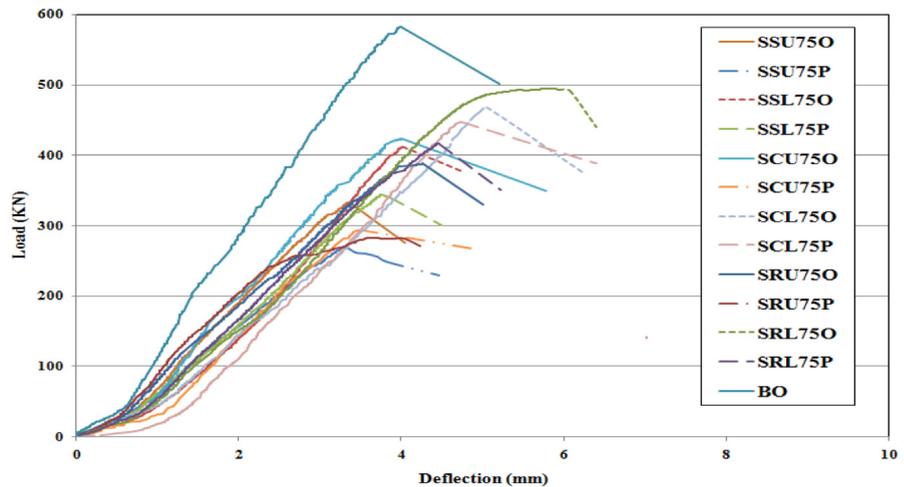
Fig. 9. Load deflection curves for beams with symmetrically opening of size 75 mm.

control deep beam could be noticed. Figs. 14, 15, 16, 17, 18, 19, 20 and 21 show the relation between type of web opening and cracking and ultimate load for tested beams.

3.1.1. Effect of opening's size

From the results, it could be found that there is a significant reduction in the ultimate and cracking loads of deep beams with 75 mm size openings more than 50 mm compared to control beam despite considering any other factors.

For the ultimate and cracking loads of deep beams with different shapes and symmetrically openings, the reduction of 75 mm size opening was ranging between 15.1% to 53.6% and 14.6% to 56.8% for the ultimate and cracking load
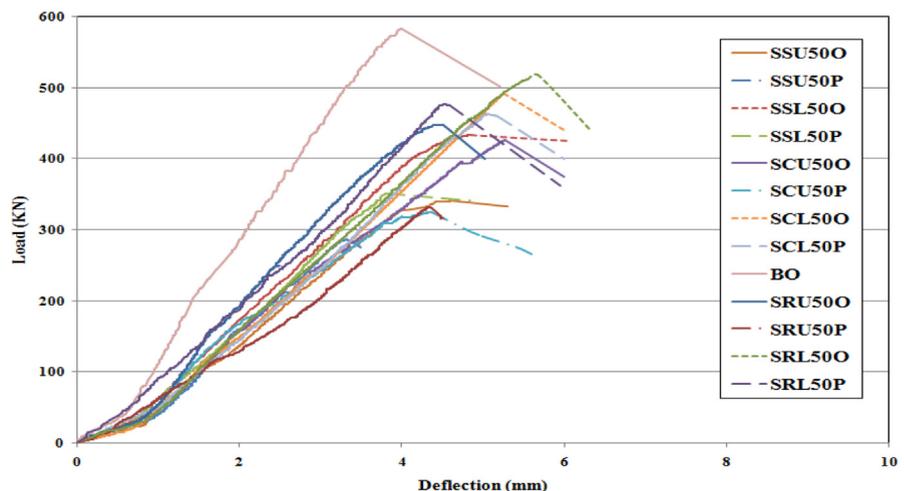
Fig. 10. Load deflection curves for symmetrically opening with size 50 mm.
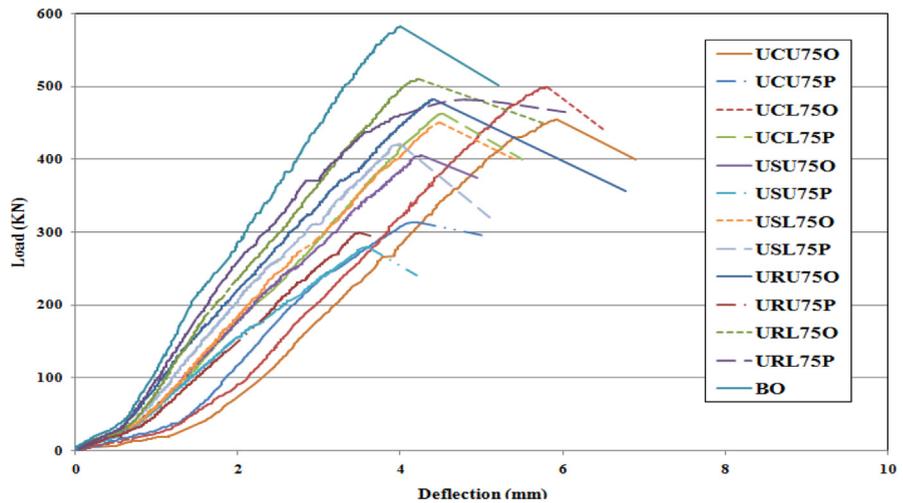
Fig. 11. Load deflection curves for unsymmetrical opening with size 75 mm.

respectively compared to control beam. The reduction for 50 mm was ranging between 11% to 50.8% and 12.3% to 52.1% of the ultimate and cracking load respectively. While the ultimate and cracking loads of deep beams with un-symmetrical openings with different shapes, 75 mm size opening gives reduction ranging between 12.5% to 52% and 13.7% to 49.2% and for the ultimate and cracking load and for 50 mm opening it was ranging between 7.4% to 49.6% and 15.2% to 45.3%. As for centered openings' ultimate and cracking loads with different shapes, the reduction of 75 mm size opening was ranging between 5.7% to 9.2% and 17.1%, 22.5% for the ultimate and the cracking load respectively while for 50 mm was ranging between 3.4% to 7.3% and 13.8% to 24.1% of the ultimate and cracking load respectively.
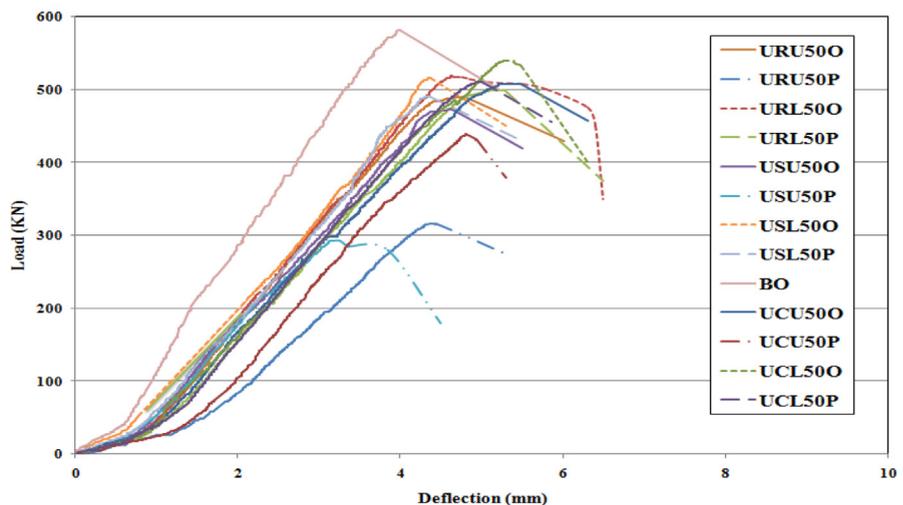

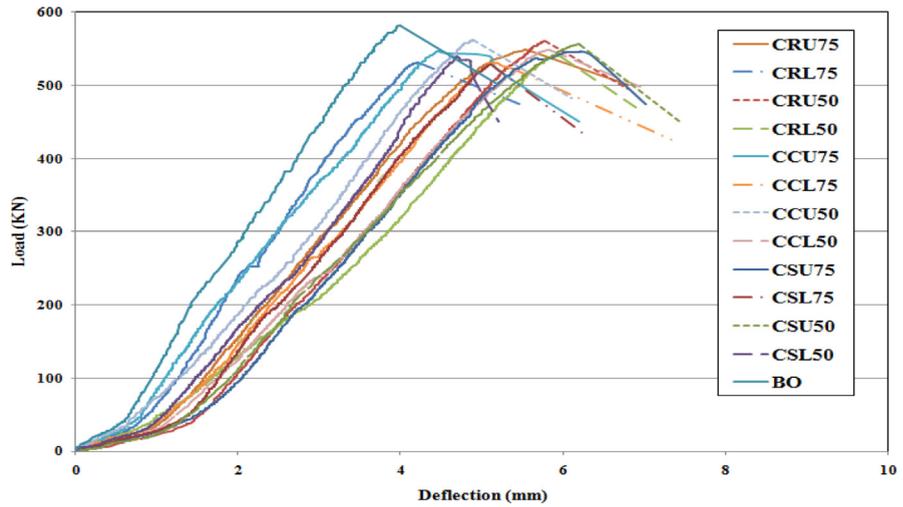**Fig. 12.** Load deflection curves for unsymmetrical opening with size 50 mm.

Fig. 13. Load deflection curves for Centered opening.

Increasing in the opening size causes more reduction in the ultimate and cracking load compared to deep beams that have smaller opening size. The load capacity reduction is due to the reduction in concrete area.

3.1.2. Effect of opening's shape

Comparing ultimate and cracking loads of the tested deep beams, it could be found that there is a significant reduction in the ultimate and cracking loads of deep beams with square shape openings more than circular and rhombus shapes openings compared to control beam despite considering any other factors.
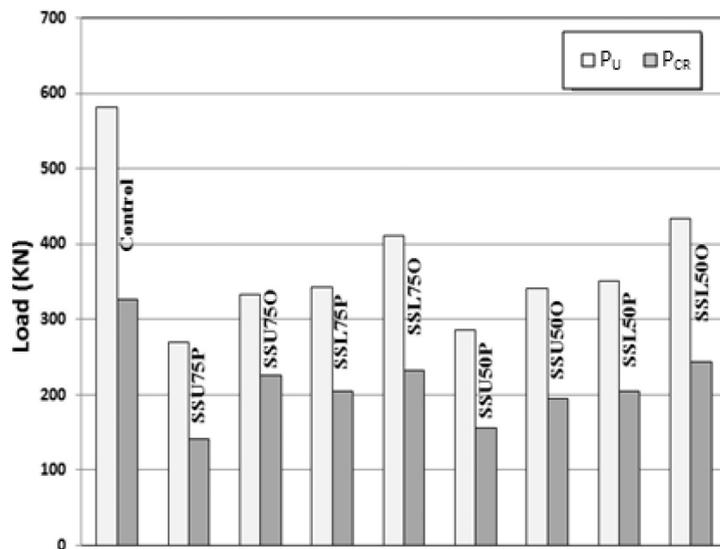

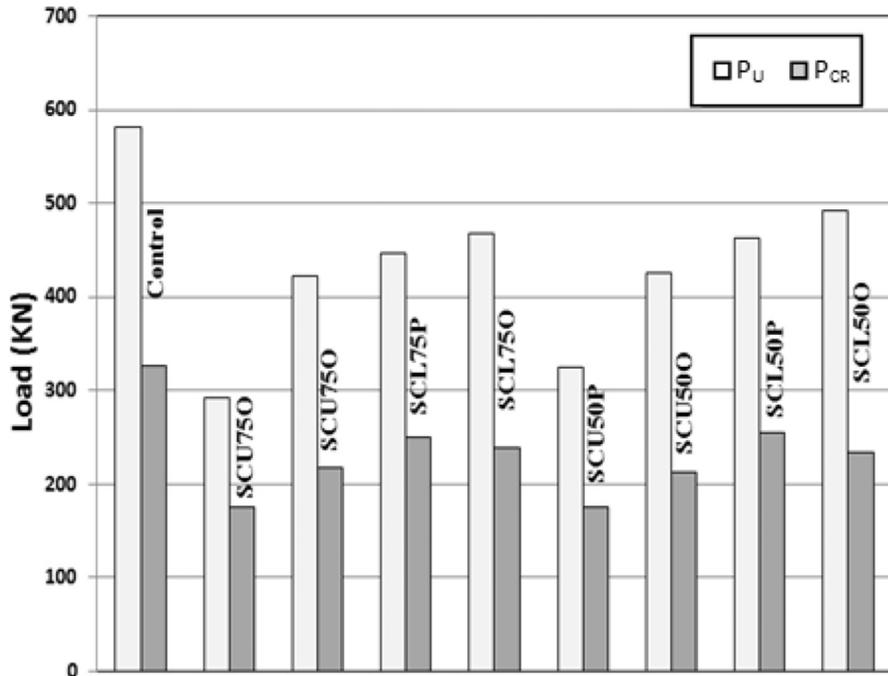**Fig. 14.** Ultimate and Cracking load for symmetrically square opening.

Fig. 15. Ultimate and Cracking load for symmetrically circular opening.

Squared shape symmetrical openings deep beam has a reduction in the ultimate and cracking load by about 25.5%−53.6% and 25.3% to 56.8% respectively compared to control beam. The reduction due to circular shaped openings was ranging between 15.5% to 49.7% and 22% to 46.1% for the
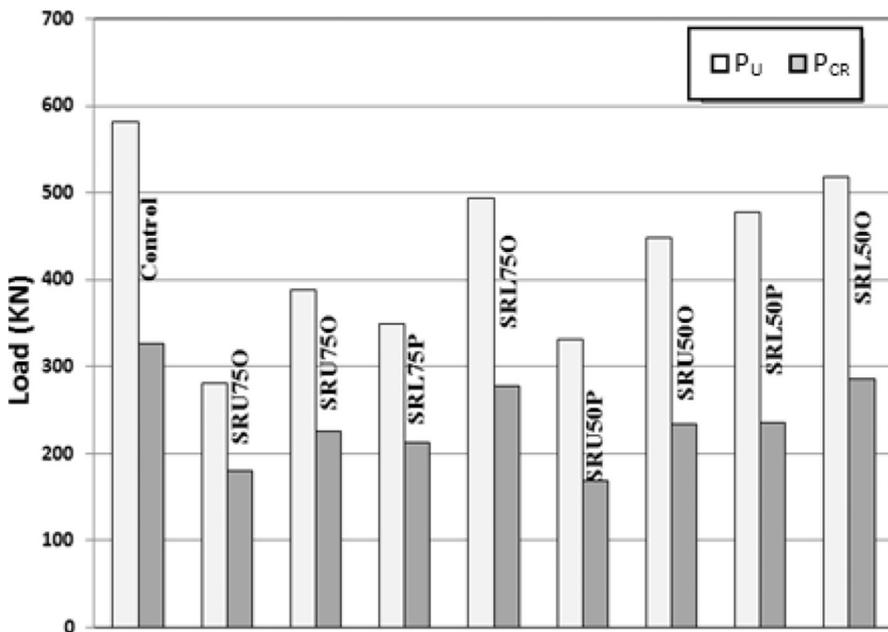

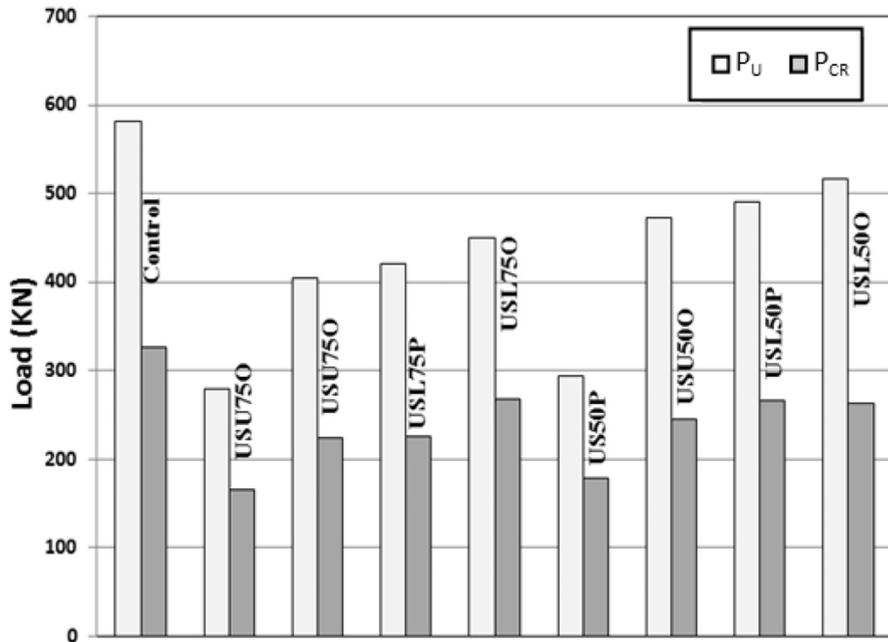**Fig. 16.** Ultimate and Cracking load for symmetrically Rhombus opening.

Fig. 17. Ultimate and Cracking load for unsymmetrical square opening.

ultimate and cracking load. As for rhombus opening shapes which could be considered as a relatively new type of opening shape in deep beam researches show a reduction ranging between 11% to 51.6% and 12.3% to 48.1% for the ultimate and cracking load respectively.
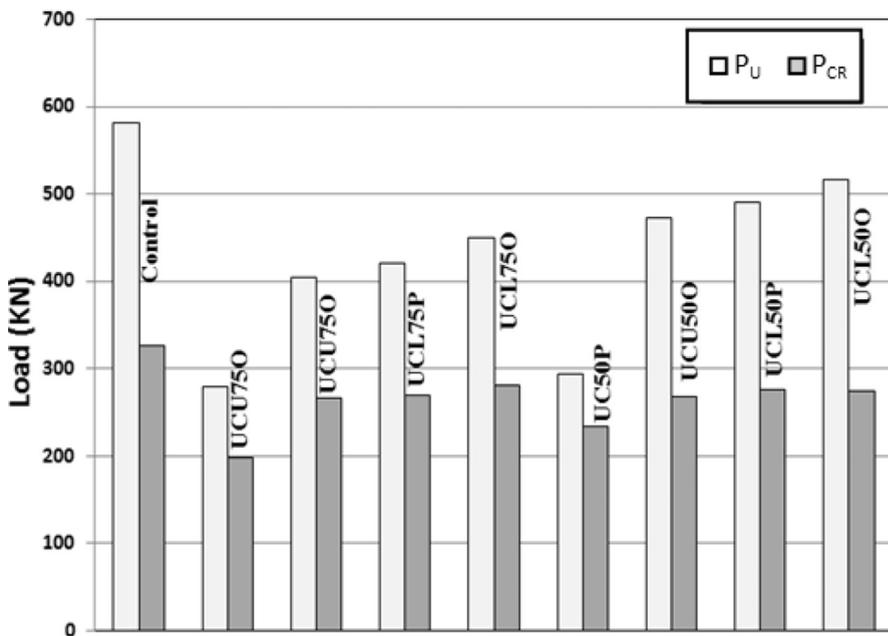

Fig. 18. Ultimate and Cracking load for unsymmetrical circular opening.
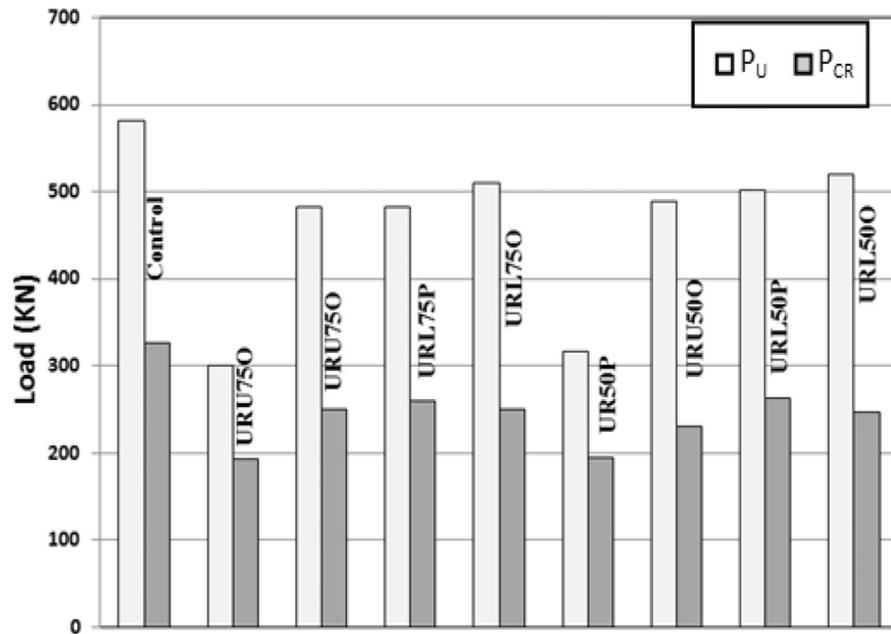
Fig. 19. Ultimate and Cracking load for unsymmetrical rhombus opening.

The effect of opening shape in the case of using unsymmetrical openings on the ultimate and cracking load flows the same bath as that of the symmetrical openings. The reduction due to unsymmetrical openings has nearly the same range as symmetrical openings for the used three shapes for the ultimate and cracking load compared to the control beam results.

Centered openings' with square shape leads to reducing the ultimate and cracking loads by about 4.4%−9.2% and 4.7%, 17.2% for the ultimate and the cracking load respectively. While for circular opening the reduction was ranging between 3.4% to 8.8% and 18% to 24.1% of the ultimate and cracking load. As for rhombus shape ranges between 3.8% to 8.8% and 16.7% to 22.5% were observed for the reduction of the ultimate and cracking load.

Comparing in terms of shape, circular and rhombus web opening offered less reduction than the square openings. Sharp corners/edges of the square shaped openings are subjected to high stress concentration that leads to initial cracking of the beam for all type of web.

3.1.3. Effect of opening's position

With respect to (N.A.), the position of the opening may be located upper or lower (N.A.).

For symmetrical type openings, openings upper (N.A) gives a reduction ranging between 23% to 53.6% and 28.1% to 56.8% for the ultimate and cracking load

respectively compared to control beam and the reduction for the symmetrical openings located lower (N.A) was ranging between 11% to 41% and 12.3% to 37.1% of the ultimate and cracking load respectively.

In the case of unsymmetrical openings reduction of the ultimate and cracking load for openings located upper (N.A.) was ranging between 12.7% to 52% and 15.2% to 49.2% for the ultimate and cracking load respectively and for that located lower (N.A.) loads reduction were ranging between 7.4% to 27.7% and 13.7% to 30.7% for the ultimate and cracking load respectively.

For centered openings, the ultimate and cracking loads for openings upper (N.A.) have reduction ranging between 3.4% to 6.2% and 4.7%, 21.3% for the ultimate and cracking load respectively compared. The reduction for centered openings located lower N.A was ranging between 5.8% to 9.2% and 17.2% to 24.1% of the ultimate and cracking load respectively.

Comparing in terms of position, lower (N.A) symmetrical and unsymmetrical opening offered less reduction than the upper openings. while for centered opening openings with position upper (N.A.) gave more reduction than the lower opening, because in symmetrical and unsymmetrical cases when the opening located at the strut (compression stress bath) as in the case of openings located upper (N.A.) the concrete area reduction (which is responsible for carrying compression stresses) leads to decrease in the deep beam loading capacity while for centered case opening located lower (N.A.) leads to weakness in the flexure zone that leads to reduction in the overall beam loading capacity.
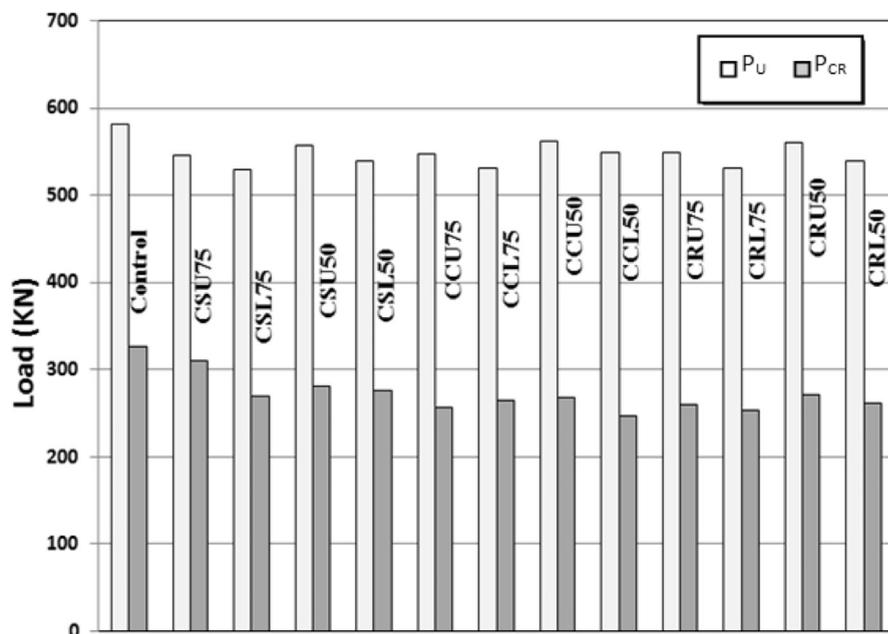

Fig. 20. Ultimate and Cracking load for centered opening.

Fig. 21. Examples for deep beam specimens (*) Cracks' Pattern * beam name is labeled on each beam.

Openings in the deep beam may be located in the load path or out of the load path according to its position.

For symmetrically openings, the reduction of the ultimate and cracking load openings ranging from 18.1% to 53.6% and 22% to 56.8% respectively for deep beam contains opening that meet the load path while for that located out of the load path there was a reduction ranging between 11% to 42.8% and 12.3% to 40% for the ultimate and cracking load respectively.

In the case of unsymmetrical openings, the reduction of the openings which meets the load path was ranging from 12.4% to 52% and 15.2% to 49.2% for the ultimate and cracking load respectively compared to control beam and the reduction for the openings located out of the load path was ranging from 7.4% to 30.5% and 13.7% to 49.2% of the ultimate and cracking load respectively.

When the opening met the load path, it makes a disturbance in the natural flow of the load so; it offered more reduction in the loading capacity than that located out of the load path.

3.1.4. Effect of opening's location

Openings may be located symmetrically about the centerline of the beam or on one side only (unsymmetrical case) or located on the center line of the beam. From the results presented in Table 3, it could be found that the biggest reduction in the ultimate and cracking loads of deep beams was for symmetrically openings case followed by unsymmetrical opening then by centered opening.

3.2. Crack pattern

From the observations while carrying out the experimental work and from the cracks pattern of tested beams, all the tested deep beams were failing in shear. Fig. 21 shows examples for 10 types of deep beams with openings for after failure. For control beam, the flexural cracks were initiated at the bottom of deep beam but stopped before penetrating compression zone and with load increasing; shear crack appeared at both sides of deep beam to form with load increasing the same shape and direction of the inclined compression strut till sudden failure.

The diagonal cracks takes place while loading deep beams with symmetrical and unsymmetrical openings. Cracks were initiated and formed at the corner of the openings. The presence of the opening caused disturbance in the natural flow path of stress which leads to high stress concentration and early cracking at corner of square openings while in circular opening the stress distributed around the diameter. As for rhombus the load path met the edge of rhombus and stress distributed at edge. As for the size of the openings it decreased the number of diagonal cracks increased. When

the openings were located at lower (N.A.), the cracks toward the support more than opening located upper (N.A.) and diagonal cracks for openings meet the critical load path less than cracks for openings located out load path.

Cracks in symmetrical web opening deep beams were appeared in both sides while for unsymmetrical opening the disturbance of load path occur in the opening side and little cracks in other side. For centered opening, the flexure and diagonal cracks were observed.

For opening located upper (N.A.), the flexural cracks appeared and propagated vertically upward, but did not meet the inclined compression strut then the flexure cracks stopped and the diagonal shear cracks appeared and increased till sudden failure through the inclined compression strut.

In case of centered web openings, the flexural cracks started from the bottom of the deep beam and propagated vertically till reaching the opening location level.

4. Conclusion

Based on the results obtained, the following conclusions could be deduced:

1. Deep beams have a narrow width and contain congested shear reinforcement. So, self-compacting concrete (SCC) is the most suitable type for casting deep beams.

2. The reduction of the ultimate and cracking load of the deep beams with web openings compared to deep beam without opening was ranging between 5 to 55 %.

3. All tested RHSSCC deep beams with web opening failed in shear.

4. Increasing web opening size leads to reduction in the ultimate and cracking load and the overall ductility of the deep beam.

5. In terms of ultimate and cracking load values and absorbed energy, the new relatively type (rhombus shape) of opening gave better results than traditionally used of square shape in all cases and gave result close to the result of circular shape opening.

6. When the opening meets the load path, it makes a disturbance in the natural flow of the load so; it offered more reduction in the loading capacity and ductility than that located out of the load path.

7. From Table 3 and considering the web opening's position with respect to (N.A.), openings located below (N.A) even symmetrical or unsymmetrical case presented less reduction in ultimate and cracking load than openings located above (N.A). On the contrary, the centered case with opening located above (N.A.) gave more reduction than opening located below (N.A.)

8. Considering the openings' location, the biggest reduction in the ultimate and cracking loads of deep beams was for symmetrically openings case followed by unsymmetrical opening then by centered opening.

Declarations

Author contribution statement

Hassan M. Hassan, Mohammed A. E-S. Arab, Ahmed I. El-Kassas: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Additional information

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References

[1] A. C. I. Committee, A. C. Institute, and I. O. for Standardization, Building Code Requirements for Structural concrete (ACI 318-08) and Commentary, 2008.

[2] A. Demir, N. Caglar, H. Ozturk, Parameters affecting diagonal cracking behavior of reinforced concrete deep beams, Eng. Struct. 184 (2019) 217–231.

[3] A.F. Ashour, G. Rishi, Tests of reinforced concrete continuous deep beams with web openings, Struct. J. 97 (3) (2000) 418–426.

[4] A.N. Hanoon, M.S. Jaafar, F. Hejazi, F.N.A.A. Aziz, Strut-and-tie model for externally bonded CFRP-strengthened reinforced concrete deep beams based on particle swarm optimization algorithm: CFRP debonding and rupture, Constr. Build. Mater. 147 (2017) 428–447.

[5] A.R. Mohamed, M.S. Shoukry, J.M. Saeed, Prediction of the behavior of reinforced concrete deep beams with web openings using the finite element method, Alexandria Eng. J. 53 (2) (2014) 329−339.

[6] B.S. Abduljalil, Shear resistance of reinforced concrete deep beams with opening strengthened by cfrp strips, J. Eng. Sustain. Dev. 18 (1) (2014) 14−32.

[7] B.S. Chen, M.J. Hagenberger, J.E. Breen, Evaluation of strut-and-tie modeling applied to dapped beam with opening, Struct. J. 99 (4) (2002) 445−450.

[8] B. S. Institution, Structural Use of concrete, British Standards Institution, 1985.

[9] B.S. Maxwell, J.E. Breen, Experimental evaluation of strut-and-tie model applied to deep beam with opening, Struct. J. 97 (1) (2000) 142−148.

[10] O. Buyukozturk, Lectures in Mechanical and Design of concrete Structures (Ductility and Deflection), Massachusetts Institute of Technology, 2004.

[11] C.S. Choo, N. Shafiq, A. Kusbiantoro, M.F. Nuruddin, Reinforced concrete deep beams with openings strengthened using FRP-A review, Adv. Mater. Res. (2014).

[12] C.-C. Chen, K.-T. Lin, Y.-J. Chen, Behavior and shear strength of steel shape reinforced concrete deep beams, Eng. Struct. 175 (2018) 425−435.

[13] E.-203 P. Committee, ECP-203: 2007-Egyptian Code for Design and Construction of concrete Structures, HBRC, Giza, 2007.

[14] G. Campione, G. Minafò, Behaviour of concrete deep beams with openings and low shear span-to-depth ratio, Eng. Struct. 41 (2012) 294−306.

[15] G. Hussein, S.H. Sayed, N.E. Nasr, A.M. Mostafa, Effect of loading and supporting area on shear strength and size effect of concrete deep beams, Ain Shams Eng. J. 9 (4) (2018) 2823−2831.

[16] H.A. Mohameda, Effect of Web Openings Size on Steel Fiber Reinforced Concrete Deep Beams, 2013.

[17] H. Chen, W.-J. Yi, Z.J. Ma, Shear size effect in simply supported RC deep beams, Eng. Struct. 182 (2019) 268−278.

[18] H. Eun, Y. Lee, H. Chung, K. Yang, On the shear strength of reinforced concrete deep beam with web opening, Struct. Des. Tall Special Build. 15 (4) (2006) 445−466.

[19] H.M. Alsaeq, Effects of opening shape and location on the structural strength of RC deep beams with openings, Proc. World Acad. Sci. Eng. Technol. 78 (2013).

[20] K.H. Tan, K. Tong, C.Y. Tang, Consistent strut-and-tie modelling of deep beams with web openings, Mag. Concr. Res. 55 (1) (2003) 65−75.

[21] K.-H. Yang, H.-S. Chung, A.F. Ashour, Influence of Shear Reinforcement on Reinforced concrete Continuous Deep Beams, 2007.

[22] M.A. Ibrahim, A. Elthakeb, A.A. Mostfa, H.A. Kottb, Proposed formula for design of deep beams with shear openings, HBRC J. 14 (3) (2018) 450−465.

[23] M. Deng, F. Ma, W. Ye, X. Liang, Investigation of the shear strength of HDC deep beams based on a modified direct strut-and-tie model, Constr. Build. Mater. 172 (2018) 340−348.

[24] M. Mohammadhassani, M.Z. Jumaat, M. Jameel, H. Badiee, A.M.S. Arumugam, Ductility and performance assessment of high strength self compacting concrete (HSSCC) deep beams: an experimental investigation, Nucl. Eng. Des. 250 (2012) 116−124.

[25] M. Moradi, M.R. Esfahani, Application of the strut-and-tie method for steel fiber reinforced concrete deep beams, Constr. Build. Mater. 131 (2017) 423−437.

[26] N.R. Yahya, Effects of Square Openings in Reinforced Concrete Deep Beams, UMP, 2014.

[27] T. El Maaddawy, S. Sherif, FRP composites for shear strengthening of reinforced concrete deep beams with openings, Compos. Struct. 89 (1) (2009) 60−69.

[28] T.M. Yoo, Strength and Behaviour of High Strength concrete Deep Beam with Web Openings, Griffith University Nathan, 2011.

[29] American Society for Testing and Materials (ASTM), ASTM C494: Chemical Admixtures, ASTM International, West Conshohocken, PA, USA, 2003.

[30] American Society for Testing and Materials (ASTM), ASTM C1240-05: Standard Specification for Silica Fume Used in Cementitious Mixtures, ASTM International, West Conshohocken, PA, USA, 2005.