

Behavior of high strength reinforced concrete Deep beams with openings

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ABSTRACT

Codes of practice offer little guidance for design of deep beams especially which have web opening provided for essential services, so an analytical model is proposed to solve this problem herein.

Thirty nine specimens analyzed to study the behavior of high strength reinforced concrete deep beams with openings. All specimens are simply supported of constant dimensions effective span 1800 mm and cross section dimensions are (120 mm x 600 mm).

The specimens divided to three sets, Set A, consists of sixteen specimens divided to four groups with same opening dimension and different locations through the vertical and horizontal directions. Set B, consists of fifteen specimens divided to three groups have same opening location and different opening shape, square or rectangle. Set C, consists of eight specimens divided to two groups studying the effect of concrete grade, four specimens are normal strength and another four specimens are high strength concrete.

KEYWORDS: Deep beams, Openings, High strength, Finite element.

1. INTRODUCTION

In recent years, concrete deep beam interconnecting systems in building and precast construction have become increasingly popular worldwide. This is because there is a huge demand for structures to be built to high elevations due to the lack of land available, especially in major modern cities. The need for an accurate design methodology for deep beams with openings [1] [2] is becoming increasingly necessary with the subsequent growth in the use of deep beams in construction industry.

Deep beams demonstrate non-flexural behavior and are considered as discontinuity regions because the sectional strain distribution deviates from linearity. A deep beam

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is a beam in which a significant amount of the load is transferred to the supports by a compression thrust joining the load and the reaction [3]. The transition from reinforced concrete shallow beam behavior to that of deep beam is imprecise.

The design of deep beams with large openings is studied [4] and it was found that the strut-and-tie model [5] accurately estimated the shear strength according to the test results, due to large opening sizes and low opening locations, the deep beams with opening could have behaved under testing conditions as normal flexural beams [6]. A method developed to predict the ultimate shear strength of deep beams with web openings but, this method was unable to predict the failure modes [7].

2. PROGRAM OF STUDY

Thirty-Nine deep beam specimens were examined. An overall beam length of 2400 mm and 600 mm thickness, the effective span 1800 mm from support to support as detailed in Figure (1), the width of all the specimens was maintained as 120 mm.

Specimens were categorized into three main Sets, Set A, B and C, aiming at examination of different mechanisms associated with varying deep beam parameters. To more effectively investigate the influence of different parameters, specimens in each Set were further classified into a number of test Groups. They are briefly explained as below;

Specimens in Set A were sixteen and tested through four Groups (Group 1, 2, 3 and 4) to observe the effect of varying locations of the 60 mm x 60 mm web opening in the deep beams. These tests included variations of the opening location along the horizontal, vertical and diagonal directions.

Set B consisted of fifteen specimens as three Groups (Group 5, 6 and 7) which focused on the behavior of deep beams when the opening size of 60 mm x 60 mm increased in the horizontal direction, the vertical direction, and in both directions.

Set C also comprised two Groups (Group 8 and 9) each consists of four specimens to evaluate the differences between normal strength reinforced concrete deep beams NSRC (40 MPa) and high strength reinforced concrete deep beams HSRC (80 MPa) with increased size of web openings under one-point loading at the center.

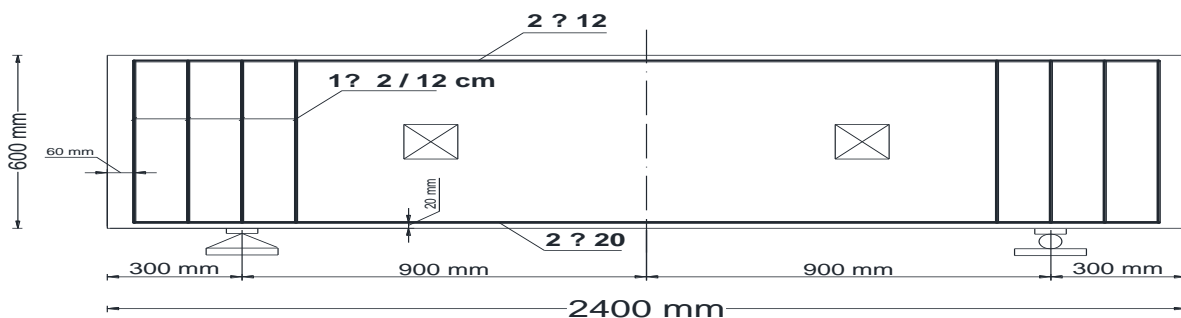


Fig. 1: Details of Deep Beam Specimens (Dimensions in mm)

Table 1: Locations and Size of openings Beam specimens

Set	Group	Specimen	a ₁ mm	a ₂ mm	X ₁ mm	X ₂ mm	Y ₁ mm	Y ₂ mm	Opening Location
Set A	Group 1 HSRC	A-1-1	60	60	460	380	260	280	10 % Toward
		A-1-2	60	60	580	260	260	280	30 % Toward
		A-1-3	60	60	340	500	260	280	10 % Outward
		A-1-4	60	60	220	620	260	280	30 % Outward

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	Group 2 HSRC	A-2-1	60	60	400	440	320	220	10 % Upward	
		A-2-2	60	60	400	440	380	160	20 % Upward	
		A-2-3	60	60	400	440	200	340	10 % Downward	
		A-2-4	60	60	400	440	140	400	20 % Downward	
	Group 3 HSRC	A-3-1	60	60	500	340	320	220	10 % Upward	
		A-3-2	60	60	580	260	390	150	20 % Upward	
		A-3-3	60	60	320	520	200	340	10 % Downward	
		A-3-4	60	60	220	620	140	400	20 % Downward	
	Group 4 HSRC	A-4-1	60	60	320	520	320	220	10 % Upward	
		A-4-2	60	60	220	620	380	160	20 % Upward	
		A-4-3	60	60	500	340	200	340	10 % Downward	
		A-4-4	60	60	580	260	140	400	20 % Downward	
Set B	Group 5 HSRC	B-5-1	60	60	400	440	260	280	10%	
		B-5-2	90	90	390	420	255	255	15%	
		B-5-3	120	120	360	420	240	240	20%	
	Group 6 HSRC	B-6-1	120	60	400	380	260	280	20 % To.	
		B-6-2	240	60	400	260	260	280	40 % To.	
		B-6-3	120	60	340	440	260	280	20 % Out.	
		B-6-4	240	60	220	440	260	280	40 % Out.	
		B-6-5	180	60	340	380	260	280	30 % 2-Dir.	
		B-6-6	240	60	320	340	260	280	40 % 2-Dir.	
	Group 7 HSRC	B-7-1	60	120	400	440	260	220	20 % Up.	
		B-7-2	60	180	400	440	260	160	30 % Up.	
		B-7-3	60	120	400	440	200	280	20 % Down.	
		B-7-4	60	180	400	440	140	280	30 % Down.	
		B-7-5	60	180	400	440	200	220	30 % 2-Dir.	
		B-7-6	60	240	400	440	180	180	40 % 2-Dir.	
	Set C	Group 8 NSRC	C-8-1	150	150	337.5	412.5	225	225	25%
			C-8-2	180	180	320	400	200	220	30%
			C-8-3	210	210	300	390	195	195	35%
C-8-4			240	240	270	390	170	190	40%	
Group 9 HSRC		C-9-1	N/A	N/A	N/A	N/A	N/A	N/A	Solid	
		C-9-2	150	150	337.5	412.5	225	225	25%	
		C-9-3	180	180	320	400	200	220	30%	
		C-9-4	210	210	300	390	195	195	35%	

Where: a_1 , a_2 , X_1 , X_2 , Y_1 and Y_2 are explained in the following figure

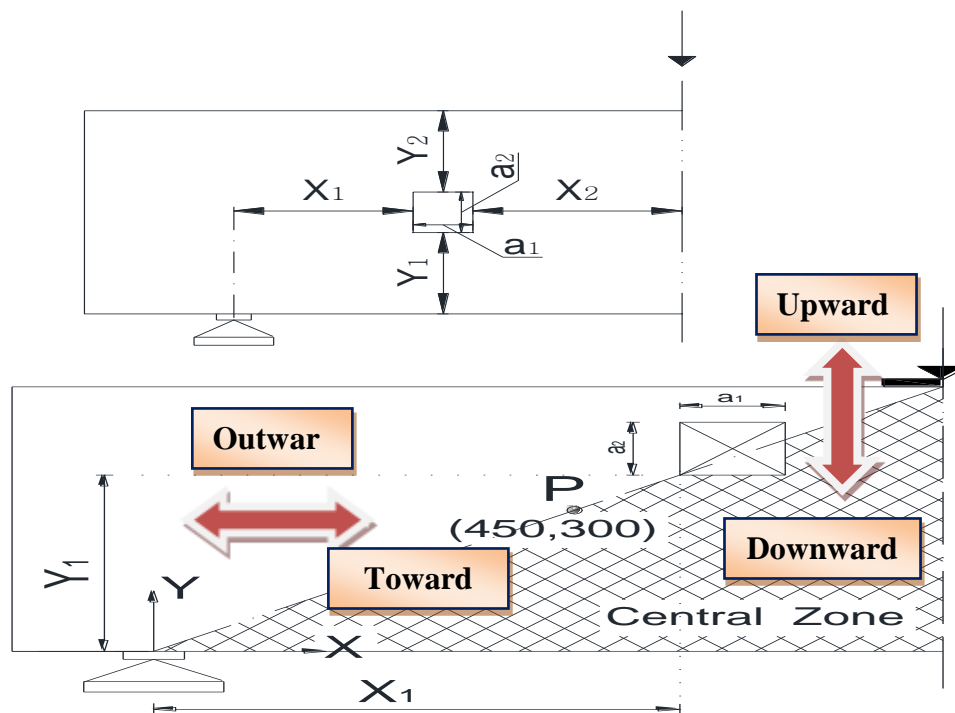


Fig. 2: Notations for Specimens Location

3. NUMERICAL ANALYSIS

A three dimensional finite-element program 'ANSYS' was used for the numerical analysis of the thirty - nine beams. In the analysis, appropriate material models were employed to represent the behavior of concrete, the steel reinforcement, and the steel plates. They are described in detail in the ANSYS manual set.

A solid element, SOLID65, is used to model the concrete in ANSYS. The solid element has eight nodes with three transitional degrees of freedom at each node. In addition, the element is capable of simulating plastic deformation, cracking in three orthogonal directions, and crushing. The steel plates at the supports for the beams are modeled using Solid185 elements. This element has eight nodes with three degrees of freedom at each node – translations in the x, y, and z directions. In order to obtain the internal strains in the reinforcement bars and keep them in their right positions, the discrete technique using the 3D spar Link180 element is followed. This element has two nodes with three degrees of freedom translations in the x, y, and z directions. This element is also capable of plastic deformation.

The mesh was taken square to obtain good results with the test one; it was taken 20 x 20 x 20 mm as shown in Figure (3). The command merge items merge separate entities that have the same location. These items will then be merged into single entities. Caution must be taken when merging entities in a model that has already been meshed because the order in which merging occurs is significant. Displacement boundary conditions are needed to constrain the model to get a unique solution. . The model being used is symmetric about two planes. The supports were modeled such as a roller and hinge support. For roller support a single line of nodes were constraint in the (UY) and (UZ) directions. For hinged

support, single lines of nodes were constraint in the (UX), (UY) and (UZ) directions. For loading boundary conditions, the force applied at steel plate as shown in Figure (3).

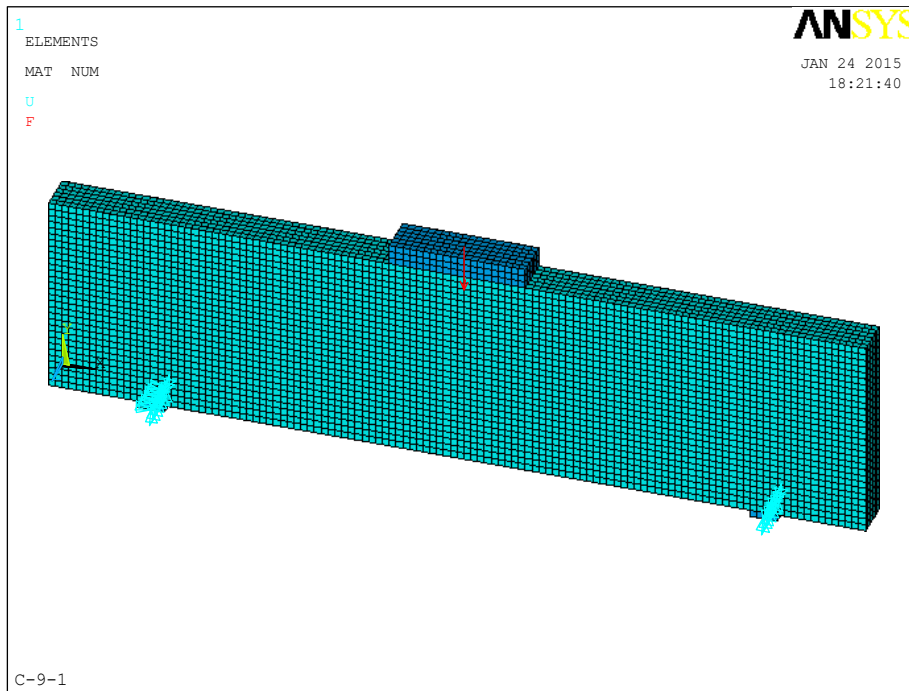


Fig. 3: Model of Boundary Condition and Loading

In this study the total load applied was divided into a series of load increments (or) load steps. Newton – Raphson equilibrium iterations provide convergence at the end of each load increment within tolerance limits. The automatic time stepping in the ANSYS program predicts and controls load step sizes for which the maximum and minimum load step sizes are require.

4. THEORETICAL RESULTS

Table 2: Experimental & Analytical Failure Load and Deflection

Set	Group	Specimen	$P_{Exp.}$ (kN)	$P_{Anal.}$ (kN)	$\frac{P_{Exp.}}{P_{Anal.}}$	Ductility (mm)	Absorbed Energy (kN.mm)
Set A	Group 1 HSRC	A-1-1	352.80	390.45	0.90	1.71	681
		A-1-2	415.80	368.70	1.13	1.50	597
		A-1-3	422.40	389.93	1.08	1.78	704
		A-1-4	422.20	395.79	1.07	1.80	893
	Group 2 HSR C	A-2-1	347.70	280.98	1.24	0.75	344
		A-2-2	401.80	394.21	1.02	1.70	678

Set A	Group 3 HSRC	A-2-3	267.90	211.48	1.27	0.50	162	
		A-2-4	240.50	190.86	1.26	0.60	124	
		A-3-1	303.10	263.36	1.15	0.70	300	
		A-3-2	254.10	212.47	1.20	0.60	162.5	
		A-3-3	189.70	135.55	1.40	0.15	54.0	
		A-3-4	177.60	189.34	0.94	0.50	123	
	Group 4 HSRC	A-4-1	454.20	390.25	1.16	1.60	709	
		A-4-2	457.80	407.66	1.12	1.60	597.5	
		A-4-3	232.30	172.86	1.34	0.26	113	
		A-4-4	185.10	186.17	0.99	0.50	133	
	Set B	Group 5 HSRC	B-5-1	309.00	262.11	1.18	0.80	293
			B-5-2	193.80	179.84	1.08	0.40	86.5
			B-5-3	112.80	141.88	0.80	0.25	71.0
Group 6 HSRC		B-6-1	166.80	141.88	1.18	0.20	50.0	
		B-6-2	122.60	135.55	0.90	0.20	95.5	
		B-6-3	174.40	175.1	1.00	0.30	128	
		B-6-4	122.80	141.88	0.87	0.20	78.0	
		B-6-5	146.10	141.22	1.03	0.16	86.5	
		B-6-6	138.20	135.55	1.02	0.20	79.0	
Group 7 HSRC		B-7-1	306.60	291.12	1.05	1.20	326	
		B-7-2	157.90	141.88	1.11	0.20	56.5	
		B-7-3	135.20	129.22	1.05	0.15	40.2	
		B-7-4	111.80	116.56	0.96	0.15	11.6	
		B-7-5	109.80	135.55	0.81	0.20	66.0	
		B-7-6	81.40	116.56	0.70	0.15	12.0	
Set C		Group 8 NSRC	C-8-1	88.10	91.25	0.97	0.15	10.0
			C-8-2	87.00	91.25	0.95	0.15	42.5
			C-8-3	79.80	91.25	0.87	0.28	52.0
	C-8-4		72.40	57.50	1.26	0.16	13.2	
	Group 9 HSRC	C-9-1	489.50	470.54	1.04	2.15	1035.5	
		C-9-2	125.60	116.56	1.08	0.15	11.0	
		C-9-3	73.20	101.38	0.72	0.13	28.0	
		C-9-4	78.90	91.25	0.86	0.13	8.75	

Figure (4) shows the load – deflection relationships for specimens in set (A); in which the opening dimensions are fixed (60 mm x 60 mm) while the opening position changed, the failure load decreases when the beam opening lies inside the central zone, for group 1 which its opening position changes in the horizontal direction has the highest values of failure load and deflection, while group 3 which its opening position changes in diagonal direction has the smallest values of failure load and deflection.

Figure (5) shows the load – deflection relationships for specimens in set (B); in which the opening dimensions are changeable while the opening position is fixed, when the opening shape is square as in group 5, it is found that as the opening area increased as the failure load decreased, for group 6 in where the opening shape is rectangular, the horizontal dimension is changeable and the vertical dimension is fixed (60 mm) it is found that the failure load values are approximately equal while their deflection values are different and for group 7 in where the opening shape is rectangular, the

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vertical dimension is changeable and the horizontal dimension is fixed (60 mm) it is found that the highest failure load is for specimen (B-7-1) in where its vertical dimension increases by 20 % upward the central zone.

Figure (6) shows the load – deflection relationships for specimens in set (C); in which the compressive strength of concrete changes from high strength reinforced concrete with compressive strength = 80 MPa to normal strength reinforced concrete compressive strength = 40 MPa, and it is found that the specimens with normal strength concrete have lower failure load but highest deflection values which make it more stiff.

Figure (7), (8) and (9) show the measurement of ductility values for specimens in sets (A), (B) and (C); in where the measurement of ductility is the deflection at 70 % of failure load, it is found that the most ductile specimen is (A-1-4); which has opening size (60 mm x 60 mm) mm and its location changes in horizontal direction by 30 % outward the central zone, while the lowest ductile values are in specimen (C-9-4); which has opening size (210 mm x 210 mm) mm and locate at mid-point.

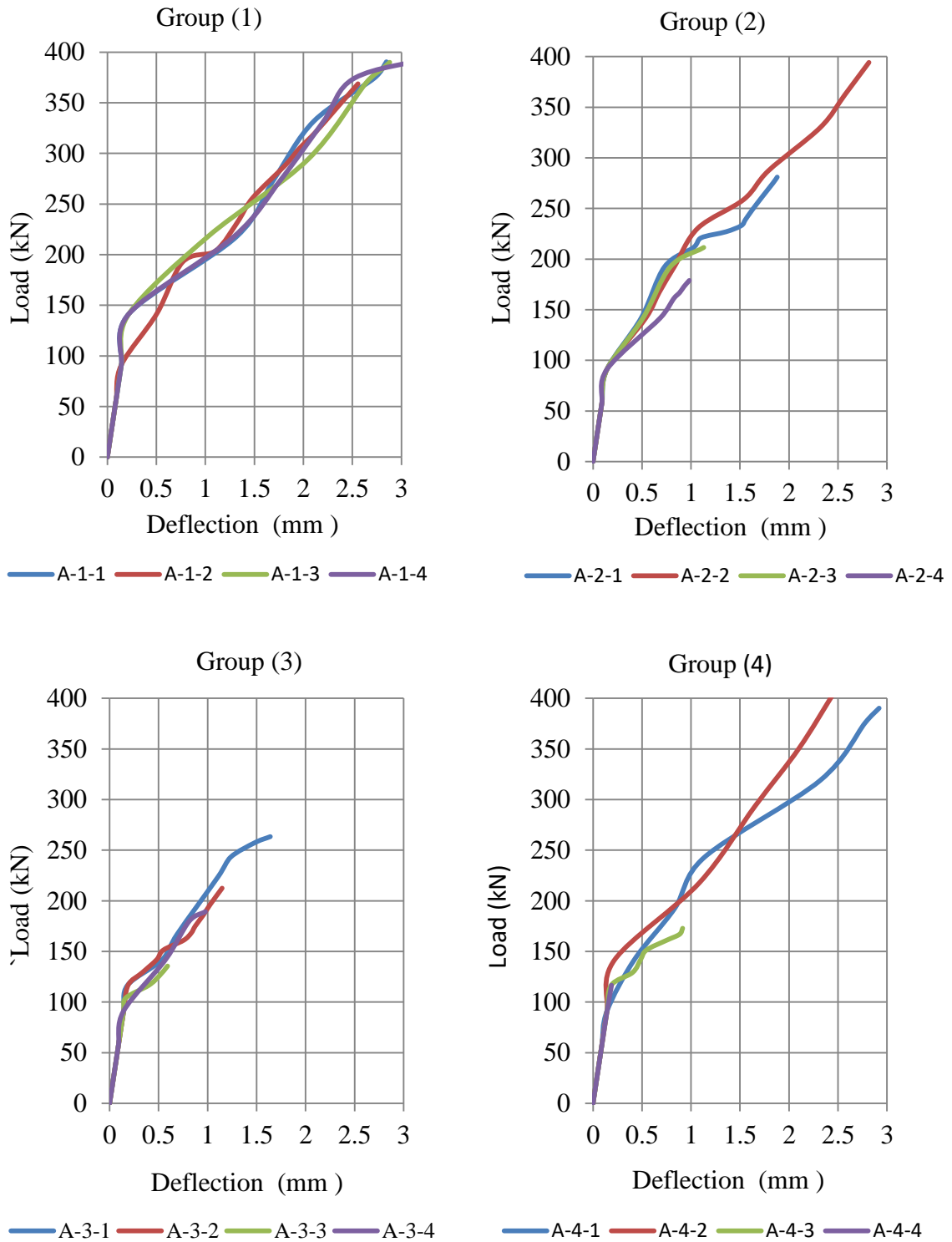


Fig. 4: Load – Deflection Relationship for Specimens in Set (A)

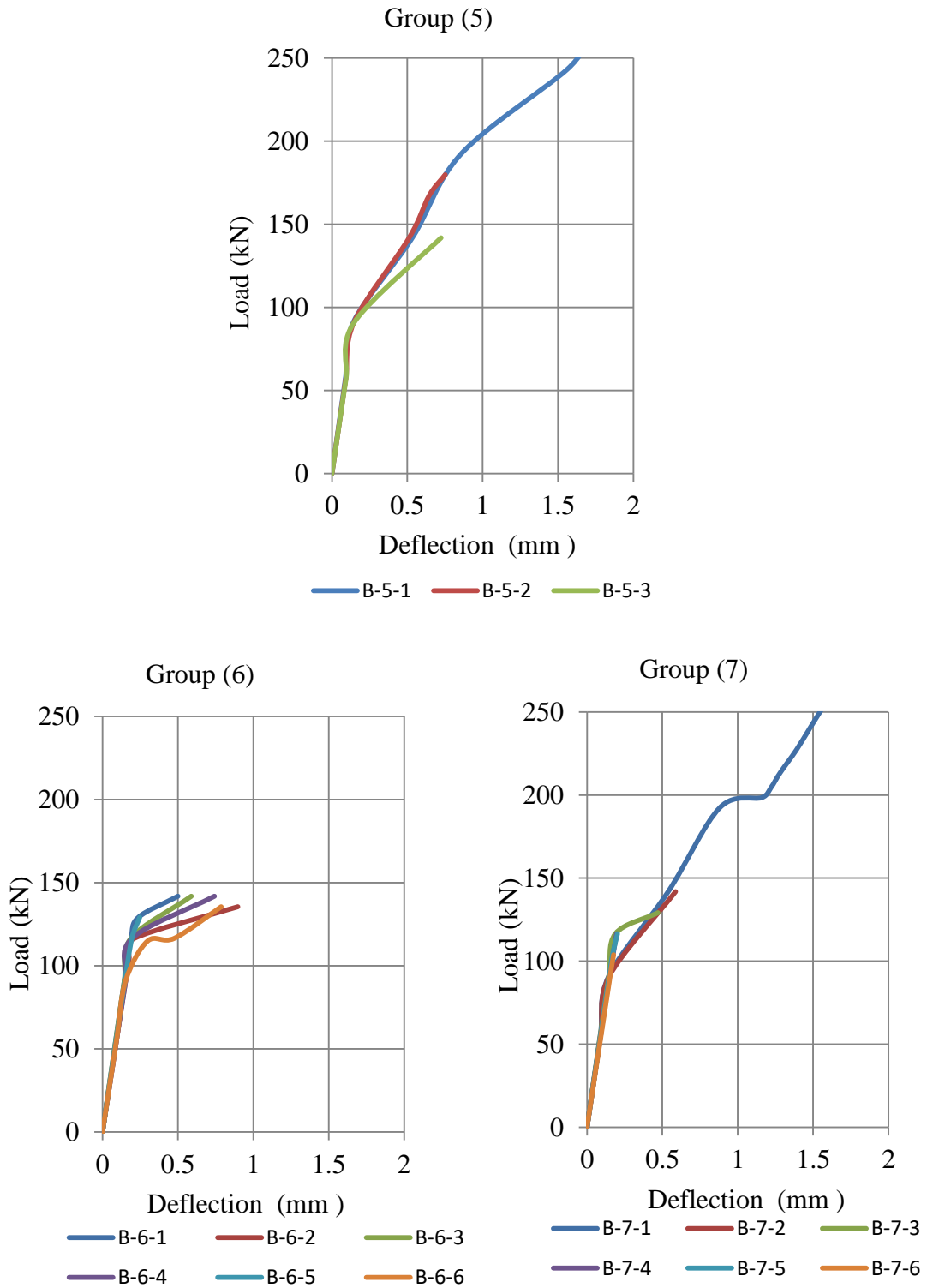


Fig. 5: Load – Deflection Relationship for Specimens in Set (B)

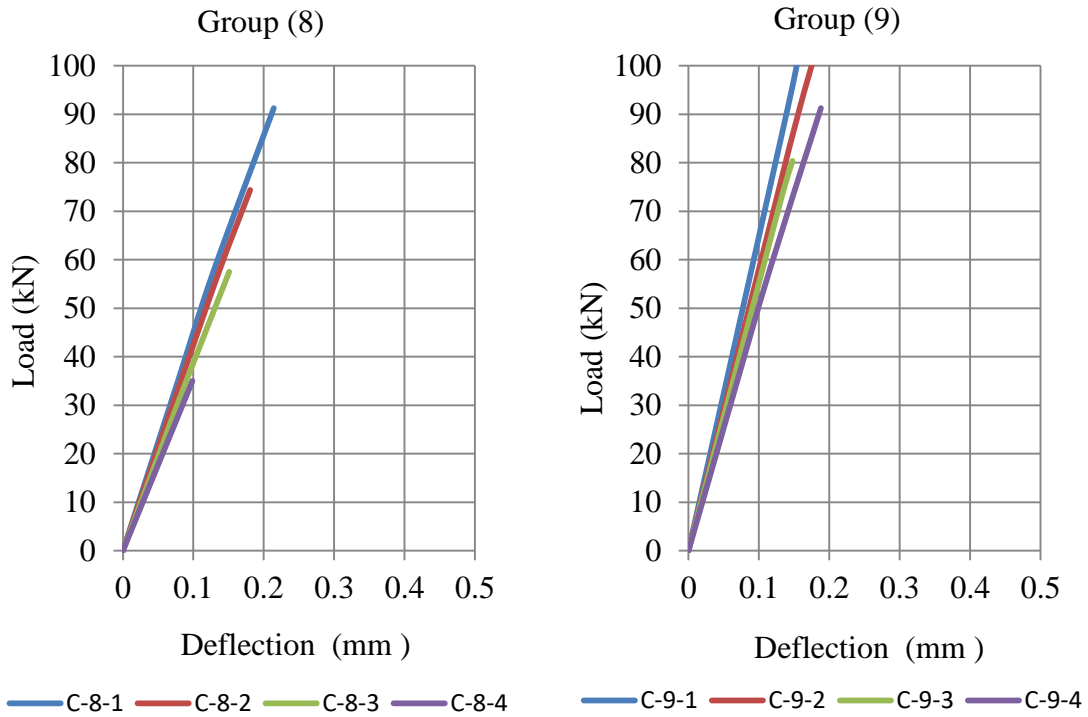


Fig. 6: Load – Deflection Relationship for Specimens in Set (C)

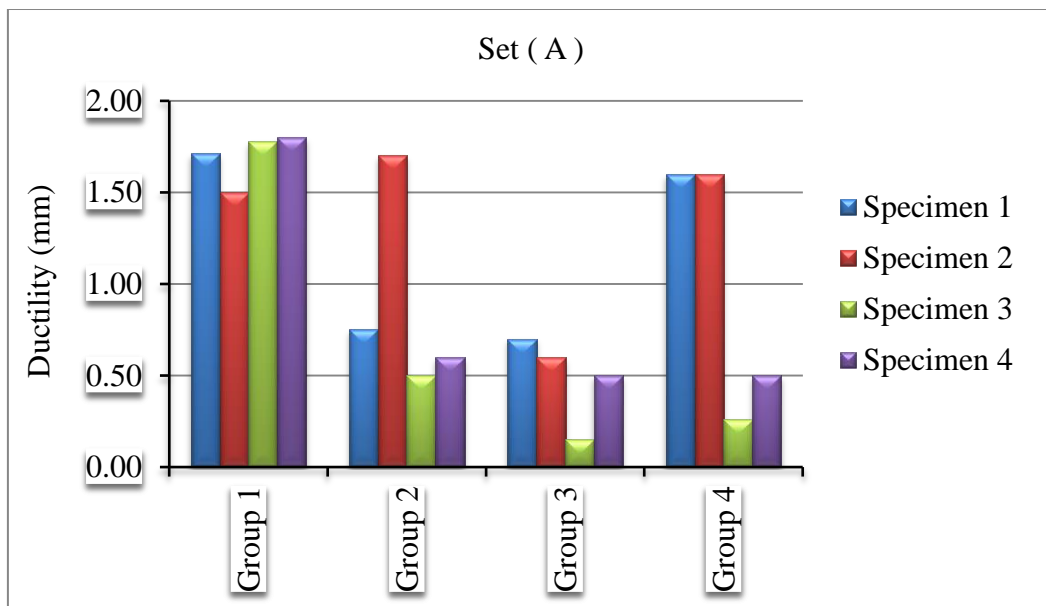


Fig. 7: Ductility for Specimens in Set (A)

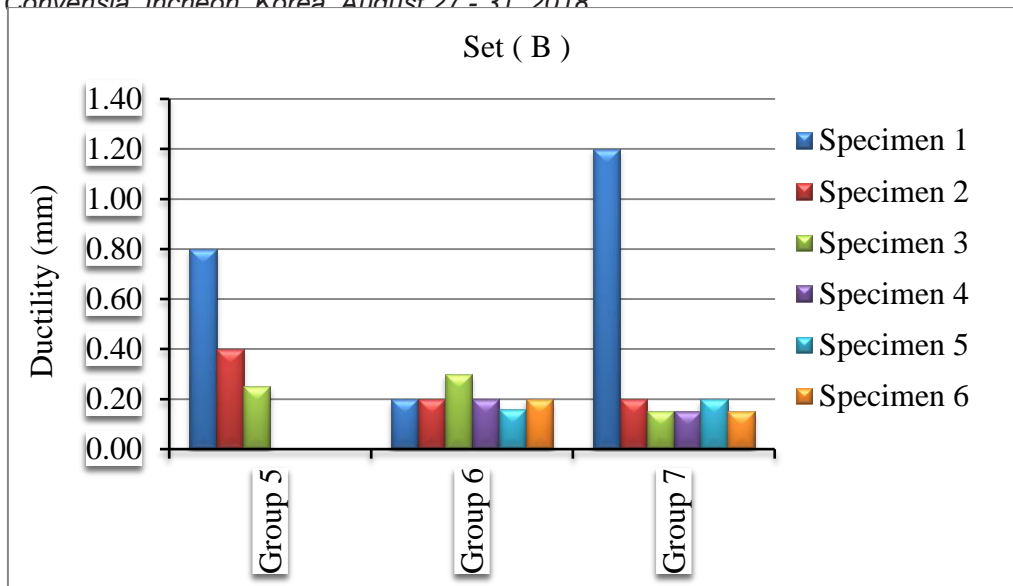


Fig. 8: Ductility for Specimens in Set (B)

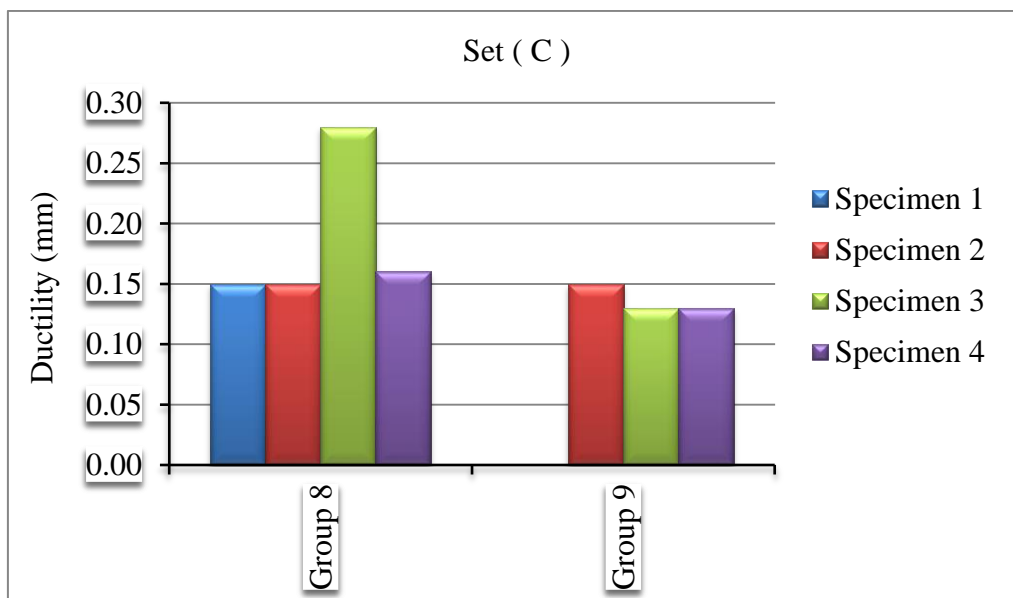


Fig. 9: Ductility for Specimens in Set (C)

Figure (10) shows the Crack pattern for specimens (A-2-2) and (A-2-4); the two specimens are in group 2 where the beam opening dimensions are fixed (60 mm x 60 mm) while its location changes in the vertical direction, it is obvious that specimen (A-2-2) where the beam opening location is 20 % upward the central zone has a large number of cracks and failure load of 394.21 kN, but specimen (A-2-4) where the beam opening location is 20 % downward the central zone has a small number of cracks and failure load of 190.86 kN.

Figure (11) shows the Crack pattern for specimens (B-5-1) and (B-5-3); the two specimens are in group 5 where the beam opening location is fixed at the midpoint while its dimensions changes in squared shape, it is obvious that specimen (B - 5 - 1) where the beam opening size is 10 % from height (60 mm x 60 mm) has a large number of cracks and failure load of 262.11 kN, but specimen (B-5-3) where the beam opening size is 20 % from height (120 mm x 120 mm) has a small number of cracks and failure load of 141.88 kN.

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Figure (12) shows the Crack pattern for specimens (B-6-1) and (B-7-1); the two specimens have fixed opening location at the midpoint and fixed rectangular opening area (10 % x 20 %) but the opening orientation is changeable, in specimen (B-6-1) the opening orientation is in horizontal direction has a small number of cracks and failure load of 141.88 kN, but in specimen (B-7-1) the opening orientation is in vertical direction has a large number of cracks and failure load of 291.12 kN.

Figure (13) shows the Crack pattern for specimens (C-8-2) and (C-9-3); the two specimens have fixed opening location at the midpoint and fixed square opening area 30 % from height (180 mm x 180 mm) but the specimen compressive strength is changeable, in specimen (C-8-2) the beam is from normal strength concrete with compressive strength 40 MPa has a large number of cracks and failure load of 91.25 kN, but in specimen (C-9-3) the beam is from high strength concrete with compressive strength 80 MPa has a small number of cracks and failure load of 101.38 kN.

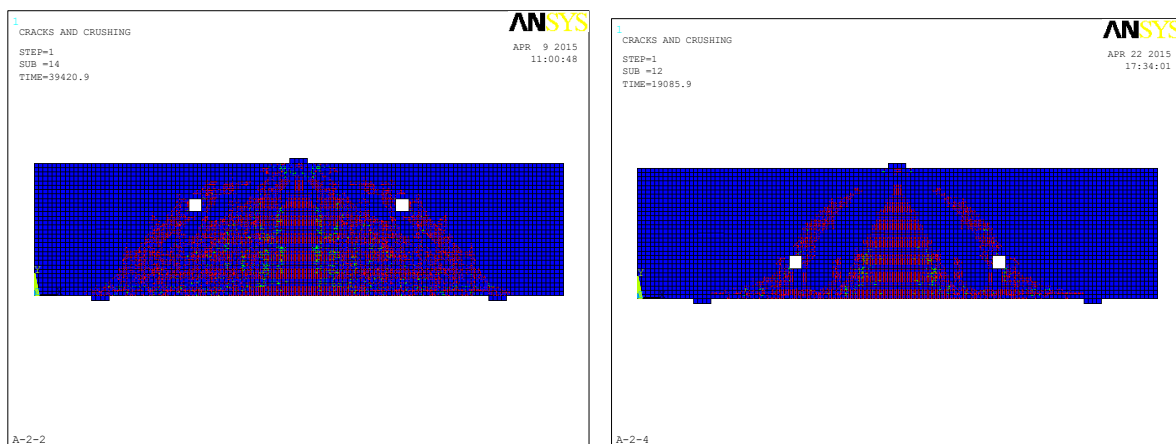


Fig. 10: Crack Pattern for Specimens (A-2-2) and (A-2-4)

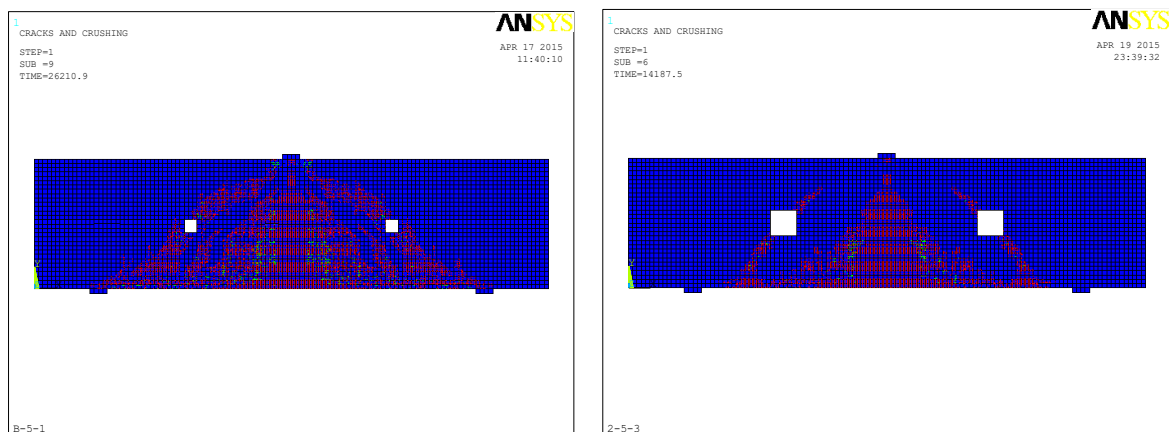


Fig. 11: Crack Pattern for Specimens (B-5-1) and (B-5-3)

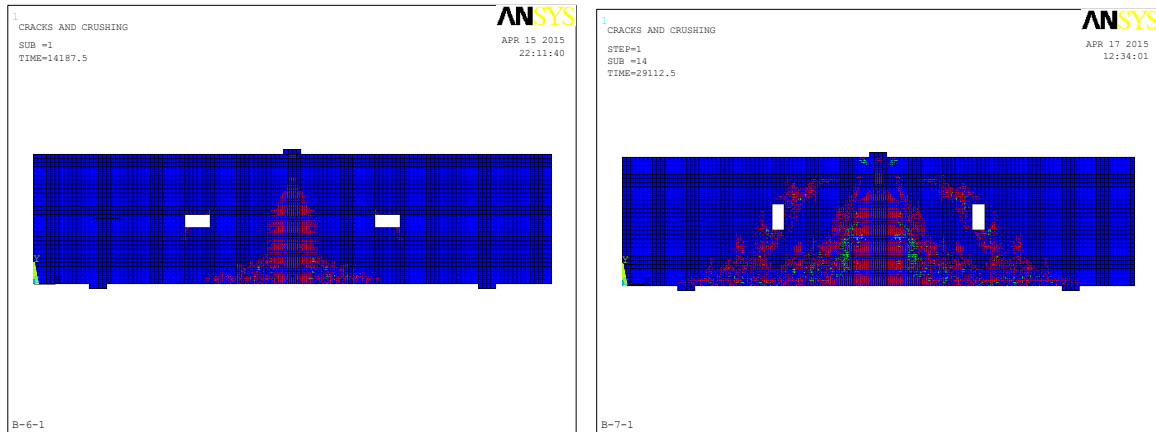


Fig. 12: Crack pattern for Specimens (B-6-1) and (B-7-1)

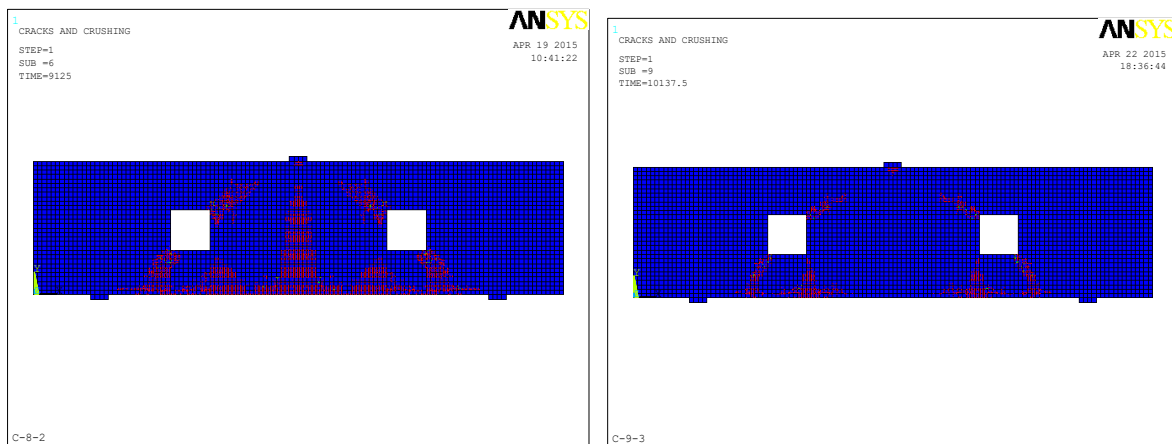


Fig. 13: Crack Pattern for Specimens (C-8-2) and (C-9-3)

5. CONCLUSIONS

According to present studies, the following conclusions can be get out:

1. As much more area of opening inside the central zone increases, the failure load decreases.
2. The best opening locations for constant square area (10 % x 10 %) is along the perpendicular direction to the diagonal strut, and 20 % upward the central zone.
3. The best opening size for square openings is (10 % x 10 %).
4. Failure load in normal strength concrete deep beams is smaller than high strength concrete deep beams, while deflection in normal strength concrete deep beams is larger than high strength concrete deep beams,
5. Beams with normal strength concrete are more ductile than beams with high strength concrete.
6. Cracks taken the strut and tie triangular shape, extents from supports to load plate, concentrated around openings corner and there is no cracks at the two zones after the supports.
7. Stresses at mid – span increases linearly till it reached to first crack, then it increases non – linear taken the shape of parabola till it reached to failure where maximum stress found.
8. At corners of openings the stress begin from zero, reaches to maximum value at first crack then it return to zero at failure.
9. Stresses decreases as the size of opening increases.

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