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Experimental and Finite Element Analysis on the Steel Fiber Reinforced Concrete Deep Beams with Web Openings

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Abstract— ***This study investigates experimentally and analytically the use of steel fiber for enhancement of reinforced concrete deep beams without web reinforcement. Experimental and analytical program include nine reinforced concrete deep beams with and without web openings, all beams are tested under two – point loading. Test variables included steel fiber volume fraction and the position of web openings in shear span. Steel fiber volume fractions of 0.0 %, 0.75 %, and 1.0 % are used. Nonlinear analysis using the finite element program (ADINA program) is used to obtain the ultimate load and deflection by using nonlinear material properties adopted from experimental study. The experimental and the numerical analysis showed a good agreement regarding both ultimate load and deflection. The results demonstrated that the best fiber volume fraction was 1.0 % for case of web opening at 15 cm and 0.75 % for case of web opening at 20 cm.***

Index: **Steel fiber; Web openings; Deep beam; Reinforced concrete; Nonlinear analysis.**

I. INTRODUCTION

Reinforced concrete deep beams appear as common structural elements in many structures ranging from tall buildings to offshore gravity structures. They are used as panel beams, foundation beams, and as deep grid walls in offshore gravity-type concrete structures [1]. Deep beam can be defined as a beam in which either clear span is equal to or less than four times the overall member depth or concentrated loads are within a distance equal to or less than two times the depth from the face of support (ACI Committee 318, 2008) [2]. Openings are inevitably installed in deep beams to facilitate conduits, air conditioning, electricity, and computer network cables.

The results of study carried out by Keun et al. [3] indicated that The width and depth of opening did not affect the mid span deflection at initial loading stages, but it significantly affected the deflection after the occurrence of diagonal cracks. The concrete strength did not largely affect the rigidity of beams with web opening due to the existence of the web opening. Based on the test results of high-strength concrete deep beams, Tan et al. [4] and Yang et al. [5] concluded that the effect of concrete strength on the nominal shear strength appears more significant in deep beams than in slender beams because most load is transferred by concrete struts.

Steel fiber added concrete (SFC) and steel fiber added reinforced concrete (SFRC) are being used in real life applications at an escalating rate recently. The addition of standard size and shape steel fibers to concrete improves crack behavior, makes the concrete ductile, increases its tensile strength, and improves its durability appreciably. Because of these established facts, both SFC and SFRC have already become standard practice in many countries. A main advantage of SFC is its high energy absorption capacity and high toughness, due to its high ductility [6].

Web openings may be provided in the compression zone of the beams and fiber content of 0.75%by volume may be added to improve the strength of the structure where the opening in the tension zone weaken the beam [7]. Large openings, if located between the loading point and the support, will disrupt the flow of force transfer and usually significantly reduce the load-carrying capacity [8], Large openings in reinforced concrete (RC) deep beams generally interrupt the load transfer by concrete struts and cause a sharp decrease in strength and serviceability. The reinforcement detailing of these deep beams based on strut-and-tie models (STMs) can be complex and, very often, these models may not predict the failure mechanism of deep beams due to localized damages [9].

Based on limited experimental studies [10,11] it is inferred that STMs provide reliable, consistent, and conservative results for deep beams with openings but fail to predict the ultimate load and failure mode. A poorly selected and detailed strut-and-tie model can lead to severe cracking and damages under service loads [11]. From the construction point of view, the primary difficulty associated in the design based on strut-and-tie models is the problem of anchorage and congestion due to large amount of reinforcement bars in the member.

II. RESEARCH SIGNIFICANCE

The experimental and analytical program are carefully designed to explain the effect of steel fiber on the behavior of reinforced concrete deep beams with and without openings in web under two point loading.

III. EXPERIMENTAL PROGRAM

A. Details of Tested Beams

The details of the tested beams are shown in figure (1)

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and are listed in table (1). The experimental program consisted of nine deep beams with and without web opening, all beams were 400 mm height, 100 mm width, and overall length 1000 mm. The shear span to depth ratio (a / h) was constant for all beams and equal to 0.7. Three beams are without web opening where six beams contained two square openings (80 x 80 mm), one in each shear span. The web openings are located at the distance 15 cm from the end of three beams, where in the other three beams, the web openings are located at the distance 20 cm. Each beam had a main longitudinal reinforcement ratio (ρ) = 1.0 %, consisting of two 16 mm diameter and there are no shear reinforcement in the shear span to investigate the effect of openings. The percentage of steel fiber was 0.0 %, 0.75 %, and 1.0 % to obtain the effect of the presence of steel fibers in reinforced concrete deep beams.

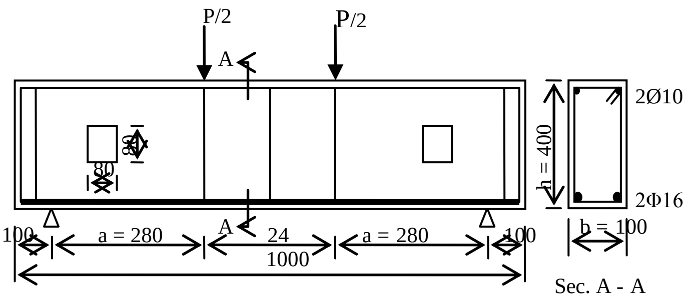

Fig 1. Specimen details (unit : mm)

Table (1) : Details of specimens.

Specimen	a / h	Size of opening (mm)	Location of opening (mm)	Fiber volume fraction (%)
S_1	0.7	Without	-	0.0
S_2	0.7	Without	-	0.75
S_3	0.7	Without	-	1.0
S_4	0.7	80 x 80	150	0.0
S_5	0.7	80 x 80	150	0.75
S_6	0.7	80 x 80	150	1.0
S_7	0.7	80 x 80	200	0.0
S_8	0.7	80 x 80	200	0.75
S_9	0.7	80 x 80	200	1.0

B. Materials Used

The cement used throughout this work was Ordinary Portland Cement (OPC). Cement is tested and the test results satisfied the requirement of Egyptian Code of Practice, the physical test results of the used cement are given in table (2). Natural sand of maximum size < 5 mm is used for concrete mixes of this investigation, where the washed natural crushed coarse aggregate of 20 mm maximum size is used. The sieve analyses of both natural sand and coarse aggregate are shown in table (3). Steel fibers are used with different volume fractions of 0.0 %, 0.75 %, and 1.0 %, these fibers are typically hooked as shown in figure (2). Table (4) shows the properties of the used steel fibers. Super plasticizer used in the experiment was sikament 5929 and is added by about 0.8 % by weight of cement.

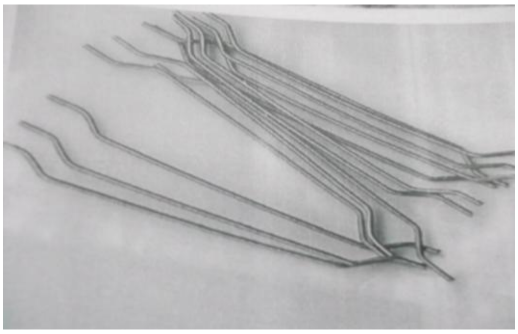

Fig 2. Shape of steel fibers

Table (2): Properties of cement.

Tests	Results	ECP 203 – 2007 Specification limits
Initial setting time	1 hours and 05 minutes	Not less than 45 min.
Final setting time	4 hours and 10 minutes	Not more than 10 hr
3 days compressive strength	20.0 N / mm^2	Not less than 18 N / mm^2
7 days compressive strength	28.5 N / mm^2	Not less than 27 N / mm^2

C. Mix Proportions

For this study, a total of three mixes are produced according to volume fraction of steel fibers, the quantities of materials used for three mixes are illustrated in tables (5), (6) and (7) according to fibers volume fraction 0.0 %, 0.75 %, and 1.0 % respectively. For all mixes, the amount of cement used was constant and equal to 300 Kg / m^3 and the ratio of fine to coarse aggregates was 40 % to 60 %.

D. Test Procedure

The deep beams are tested to failure under two – point symmetric top loading using a 2500 KN capacity testing machine. The test setup for the beam is shown in figure (3). Each of the tested beam are mounted on roller supports on the testing machine. Vertical deflections at mid – span and under one point load are monitored by LVDT's. Loading is applied in increments of 20 KN. At each load stage the deflection readings are recorded.

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During the test, the first crack load is observed and the crack propagation is marked on the surface of the beam where the surfaces of the beams are painted in a white color and magnitude of the load at which these cracks occurred is recorded.

Table (4): Properties of steel fibers

Property	Specifications
Density	7860 Kg / m^3
Length	30 mm
Diameter	0.5 mm
Aspect Ratio	60

Table (5) : Mix proportions for fiber volume fraction = 0.0 %.

Cement content (Kg /m^3)	300
Water content (Kg /m^3)	120
Coarse aggregate (Kg /m^3)	1244.6
Fine aggregate (Kg /m^3)	829.7
W / C ratio	0.40

Table (6) : Mix proportions for fiber volume fraction = 0.75 %.

Cement content (Kg /m^3)	300
Water content (Kg /m^3)	135
Coarse aggregate (Kg /m^3)	1220.7
Fine aggregate (Kg /m^3)	813.8
W / C ratio	0.45

Table (7) : Mix proportions for fiber volume fraction = 1.0 %.

Cement content (Kg /m^3)	300
Water content (Kg /m^3)	150
Coarse aggregate (Kg /m^3)	1196.9
Fine aggregate (Kg /m^3)	797.9
W / C ratio	0.50

IV. ANALYTICAL WORK

Finite element failure analysis is performed by using the ADINA program for all test beams. Model of concrete and reinforcement, as well as mesh geometry used for concrete and reinforcement are illustrated in figure (4). Steel fibers are presented in ADINA program by making change in the physical properties of concrete represented in cube compressive strength and split tensile strength.

Fig 3. Test setup for deep beams.

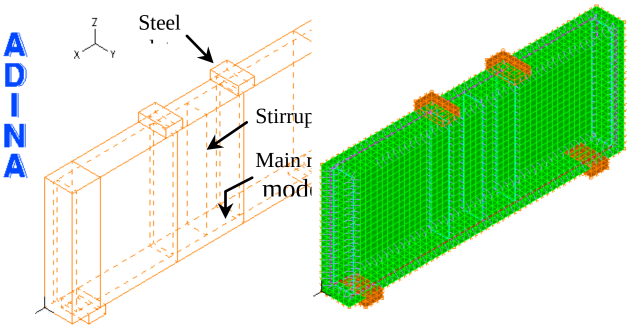

Fig 4. a) The concrete and reinforcement model; b) The mesh geometry for the concrete and reinforcement.

A. Material Properties

In this study there are two material models to represent concrete and reinforcement. Material model1 refers to concrete, the concrete requires nonlinear material properties to properly model concrete. The value of compressive and tensile strength is adopted as obtained from experimental work as shown in table (8). Poisson's ratio is assumed to be 0.2. Reinforcement is idealized by truss element and is represented by two – noded axial element embedded any where within a concrete element along local coordinates lines. Perfect bond between the concrete and steel is existed.

Table (8) : Physical properties of concrete

Fiber content	Avg. cube compressive strength (N/mm^2)	Avg. split tensile strength (N/mm^2)
0.0 %	34.6	3.15
0.75 %	40.8	4.01
1.0%	41.0	4.08

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V. TEST RESULTS AND DISSCUSION

A. Load – deflection at Mid Span

The loads are plotted versus mid – span deflection of test specimens according to steel fiber content and web openings as shown in Figure (5) and Figure (6) respectively. It is found that after the appearance of first diagonal crack, the value of deflection increased due to the decrease in the rigidity of the beams. As more cracks are formed and propagated, there was a reduction in the beams stiffness. It is also observed that the stiffness of the beam depend largely on the existence of web openings. Figures (5 – a), (5 – b), and (5 – c) show the effect of fiber content on the values of deflection for beams without openings, with web openings at 15 cm, and with web openings at 20 cm, respectively. It is observed that for beams without web openings and with openings at 20 cm, the deflection is decreased as the steel fiber content increases by small rate. However, the deflection of the beams with openings at 15 cm is decreased by about 25 % and 46 % by the increase in steel fiber from 0 % to 0.75 % and from 0.75 % to 1.0 % respectively. The effect of web openings is shown in figures (6 – a), (6 – b), and (6 – c) for beams without fiber, with fiber content = 0.75 %, and with fiber content = 1.0 %, respectively. It is illustrated that the beams with web openings behaved in a stiff manner when the steel fibers are added especially when the web openings at 15 cm, where the deflection is decreased by about 47.6 % from beam with opening at 20 cm to that with opening at 15 cm and steel fiber content = 1.0 %.

B. Ultimate Load

The effect of both increasing in steel fiber fraction (V_f) and existence of web openings on the ultimate load is shown in figure (7). The figure demonstrated that the ultimate load is significantly increased as the fiber content increases. The increase in ultimate load of deep beams with steel fibers, may be attributed to the role of steel fiber in improving the properties of reinforced concrete beams with web opening in resisting additional shear forces. The figure also indicated that the presence of web opening especially at 20 cm from the end of the beam leads to the decrease in the ultimate load value. Beam S_7 gives the smallest ultimate load of all test beams, the reason for this result was the beam had web opening at 20 cm and without fiber content. Where beam S_3 gives the highest ultimate load, this is because the beam had fiber volume fraction (V_f) = 1.0 % and without web opening. Tables (9) and (10) show the percentage of the increase and the decrease in the ultimate load due to fiber volume fraction and the presence of web opening, respectively.

The results of table (10) show that the percentage of decrease in the ultimate load is almost the same for fiber volume fraction (V_f) = 0 % and 0.75 % in the case of web opening at 15 cm. However, in case of web opening at 20 cm, the percentage of decrease is almost the same for (V_f) = 0.75 % and 1.0 %. Accordingly, the best fiber volume fraction was 1.0 % in case of web opening at 15 cm and 0.75 % in case of web opening at 20 cm.

Table (9) : Effect of increasing steel fiber volume fraction (V_f) on the ultimate load of deep beams

Beam	V_f (%)	P_u (KN)	Percentage of increase	
S_1	0	240	-	**Without web opening**
S_2	0.75	259	8	
S_3	1.0	275	14.6	
S_4	0	182	-	**With opening at 15 cm**
S_5	0.75	193	6	
S_6	1.0	220	20.9	
S_7	0	153	-	**With opening at 20 cm**
S_8	0.75	188	22.9	
S_9	1.0	200	30.7	

Table (10) : Effect of web openings on the ultimate load of deep beams.

Beam	web opening	P_u (KN)	Percentage of decrease	
S_1	without	240	-	**V_f = 0 %**
S_4	at 15 cm	182	24.2	
S_7	at 20 cm	153	36.3	
S_2	without	259	-	**V_f = 0.75 %**
S_5	at 15 cm	193	25.5	
S_8	at 20 cm	188	27.4	
S_3	without	275	-	**V_f = 1.0 %**
S_6	at 15 cm	220	20.0	
S_9	at 20 cm	200	27.3	

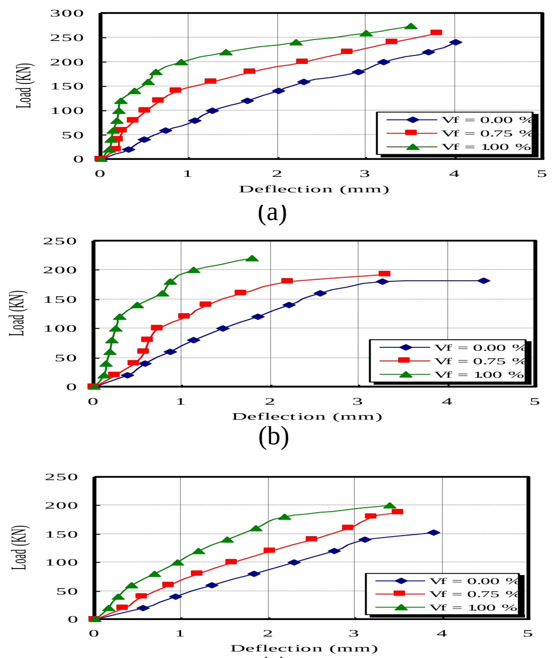

Fig 5. Effect of fiber content on the values of deflection : a) Without openings; b) With web opening at 15 cm; c) With web opening at 20 cm.

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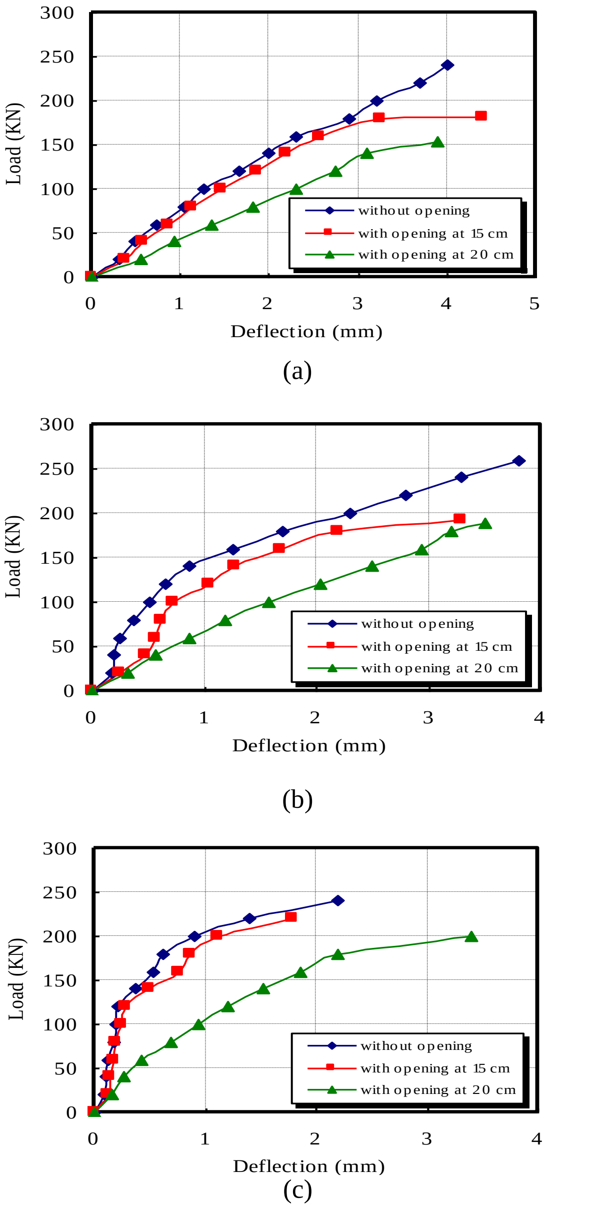

Fig 6. Effect of Web openings on the values of deflection : a) Without steel fiber; b) With fiber volume fraction 0.75%; c) With fiber volume fraction1.0 %.

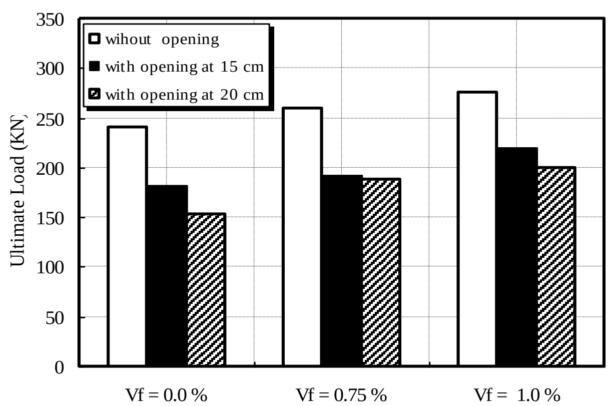

Fig 7. Effect of steel fiber and web openings on the ultimate load

C. Crack Pattern and Failure Mode

Figures (8), (9) and (10) show the crack patterns of beams without web opening, with web openings at 15 cm, and with web openings at 20 cm respectively. In beam S_1 without web opening and steel fiber, At first a little flexural vertical cracks are appeared at the mid span of the beam with small width, and theses are followed by diagonal cracks at the middle of shear span, with the increase in loading, cracks are propagated towards the support and point of loading and other inclined cracks are formed. However, the flexural cracks didn't develop any more. The same behavior is occurred in beams S_2 and S_3 but the number and the width of cracks are decreased due to the presence of steel fiber.

In deep beams with openings, the first diagonal cracks are appeared at the bottom and the top corners of the openings. These cracks are propagated towards the support and loading points, by load increasing, newly diagonal cracks are formed parallel to the first one. At later stages of loading, flexural cracks are appeared, but these cracks hardly penetrate beyond the mid depth for beam with openings and didn't affect the final collapse. By adding steel fiber to deep beams with openings, the cracks are formed more slowly and their widths are reduced. From crack patterns, it is shown that the concrete strut, which is the lower part of the opening, ultimately failed by the tie action of longitudinal reinforcement as proposed by Kong and Sharp [4]. Thus, it should be recognized that the lower load path is more critical than the upper load path.

VI. FINITE ELEMENT RESULTS

A. Effect of Web Openings

Figure (11) shows the deformed shape for deep beams with web openings. The figure indicated that the web opening decreased the stiffness of the beam and increased maximum vertical deflection especially for the position of web opening at 20 cm. Figure (12) shows the displacement and the stresses contours at the same load in case of deep beams without steel fiber. This figure demonstrated that, the distribution of the displacement is minimized in case of beam without openings. Also, the stresses are decreased in case of beam without openings due to the distribution of forces along the full beam.

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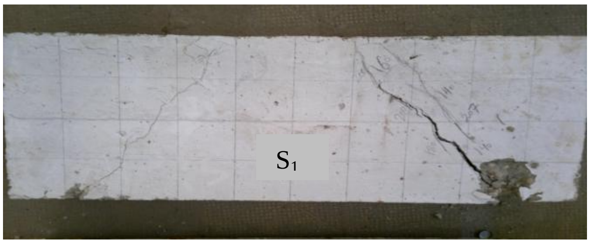
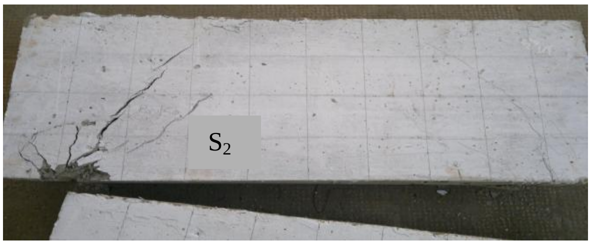
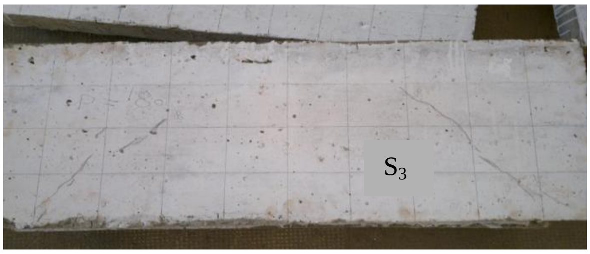


(a)

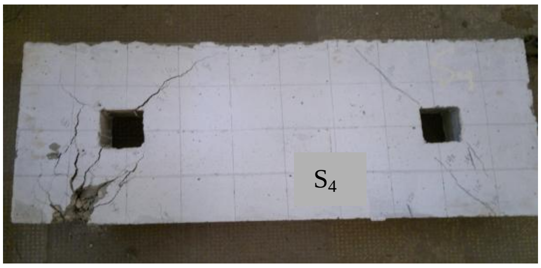


(b)



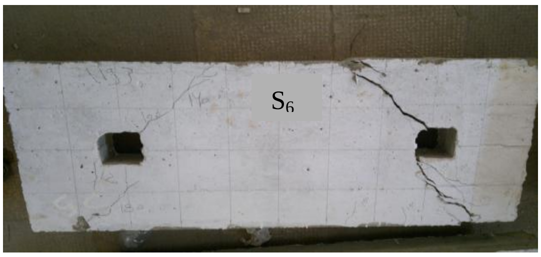
(c)

Fig 8. Crack pattern at failure of beams without web opening: (a) V_f = 0 %, (b) V_f = 0.75, (c) V_f = 1.0 %.



(a)

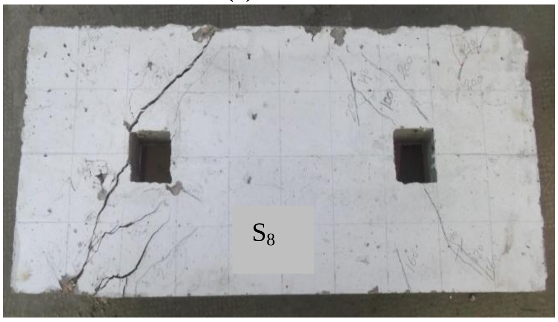
(b)



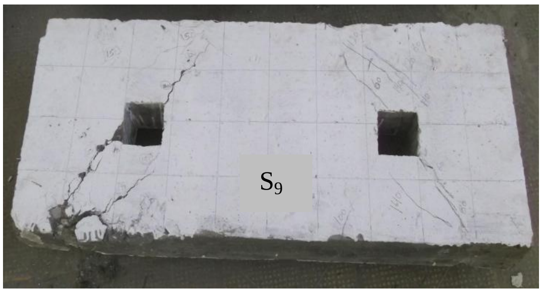
(c)

Fig 9. Crack pattern at failure of beams with web opening at 15 cm: (a) V_f = 0 %, (b) V_f = 0.75, (c) V_f = 1.0 %.

(a)

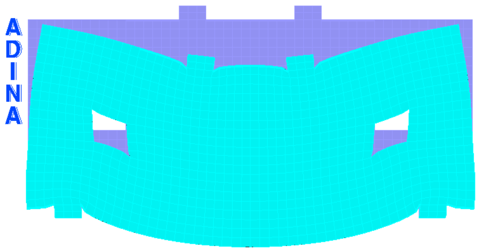


(b)

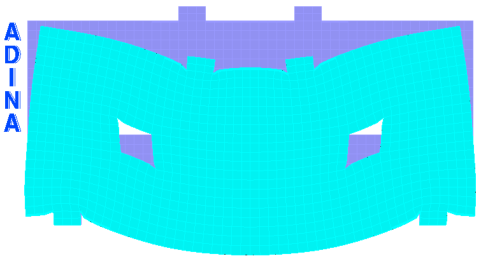


(c)

Fig 10. Crack pattern at failure of beams with web opening at 20 cm: (a) V_f = 0 %, (b) V_f = 0.75, (c) V_f = 1.0 %.



(a)



(b)

Fig 11. Deformed shap for deep beam without steel fiber with web opinings: (a) at 15 cm; (b) at 20 cm.

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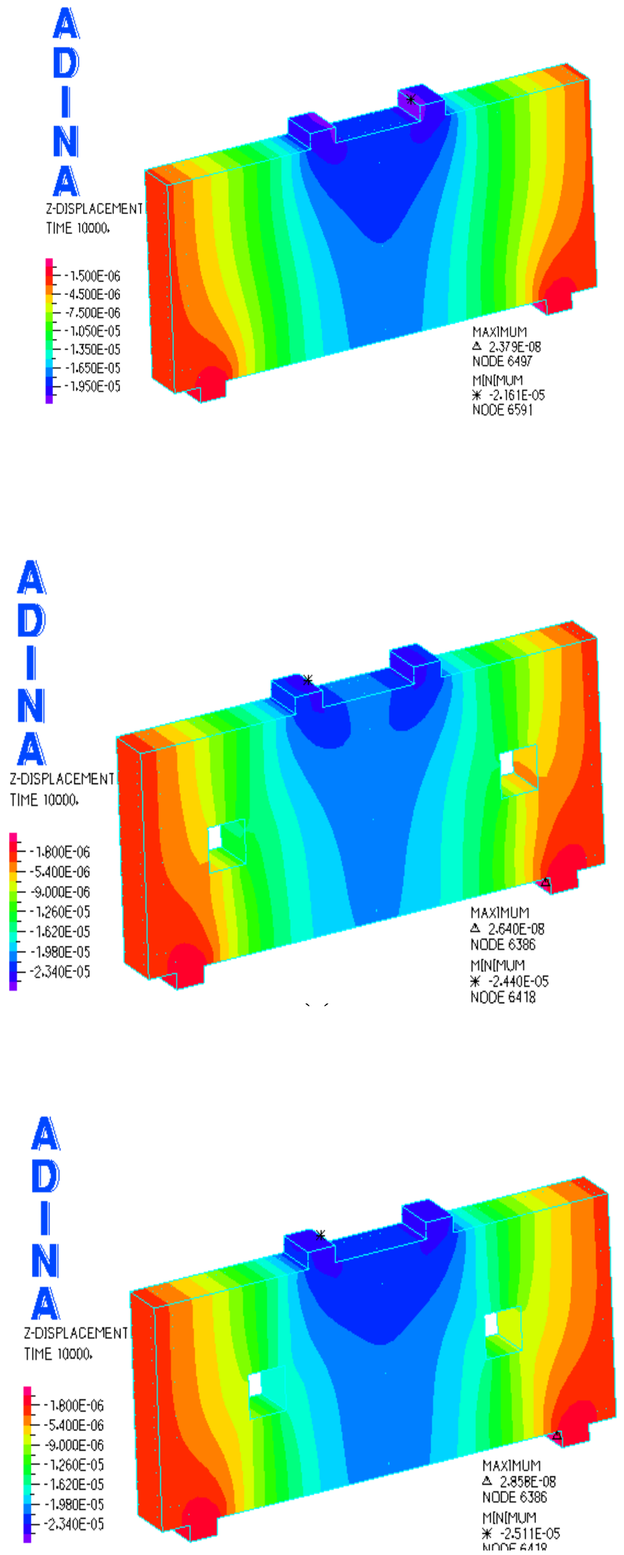

Fig (12- a): Vertical Displacement contour for beams without steel fiber and without web opening, with web openings at 15 cm, and with web openings at 20 cm.

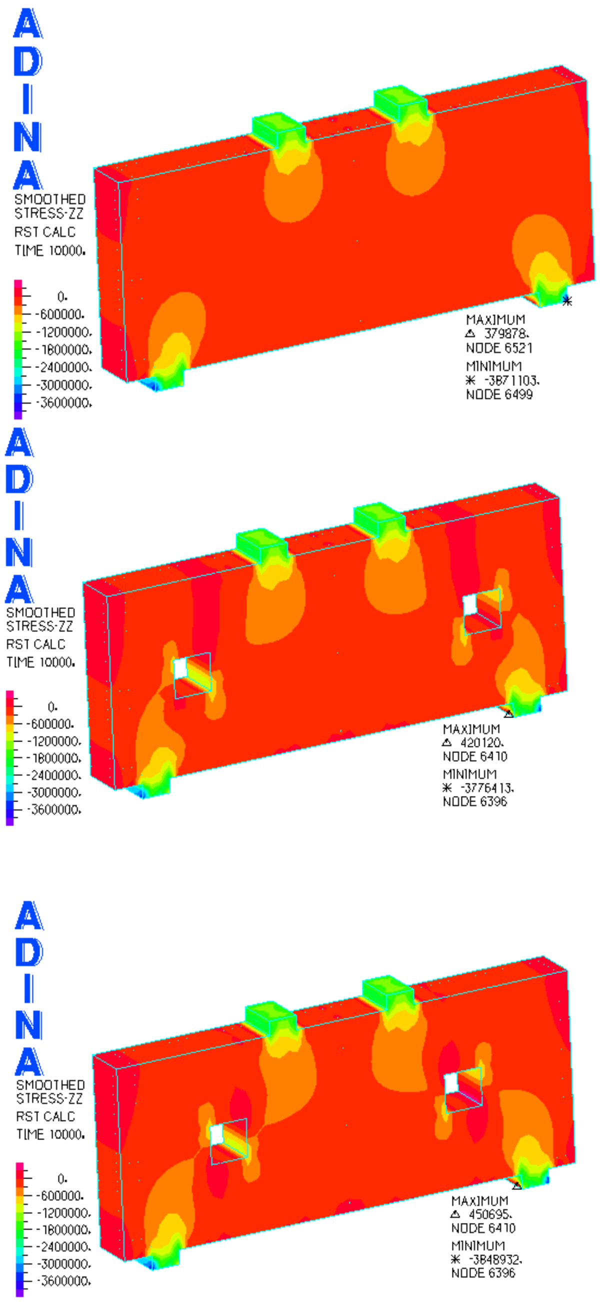

Fig (12- b): Vertical stress contour for beams without steel fiber and without web opening, with web openings at 15 cm, and with web openings at 20 cm.

A. Effect of Steel Fiber

Figure (13) shows the displacement and stresses contours in cases of deep beams with web openings at 20 cm and different fiber volume fraction (0 %, 0.75 %, and 1.0 %). From this figure, one can be notice that the increase in fiber volume fraction the decrease in the distribution of the displacement and stresses. This reflects the fact that, the steel fiber increases the stiffness of the deep beam and makes the redistribution of the forces and displacement in all the beam parts.

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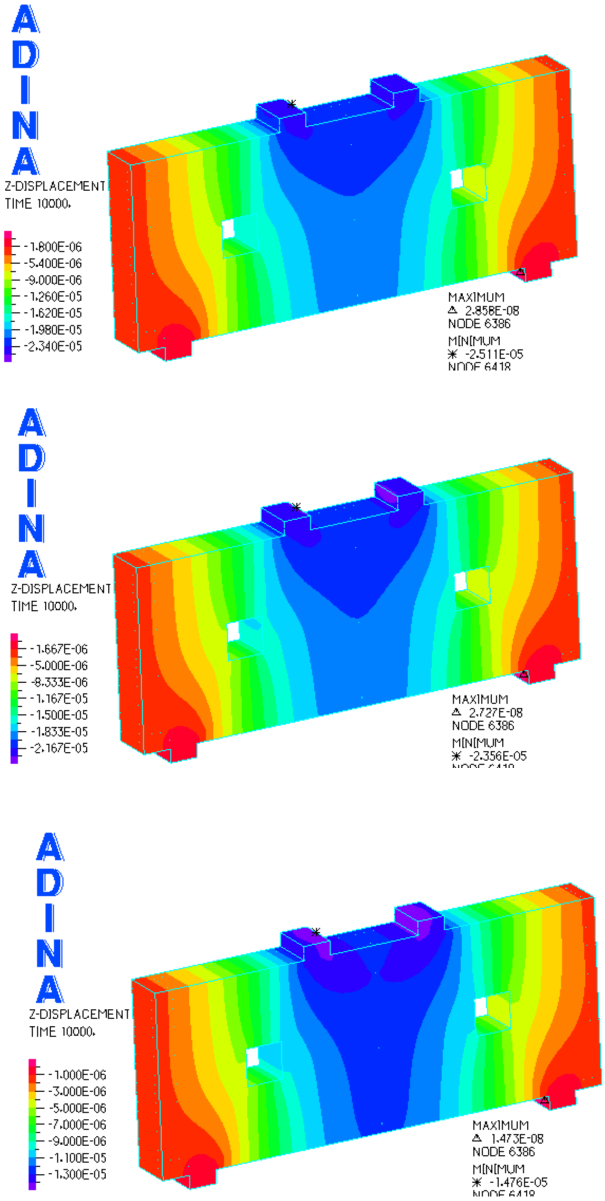
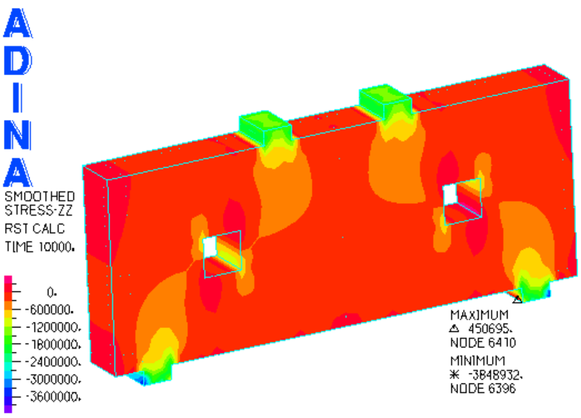


Fig (13- a): Vertical Displacement contour for beams with web openings at 20 cm and fiber volume fraction = 0 %, 0.75 %, and 1.0 %.



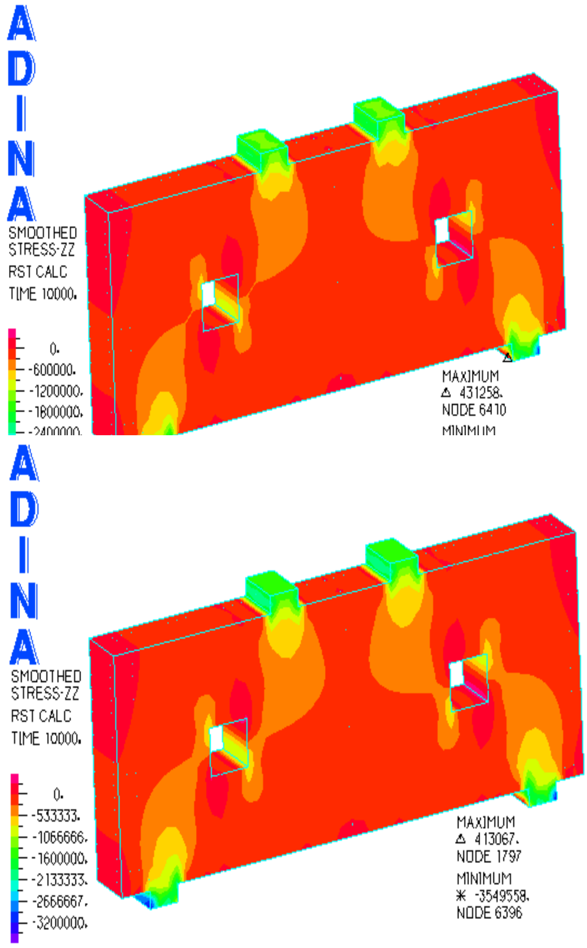


Fig (13- b): Vertical stress contour for beams with web openings at 20 cm and fiber volume fraction = 0 %, 0.75 %, and 1.0 %.

VI. COMPARISON OF EXPERIMENTAL AND FINITE ELEMENT RESULTS

Figure (14 – a) shows the values of mid span deflection against steel fiber content for all cases of test study against that obtained from finite element results, where the load – deflection responses for one case of study that for the beam with $V_f = 1.0$ % and without opening from the test results are plotted against the finite element results in figure (14 – b). The mid span deflection at ultimate load of the beam recorded in the tests and finite element are close to each other as shown in figure (14 – b). In general, the values of deflection plot for the beam from the finite element analyses agree quite well with the experimental data.

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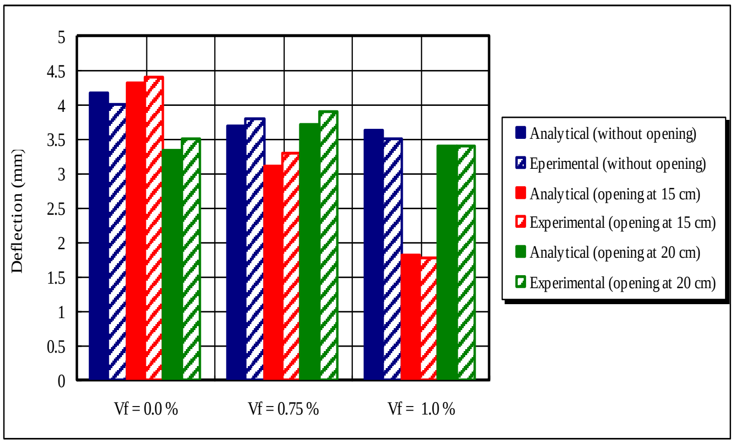
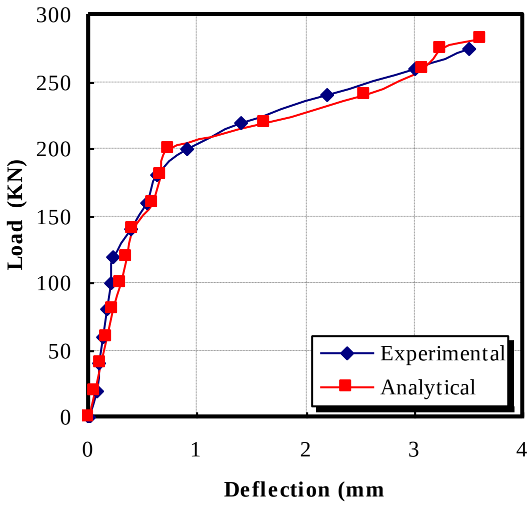


(a)

Fig (14- a): Effect of fiber content on the values of deflection from finite element results.



(b)

Fig (14 - b): Experimental and finite element load – deflection responses

VII. CONCLUSION

This paper presents an experimental program and analytical analysis by using ADINA program to describe the effect of steel fiber on the behavior of reinforced concrete deep beams with and without web openings. The following conclusions can be drawn from the experimental and analytical results:

- The deflection is decreased as the steel fiber content increases by small rate for beams with openings at 20 cm. However, the deflection of the beams with openings at 15 cm is decreased by about 25 % and 46 % by the increase in steel fiber from 0 % to 0.75 % and from 0.75 % to 1.0 % respectively.
- The beams with web openings behaved in a stiff manner when the steel fibers are added especially when the web openings at 15 cm, where the deflection is decreased by about 47.6 % from beam with opening at 20 cm to that with opening at 15 cm and steel fiber content = 1.0 %.
- The presence of web openings, especially at distance 20 cm from the end of the beam reduces the values of ultimate load.
- When the steel fiber volume fraction is increased, the ultimate loads are increased. The best fiber volume fraction was 1.0 % in case of web opening at 15 cm and 0.75 % in case of web opening at 20 cm.
- The distribution of the displacement is minimized in case of beam without openings. Also, the stresses are decreased in case of beam without openings due to the distribution of forces along the full beam.

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Sieve size (mm)	37.5	20	14	10	5	2.36	1.18	0.60	0.33	0.15	0.075
passing (dolomite)	100	96.2	81.5	45	15	-	-	-	-	-	-
% passing (sand)	-	-	-	-	98.6	95.6	86.4	63.6	26	2.2	0.58

Table (3): Grading of fine and coarse aggregates