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Finite Element Analysis of Steel Fiber Reinforced Concrete Beams

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Abstract

This paper is a numerical analysis to study the shear behaviour of steel fiber reinforced concrete (SFRC) beams with high strength reinforced using finite element modelling. Five steel fiber reinforced concrete beams (B00, B0.50, B1.00, B1.50 and B2.00) which have steel fiber volume fraction (0, 0.5, 1, 1.5, 2) % respectively, without web reinforcement have been carried out. The analytical results obtained from finite element modelling have been compared with available data. Good agreement has been obtained between the finite element solutions and experimental results. The analytical results such ultimate shear force, shear force-deflection curve and crack pattern are presented. Also, a comparison between analytical results and the modification of ACI building equation by Ashour et al. are presented in this paper. A parametric study has been done to investigate the effect of shear span to depth ratio (a/d), and using minimum stirrups on the behaviour of shear strength.

Keywords: Finite element. Shear capacity. Steel fiber reinforced concrete beam.

1. INTRODUCTION

In the reinforced concrete beam, the addition of steel fibers is known to increase its shear strength and if an appropriate amount of fibers is added, a brittle shear failure can be restrained.

There are numerous experimental studies of steel fiber reinforced concrete beams.

Previous studies demonstrated that the addition of steel fiber increases the shear strength of concrete [1], [2], [3], [4]. [5] showed that the increase in shear strength as a result of addition steel fiber depends on the amount of fibers and the anchorage conditions of the steel fibers.

[6] tested twelve reinforced concrete (RC) without stirrups, with several parameters, three steel fiber volume ratios (0, 0.5, and 0.75) %, concrete compressive strength (31 and 65) Mpa, and shear span to depth ratio (2, 3 and 4). The results showed that the ultimate shear strength increased with increasing fiber volume, increasing concrete compressive strength and decreasing shear span to depth ratio.

[7] tested experimentally eighteen RC beams having steel fiber dosages of (0, 30, and 60) kg/m3 with C20 and C30 class concrete. The load-midspan deflection relationships of all reinforced concrete and steel fiber reinforced concrete beams under bending were recorded. As a result of bending test, it was concluded that both the ultimate loads and the toughness of reinforced concrete beams produced with concrete classes (C20 and C30) with 30 kg/m3 steel fiber, increase noticeably as compared to those reinforced concrete beams without steel fibers.

[8] investigated the effect of steel fiber volume ratio on the shear behaviour of beams with high strength reinforcement. A total of three reinforced concrete beams and eight steel fiber reinforced concrete beams was carried out. The experimental results showed that the addition of steel fiber increases the ultimate shear capacity and the stiffness of the beams. Also, the values of the ultimate shear stresses were compared with the values evaluated by ACI544.4R and CECS38;2004.

Researchers had also developed an equation for calculating the ultimate shear stress (Vu), such as [9] [10].

The present work investigates the behaviour of five steel fiber reinforced concrete (SFRC) beams with high strength reinforcement, by using a 3D finite element program (Ansys V15.0). The results obtained by a finite element program have been compared with available experimental data [8] and modification of the ACI building equation by [10]. Design equation calculated by Ashour et al. to predict the shear strength of rectangular steel fiber reinforced concrete beams without shear reinforcement.

$$Vu = \left(0.7 * \sqrt{f'c} + 7F\right)\frac{d}{a} + 17.2.\rho.\frac{d}{a} \quad \text{in Mpa ... (1)}$$

Where:

Fiber factor $F = \left(\frac{L}{D}\right).\rho_f.d_f$

L/D: Fiber aspect- ratio.

ρ_f: Fiber volume fraction.

d_f : Bond factor that accounts for differing fiber bond characteristics.

ρ: Steel reinforcement ratio.

2. MATERIAL MODELLING

2.1 Concrete

2.1.1 Compressive strength of concrete

For concrete in compression, excessively accepted [11] uniaxial stress-strain relationship is used in this study. Fig. 1 shows a compressive uniaxial stress-strain curve.

$$f'c = \frac{\varepsilon Ec}{1+\left(\frac{\varepsilon}{\varepsilon_0}\right)^2} \quad \text{for} \quad \varepsilon_1 \le \varepsilon \le \varepsilon_0 \quad ..(2)$$

$$\varepsilon_0 = \frac{2f'c}{E_c} \quad ..(3)$$

$$\varepsilon_1 = \frac{0.3f'c}{E_c} \quad ..(4)$$

$$E_c = \frac{\sigma}{\varepsilon} \quad \text{for} \quad 0 \le \varepsilon \le \varepsilon_1 \quad ..(5)$$

Where;

$\sigma =$ stress at any strain $\varepsilon, N/mm^2$

$\varepsilon =$ strain at stress σ

$\varepsilon_0 =$ strain at the ultimate compressive strength $f'c$

ε_1 = strain corresponding to ($0.3 * f'c$)

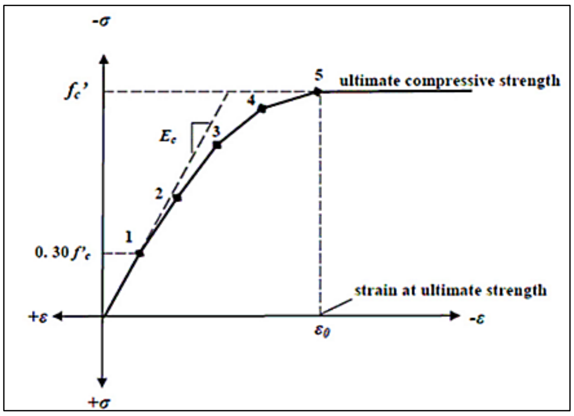

Fig. 1. Uniaxial stress-strain curve for concrete in compression

2.1.2 Tensile behaviour of concrete

The stress-strain relationship for concrete in tension is linear elastic up to concrete cracking. After concrete cracking the tensile stress decreases linearly to zero as the concrete softens [12].

The modulus of rupture (ultimate tensile strength) is taken as $fr = 0.7\sqrt{f'c}$,[13]

Where, $f'c =$ concrete compressive strength, in Mpa

A shear transfer coefficient β, represents a shear strength reduction factor. B range from (0) to (1), which (0) representing a smooth crack -complete loss of shear transfer-, while (1.0) representing a rough crack -no loss of shear transfer-[14].

2.2 Steel reinforcement

The stress-strain curve of the steel bar is idealized as a bilinear in the compression and tension sides. The first stage is elastic up to steel yield strength, followed by linear strain hardening stage as shown in Fig. 2.

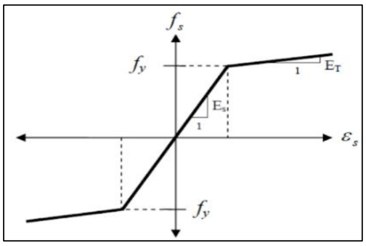

Fig. 2. Stress-strain curve for concrete in tension

3. FINITE ELEMENT MODELLING

3.1 Element Type

To model concrete in Ansys, the 8-node brick element (Solid 65) is used in this study. Fig. 3.

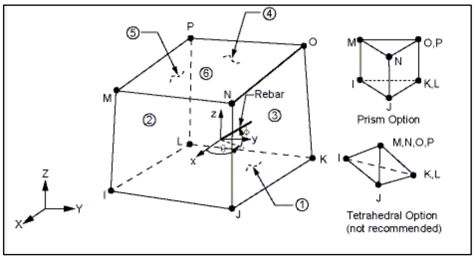

Fig. 3. Solid (65) element [14]

The steel fiber is represented as a smeared layer in (Solid 65) element. Therefore, the steel fiber volume ratio is entered as a real constant in this element.

A (Link 180) element is used to model steel reinforcement. This element has two nodes. Fig. 4.

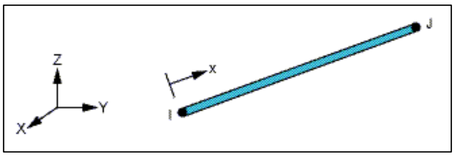

Fig. 4. Link (180) element [14]

A (Solid 185) element is used to model the loading and support plates. This element has eight nodes. Fig. 5.

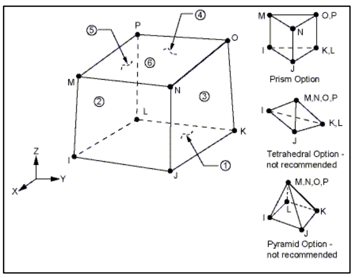

Fig. 5. Solid (185) element [14]

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3.2 Case Study

The geometry and details of the beams are shown in Fig. 6. Five steel fiber reinforced concrete beams tested by [8] are modelled using Ansys (15.0). The details and material properties of all the beams are given in Table 1.

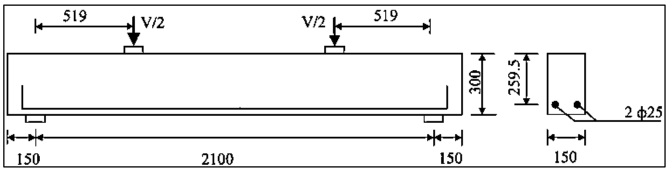


Fig. 6. Dimensions of the beams in (mm)

3.3 Modelling Methodology

Due to symmetry about the vertical axis, half of the full beam is used for modelling (SFRC) beam with proper boundary conditions. The concrete beam, loading and support plates are modelled as volumes, Fig. 7. shows (FE) modelling of the beam. Steel reinforcement is created as a discrete reinforcement through the nodes created by the mesh of the concrete volume.

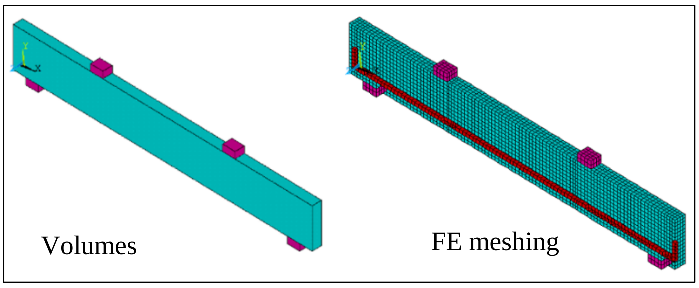


Fig. 7. (FE) modelling of the beam

Boundary conditions are required to obtain a suitable solution for the model. Simply supported boundary conditions with a hinge (nodes are restricted in x, y directions) and roller (nodes are restricted in y direction) supports are applied across the centreline of the plates. On a plane of symmetry (x, y plane), the nodes are prevented to displace in z- direction. The load is applied across the centreline nodes of the steel plates as shown in Fig. 8.

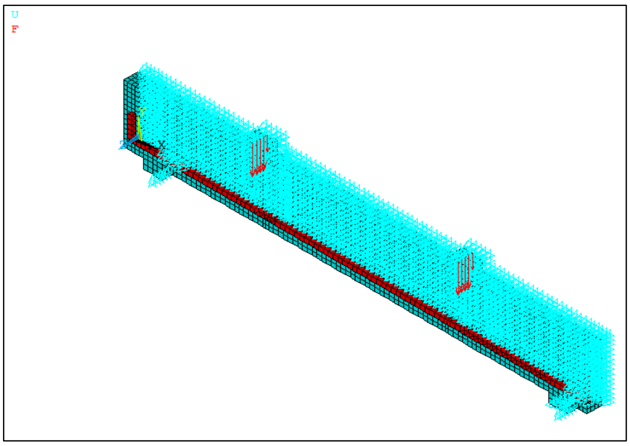


Fig. 8. Boundary conditions and loading

Table 1. Details and Material properties

Beams ID		**B00**	**B0.5**	**B1.0**	**B1.5**	**B2.0**
Length (mm)		2500				
Span to depth ratio (a/d)		2				
Steel fiber volume ratio, %		0	0.5	1	1.5	2
Concrete	**Compressive strength $f'c$, Mpa**	33.03	34.45	36.08	37.13	35.26
	Modulus of rupture fr, Mpa	4.02	4.11	4.21	4.265	4.1566
	Modulus of elasticity Ec, Mpa	23713	24856	25968	27211	26802
	Poisson's ratio υ	0.2				
	β_o	0.8	0.7	0.6	0.85	0.2
	β_c	0.9	0.9	0.9	0.9	0.9
Steel reinforcement	**Yield strength fy, N/mm^2**	567.8				
	Modulus of elasticity Es, Mpa	$200*10^3$				
	Poisson's ratio υ	0.3				
Steel plate	**Modulus of elasticity Es, Mpa**	$200*10^3$				
	Poisson's ratio υ	0.3				

3.4 Analysis Type

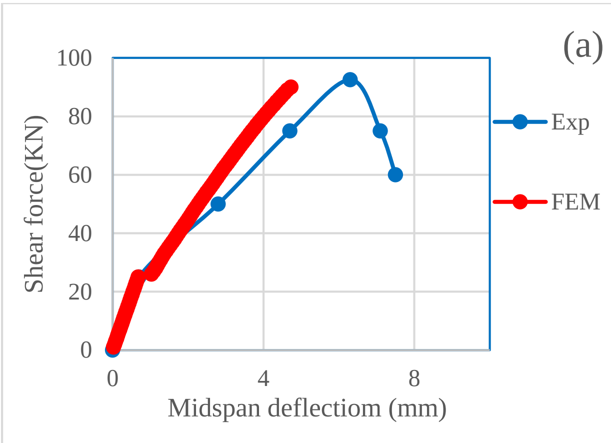
A nonlinear analysis is performed to study the nonlinear behaviour of SFRC beams. The Ansys program employs Newton-Raphson method to solve nonlinear problems. The total load is applied in small increments as recommended in testing reinforced concrete structures to avoid nonconvergence problems.

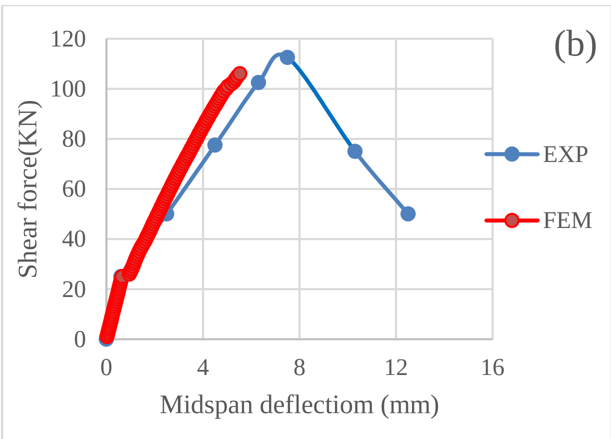
4. RESULTS AND DISCUSSION

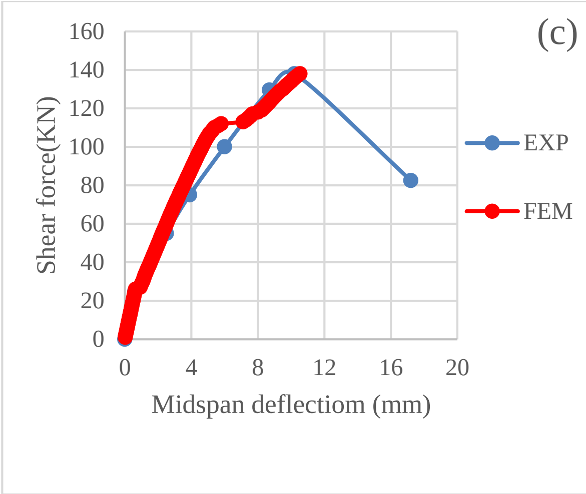
4.1 Verification of finite element model

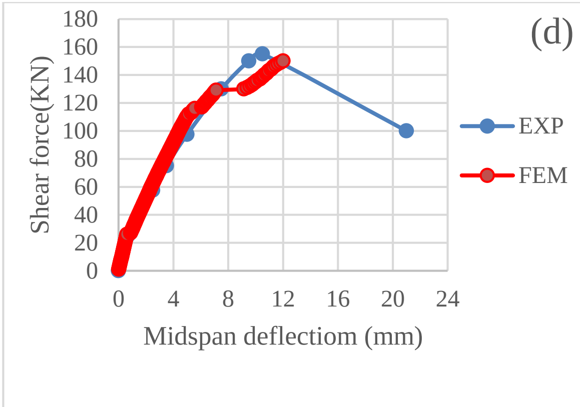
To validate the FE model, a comparison is conducted by comparing the ultimate shear force and shear force-deflection curve of the experimental SFRC beams with FE model. In general, good agreement has been carried out between the results. Fig. 9. plots the shear force-deflection curves of the experimental beams and FE model. Generally, the curves can be separated into two stages. The first stage is the linear elastic stage (no flexural or shear crack appears). The first cracking load of the FE beams is (52-54) KN.

Then, when increasing the load, the finite element beams proceed to the second stage, nonlinear inelastic stage, in which flexural cracks are remarkable .The shear force obtained by experimental test, modification of the ACI building equation by [10] and that predicted by the FE solutions are listed in Table 2.









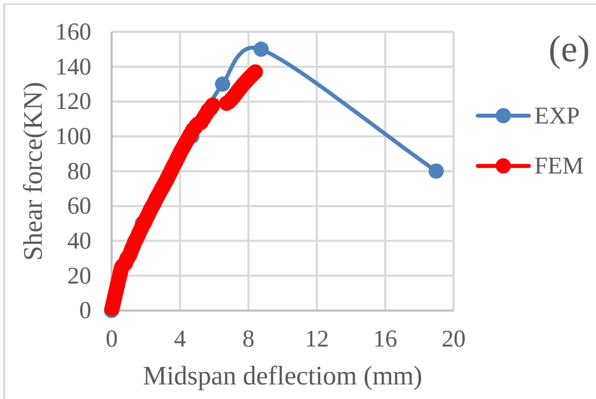


Fig. 9. Shear force-midspan deflection for a) B00, b) B0.5, c) B1.0, d) B1.5 and e) B2.0

Table 2. Comparisons between shear force obtained by experimental, Ashour equation and FE

Beam	Shear force (KN)			Experimental result / FE result	Ashour eq. / FE result
	Experimental result	Ashour eq.*	FE result		
B0.0	92.5	73	90	1.027	0.81
B0.5	112.5	94.5	106	1.06	0.89
B1.0	138	116.5	138	1	0.84
B1.5	155	137.5	152	1.019	0.9
B2.0	148.5	156	137	1.08	1.13

Fig. 10. shows the shear force-midspan deflection curves of the SFRC beams. It can be seen that, the shear capacity is enhanced with increasing steel fiber volume fraction, indicating that steel fiber increases stiffness, shear capacity as well as ductility of the beams.

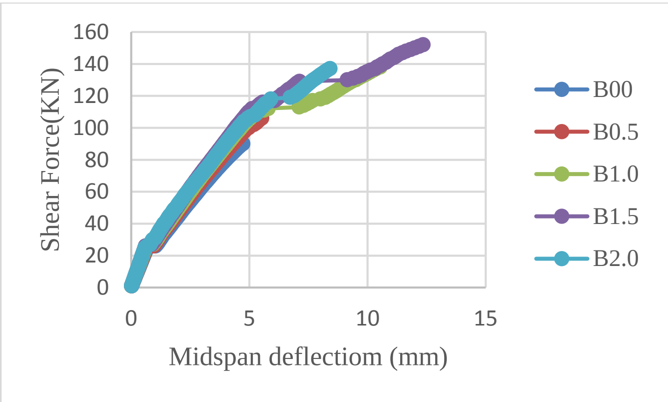


Fig. 10. shear force-midspan deflection curves of the SFRC beams

The shear capacities of the SFRC beams are shown in Fig. 11., It can be noticed that the shear capacities of the SFRC beams are improved by increasing the steel fiber volume fraction, except for B2.0 beam. The main reason is that when the steel fiber volume fraction is (2%), there are more flaws in concrete because of the tensile strength of B1.5 (V_f= 1.5%) is more than that of B2.0 (V_f = 2%).

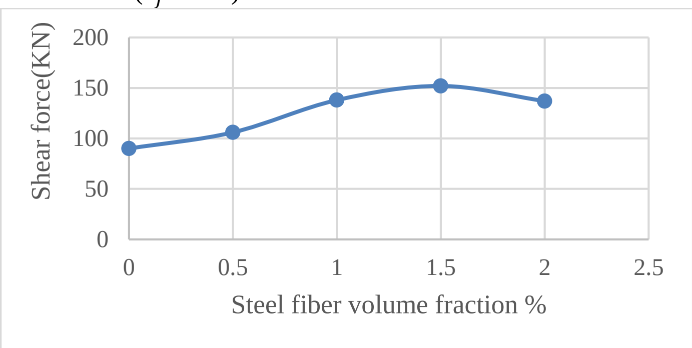
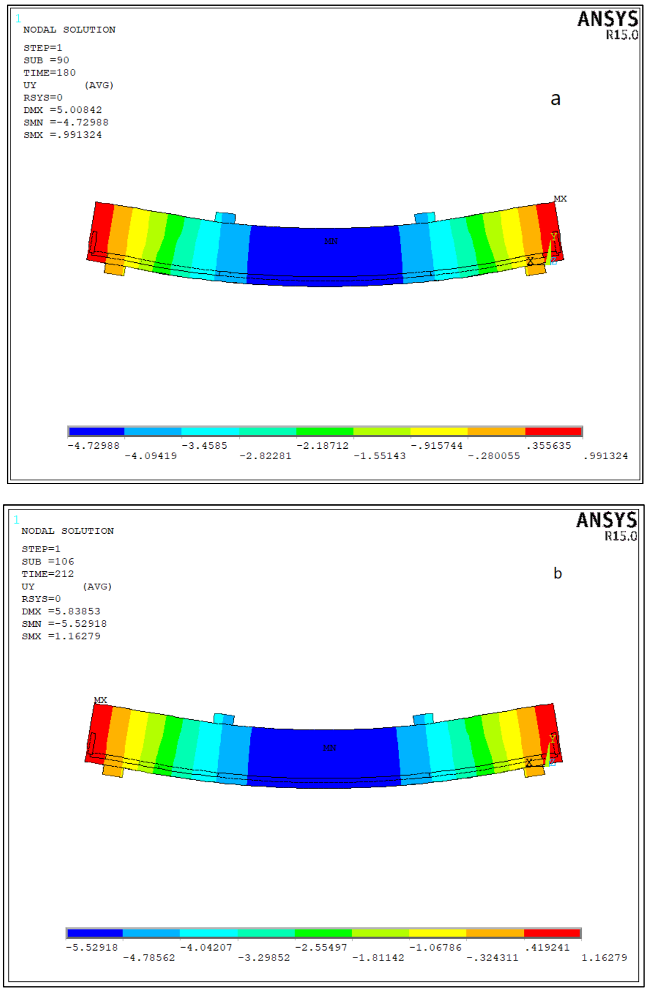


Fig. 11. Relationship of shear force and steel fiber volume fraction.

The variation of vertical displacement along the beams (B00, B0.5, B1.0, B1.5 and B2.0) at ultimate shear force are given in Fig. 12.



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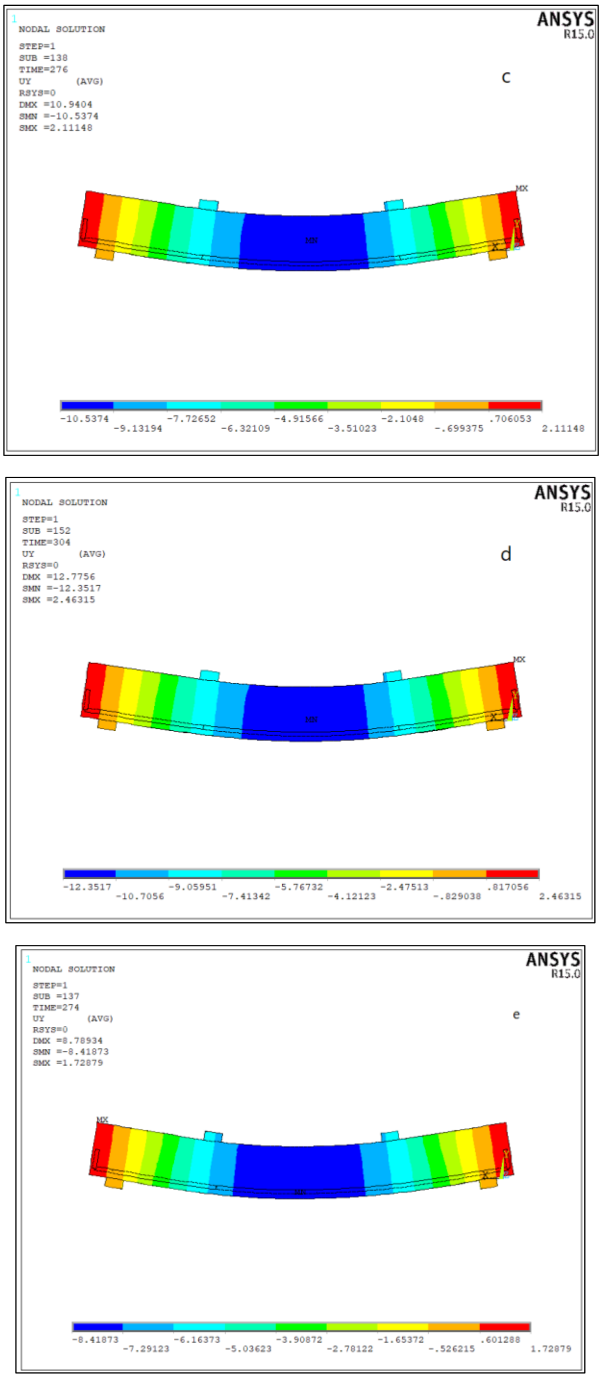

Fig. 12. The variation of displacement along the beams a) B00, b) B0.5, c) B1.0, d) B1.5 and e) B2.0) at ultimate shear force.

The crack patterns (first crack and cracks just before failure) obtained by the finite element model are shown in Fig. 13., The (FE) model showed that the first crack occurs between (52-54) KN for all the beams. Flexural cracks formed as a result of the flexural stresses in the zone of the cross section below the neutral axis, Cracking expanded in the constant moment zone. Shear cracks appear as a result of the inclined tensile stresses acting on the web of the beam. Subsequently, the model started cracking out towards the supports. Then, the cracks increased and expanded to the compression region.

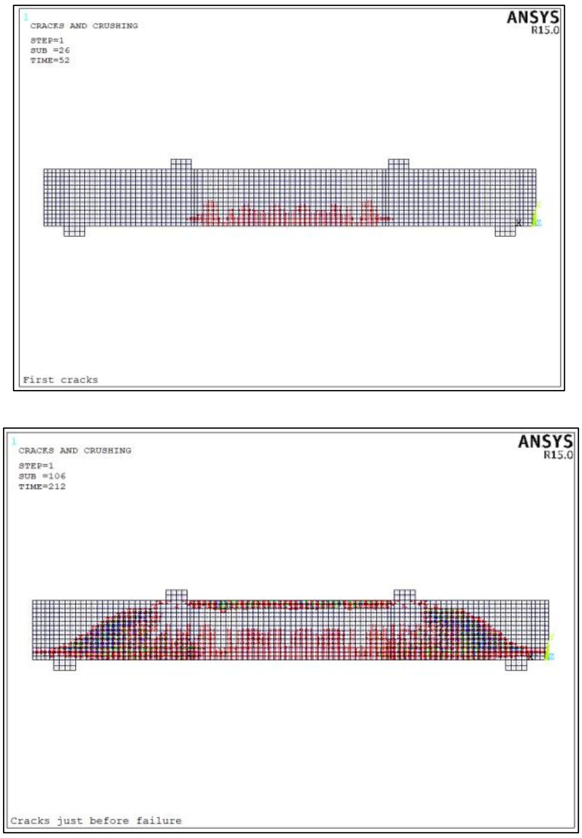

Fig. 13. Crack pattern

4.2 Parametric study

4.2.1 Effect of shear span to depth ratio

The shear strength of SFRC beams corresponding to shear span to depth ratio (a/d) ranging from (2 to 3) has been predicted using Ansys (15.0) software. The ultimate shear force obtained for different (a/d) by Ansys and Ashour equation is listed in Table 3. The influence of the (a/d) ratio and steel fiber volume fraction of the shear strength of the RC beams is given in Fig. 14. The results indicate that increasing the ratio of steel fiber with decreasing shear span to depth ratio is effective in enhancing the shear strength of RC beams.

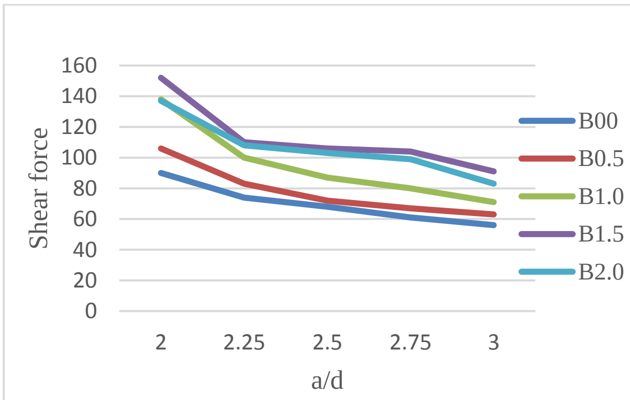

Fig. 14. Shear force-shear span to depth ratio relations for the beams

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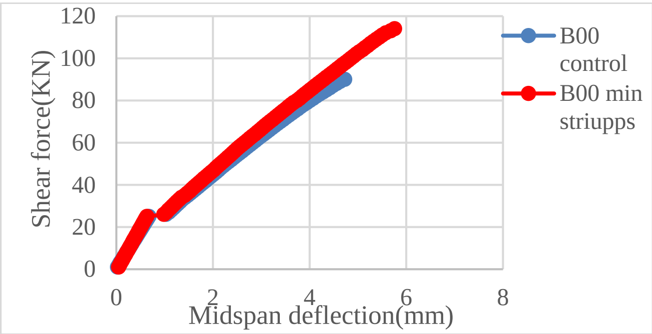
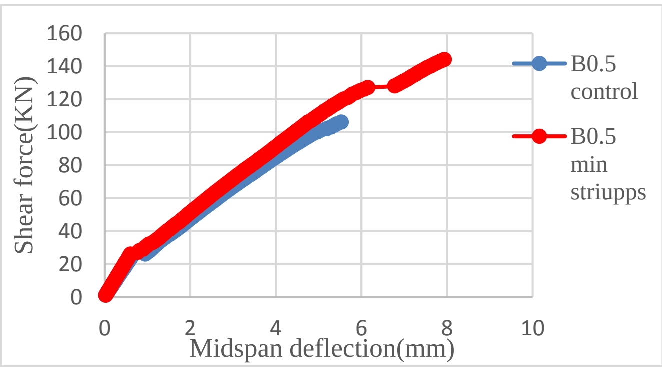
Table 3. Effect of shear span to depth ratio (a/d) on ultimate shear force

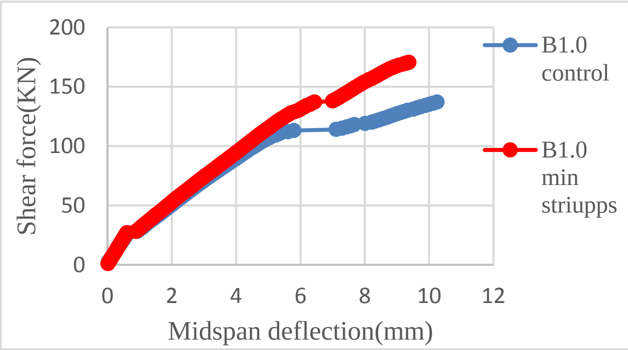
(a/d)	Shear force Vu (KN)	B00	B0.5	B1.0	B1.5	B2.0
2	**Vu control**	90	106	138	152	137
2.25	**Vu, ($\frac{Vu\ contol-Vu}{Vu\ control}$)**	74 (0.18)	83 (0.22)	100 (0.28)	108 (0.29)	108 (0.22)
	Vu Ashour	65	84	103	122	138
2.5	**Vu, ($\frac{Vu\ contol-Vu}{Vu\ control}$)**	68 (0.25)	72 (0.32)	87 (0.37)	106 (0.31)	103 (0.25)
	Vu Ashour	58	75	93	110	125
2.75	**Vu, ($\frac{Vu\ contol-Vu}{Vu\ control}$)**	61 (0.33)	67 (0.37)	80 (0.42)	104 (0.32)	99 (0.28)
	Vu Ashour	53	68	85	100	113
3	**Vu, ($\frac{Vu\ contol-Vu}{Vu\ control}$)**	56 (0.38)	63 (0.41)	71 (0.49)	91 (0.41)	83 (0.4)
	Vu Ashour	48	63	77	92	104

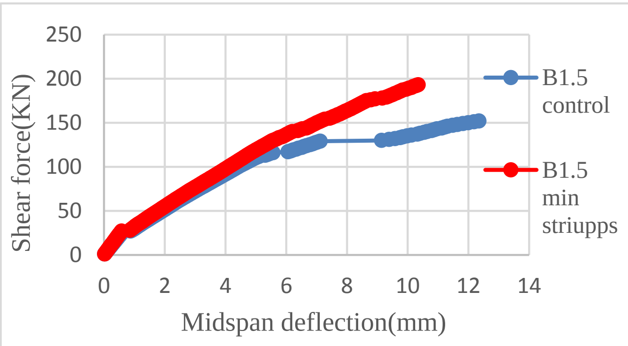
4.2.2 EFFECT OF USING MINIMUM SHEAR REINFORCEMENT

Fig. 15. shows the shear force-deflections curves of SFRC beams with minimum shear reinforcement ratio. It can be noticed that using minimum stirrups ratio (0.335%) significantly increased the shear force as well as the stiffness of the beams. The ultimate shear force obtained from control beam (without shear reinforcement) and the same beams with minimum shear reinforcement are listed in Table 4. It can be observed that shear force increased by about (21,26,19,21 and 23) % for B00, B0.5, B1.0, B1.5 and B2.0 respectively, when using the minimum stirrups ratio (0.335%).









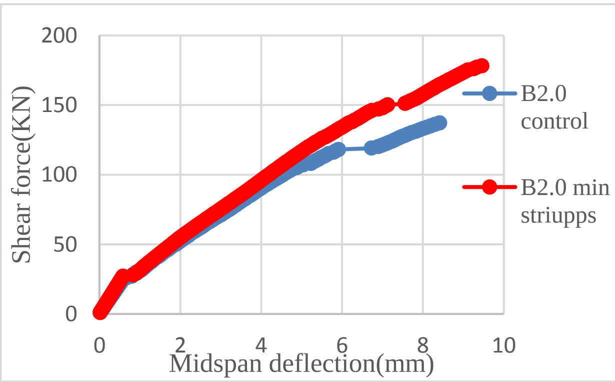


Fig. 15. Shear force-deflections curves of the beams with minimum shear reinforcement.

Table 4. Comparisons between ultimate shear force obtained for control beams and beams with minimum shear reinforcement

	Shear force (KN), Vu		$\frac{\textbf{Vu min. shear reinforcement} - \textbf{Vu control specimens}}{\textbf{Vu min. shear reinforcement}}$
	Control beams (without shear reinforcement)	**beams with min. shear reinforcement**	
B00	90	115	0.21
B0.5	106	144	0.26
B1.0	138	170	0.19
B1.5	152	193	0.21
B2.0	137	178	0.23

5. CONCLUSION

1. The finite element (FE) model used in this study is able to simulate the shear behaviour of steel fiber reinforced concrete (SFRC) beams. The results indicated that the ultimate shear force and the shear force-midspan deflection behaviour and are in good agreement with the experimental results. The maximum ratio of the experimental ultimate shear force to the predicted (FE) ultimate shear force has an average value of (1.08), and the maximum ratio of Ashour equation shear force to the predicted (FE) ultimate shear force has an average value of (0.81).
2. The (FE) results indicated that the shear capacity is enhanced with increasing steel fiber volume fraction, indicating that steel fiber increases the stiffness as well as ductility of the RC beams.
3. According to the results obtained from the FE analyses of SFRC beams, it is found that the increasing of shear span to depth ratio has insignificant effect on the shear behaviour of SFRC beams.
4. The (FE) results indicated that the shear capacity increased by about (21,26,19,21 and 23) % for B00, B0.5, B1.0, B1.5 and B2.0 respectively, when using the minimum stirrups ratio (0.335%).

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