Journal of Engineering Research

Volume 7 | Issue 1 Article 12

2023

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Recommended Citation

Kamel, Mohamed (2023) "Shear Strength of Fiber Reinforced Concrete (FRC) Beams without Stirrups," *Journal of Engineering Research*: Vol. 7: Iss. 1, Article 12.
Available at: https://digitalcommons.aaru.edu.jo/erjeng/vol7/iss1/12

Journal of Engineering Research (ERJ)
Vol.7 – No. 1, 2023
©Tanta University, Faculty of Engineering
ISSN: 2356-9441
https://erjeng.journals.ekb.eg/
e ISSN: 2735-4873

Shear Strength of Fiber Reinforced Concrete (FRC) Beams without Stirrups

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***Abstract*: This paper presents the results of twelve shear tests carried out on simply supported rectangular beams, with a shear span to depth ratio (a/d) of 2.4, under a single concentrated load. Six of the beams contained conventional stirrups and six beams were reinforced with steel fibers as web reinforcement. The parameters were: the effect of fiber volume content (0, 0.5, 1.0, and 1.5%), fiber type (end-hooked or corrugated), and the presence of minimum stirrups. The beam span, beam dimensions, shear span to depth ratio (a/d), and percentage of longitudinal reinforcement were all kept constant. Beam deflection, steel strains, crack propagation, and failure modes were recorded for all the tested beams. The test results showed that the shear cracking, and the ultimate shear stress increased with the increase of fiber volume content. When steel fibers with a content of 1.5% were added to the beams with minimum stirrups, the brittle shear failure was changed to ductile flexure failure. The test results were compared with some empirical equations developed to estimate the shear strength of steel fiber reinforced concrete beams without stirrups. The comparison indicated that the equations proposed by Narayanan and Darwish 1987 and Kara 2013 provided the most accurate estimation when compared to the test results.**

***Keywords*: Beams; Shear strength; Steel fiber; Shear reinforcement**

I. INTRODUCTION

Shear failure is undesirable in reinforced concrete beams due to the fact that the nature of this failure is brittle and less predictable. The addition of steel fibers to reinforced concrete beams is known to increase its shear strength, and if sufficient fibers are added, the brittle shear failure may change to a ductile one. The steel fibers are characterized by high elastic modulus, high tensile strength, and can be easily dispersed into concrete mixtures. The primary role of steel fibers is to bridge cracks due to tension in the concrete and increase concrete tensile performance.

There are a considerable number of researches studied the shear behavior of steel fiber reinforced concrete (SFRC) beams. The first scientific investigation regarding the use of steel fibers as shear reinforcement was conducted by Batson et al. (1972) [1]. They believed that smaller size of steel fibers performed better than larger sized ones because more fibers could be added with the same volume fraction of fibers.

Narayanan and Darwish (1987) [2] developed an equation to estimate the shear strength of SFRC beams through an experimental program by testing 49 SFRC beams. In this equation, the authors took into account the effect of the shear contribution of fiber reinforced concrete through the splitting tensile strength, shear span-to-effective depth ratio, dowel action, arch action, and fiber pullout forces along the inclined crack. In addition, they neglected the shear contribution of the compression zone and the aggregate interlocking. Regardless of this, their formula was reported to be accepted.

Shin et al. (1994) [3] developed an empirical equation by testing 22 reinforced concrete beams. The main variables in this experimental program were the fiber volume content; V_f, shear span to depth ratio, amount of longitudinal reinforcement, and amount of shear reinforcement. Shin et al. (1994) [3] took into account the same assumptions of Narayanan and Darwish (1987) [2] but neglected the arching action effect. Also, Kwak et al. (2002) [4] developed their empirical equation taking into account the same assumptions of Narayanan and Darwish (1987) [2] using a similar experimental program. Cucchiara et al. (2004) [5] tested sixteen simply supported beams under two-point loading with the same dimensions, longitudinal reinforcement, and different fiber volume fractions. It was observed that in terms of ultimate strength, a similar performance is obtained by using steel fibers instead of stirrups for shear reinforcement when used with adequate dosage. Also, the inclusion of fibers can modify the brittle shear mechanism into a ductile flexural mechanism.

Dinh (2009) [6] carried out an experimental program on a total of 28 simply-supported beams. The studied parameters included fiber type, fiber volume fraction, longitudinal tension reinforcement ratio; ρ, and beam depth. Of the four parameters evaluated, fiber volume fraction had the strongest influence on the shear strength of SFRC beams. Dinh concluded that any of the three types of hooked steel fibers used in this investigation, when used in a volume fraction greater than or equal to 0.75%, can be used in place of the minimum stirrup reinforcement required by ACI Committee 318 [7]. In addition, Dinh [6] used the experimental results to suggest a simple model which resulted in an expression to estimate the shear strength of SFRC beams without stirrups. This expression is limited to the end-hooked steel fiber with fiber volume fraction more than 0.5%, $\rho \leq 2\%$, and concrete compressive strength ranging from 20 to 55 N/mm^2.

Tahenni et al. (2016) [8] tested twenty-four steel fiber reinforced concrete beams under two concentrated loads to

DOI: 10.21608/ERJENG.2023.187401.1145

study the replacement of transverse reinforcement with steel fibers. They concluded that the addition of steel fibers improved the ductility and shear strength of the tested beams. The increase in shear strength varied from 47% for a volume of fibers (V_f) of 0.5% to 88% for V_f = 3%. As a result, transverse reinforcement could be replaced by sufficient steel fibers.

Yoo and Yang (2018) [9] studied the effectiveness of steel fibers and the minimum amount of stirrups on the shear behavior of concrete beams. A total of six RC beams were tested. It was concluded that the shear strength of RC beams containing steel fibers without stirrups was more influenced by the size effect than those with stirrups, and a clear decrease of the shear strength of reinforced SFRC beams was observed with an increase in the effective depth.

Bui et al. (2020) [10] conducted an experimental program on four beams. They concluded that fibers with volume fraction of 1.27% (100 kg/m3) were capable to replace the traditional transverse reinforcement (stirrups). Nayak (2021) [11] tested eighteen RC beams by varying fiber volume fractions, and two shear span to depth ratios. The results showed that the maximum deflection and the failure load increased with an increase in fiber content for both cases. Also, the beam carried a significant load after first cracking. Hyun-Do et al. (2022) [12] tested six steel fiber concrete beams with the same fiber volume fraction and having the same properties except the fiber tensile strength. The main conclusion of this study was that the tensile strength of steel fiber does not have a significant effect on the shear strength of SFRC beams, but it has an effect on the ductility.

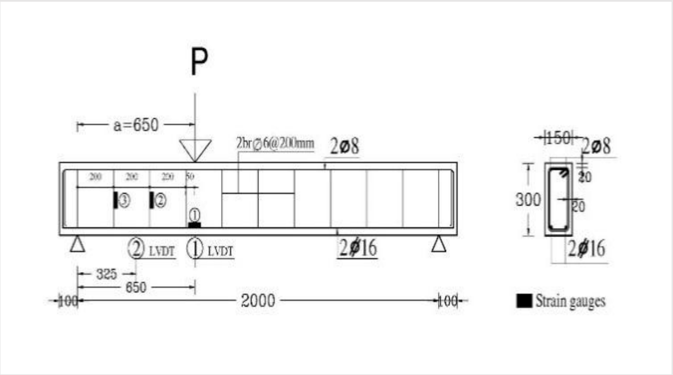
Many researchers tried to develop an empirical equation to estimate the shear strength of SFRC beams. Kara (2013) [13] used gene expression programming (GEP) to predict the ultimate shear strength of SFRC beams without stirrups. A database of 101 tests was used to build the GEP model. The results of the proposed model were compared to different formulas and calibrated against other experimental data. It gives relatively more accurate predictions.

II. RESEARCH SIGNIFICANCE

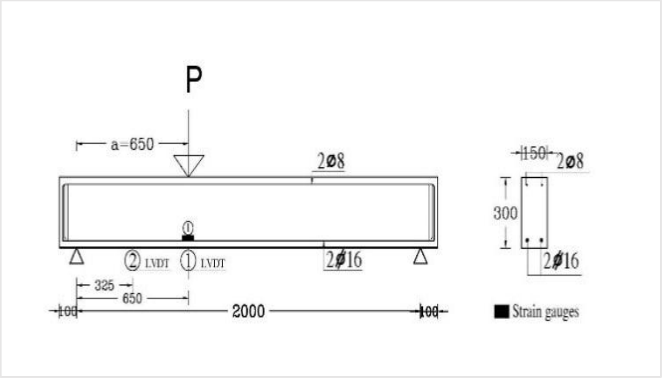
The study reported in this paper aims to extend the application of the use of steel fibers as a substitute of conventional shear reinforcement in reinforced concrete beams. Since most building codes do not take into consideration the contribution of steel fibers to the shear strength of concrete beams, the experimental work carried out in the present study was necessary to evaluate the role of steel fibers in the improvement of concrete tensile properties, post-cracking behavior, and the shear strength.

III. EXPERIMENTAL PROGRAM

Twelve simply supported reinforced concrete beams of rectangular cross-section 150 x 300 mm and span of 2.0 m were tested up to failure under a single concentrated load with a shear span to depth ratio (a/d) for all beams 2.4. The dimensions of the tested beams and details of reinforcement are shown in Fig. 1. Also, all details of the tested beams are given in Table 1. The test program was divided into two groups as follows:



A. Beam reinforcement details for B0, B2, B4, B6, B8, and B10



B. Beam reinforcement details for B1, B3, B5, B7, B9, and B11

Figure 1. Details of the tested beams

Group 1 consisted of six beams: B1, B3, B5, B7, B9, and B11. All beams in this group were without stirrups. The reference beam B1 was tested without fibers. End-hooked steel fibers were added with fiber volume content = 0.5, 1.0, and 1.5% for beams B3, B5, and B7, respectively, while corrugated steel fibers with fiber volume content 0.5 and 1.0% were used for beams B9, and B11, respectively. The aim of this group was to study the efficiency of using steel fibers for resisting shear stresses in beams without stirrups.

Group 2 contained the reference beam; B0 together with five beams: B2, B4, B6, B8, and B10. All beams in this group had a minimum amount of vertical stirrups (6 mm diameter and spaced at 200 mm), as recommended by the Egyptian Code 2017 [14]. End-hooked steel fibers of V_f = 0.5, 1.0, and 1.5% were added to beams B2, B4, and B6, respectively. Also, corrugated steel fibers of V_f = 0.5 and 1.0% were used for beams B8, and B10, respectively. This group aimed to study the effect of steel fiber content on the shear behavior and strength of the beams with the presence of the minimum amount of shear reinforcement.

One concrete mix was used for all the tested beams. The mix consisted of Ordinary Portland Cement (Type 1), sand, crushed stone with a maximum size of 10 mm, and water. The mix proportions by weight were 1:1.6:2.6 with a water/cement ratio of 0.48. Two types of fibers were used in this study: end-hooked

Journal of Engineering Research (ERJ)
Vol.7 – No. 1, 2023
©Tanta University, Faculty of Engineering
ISSN: 2356-9441
https://erjeng.journals.ekb.eg/
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steel fibers and corrugated segment steel fibers. Table 2 gives the properties of fibers while Fig. 2 shows the fiber shapes used in this study. Wooden molds were used for casting the tested beams and the mixing process lasted for about 12 mins. Three concrete cubes of 150 mm side length and two standard cylinders (150 x 300 mm) were casted with each beam, cured, and tested after 28 days to obtain the cube compressive strength; f_{cu} and splitting tensile strength of concrete; f_{sp}., and these values are given in Table 1.

Table 1. Details of the tested beams

Beam	f_{cu}, N/mm^2	f_{sp}, N/mm^2	Fibers		Vertical stirrups
			Type	Volume content; V_f, %	
Group 1					
B1	43.0	3.2	----	----	-----
B3	40.0	3.9	E-H	0.5	-----
B5	45.0	4.8	E-H	1.0	-----
B7	44.0	5.5	E-H	1.5	-----
B9	42.0	4.0	C-G	0.5	-----
B11	41.0	4.9	C-G	1.0	-----
Group 2					
B0	42.0	3.1	----	----	ϕ 6 @ 200 mm
B2	41.0	3.9	E-H	0.5	ϕ 6 @ 200 mm
B4	44.0	4.8	E-H	1.0	ϕ 6 @ 200 mm
B6	42.0	5.4	E-H	1.5	ϕ 6 @ 200 mm
B8	40.0	3.9	C-G	0.5	ϕ 6 @ 200 mm
B10	42.0	4.9	C-G	1.0	ϕ 6 @ 200 mm

Note: f_{cu}, concrete cube compressive strength; f_{sp}, concrete tensile splitting strength; E-H, End-hooked steel fibers; CG, Corrugated steel fiber.

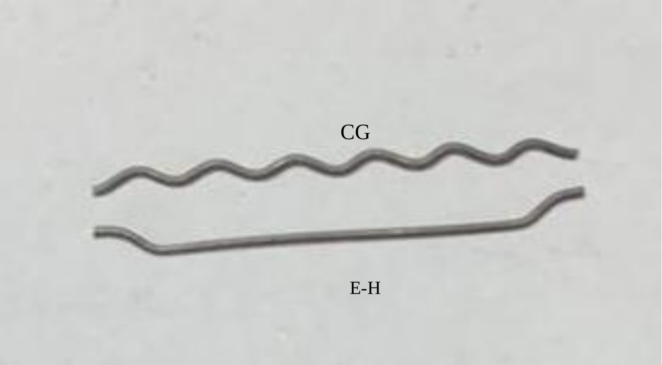

Figure 2. The two types of steel fiber

Table 2. Fiber Properties (Source: from supplier)

Fiber type	End-Hooked steel fiber	Corrugated steel fiber
Cross section	Rounded	Rounded
Length; L_f, mm	50.0	50.0
Diameter; d_f, mm	1.0	1.0
Aspect ratio; L_f / d_f	50	50
Modulus of elasticity; E_f, N/mm^2	200000	200000
Density, N/mm^2	7800	7800
Minimum tensile strength, N/mm^2	1000	1000

The load was applied in increments of about 5 kN using a calibrated load cell and hydraulic jack. Two linear variable displacement transducers (LVDTs) with an accuracy of 0.01 mm were used to record the deflection of the beam. Also, electric strain gauges with 10 mm gauge length were fixed to both the longitudinal bottom bars and on two of the transverse vertical stirrups. The location of LVDTs and strain gauges for all the tested beams are shown in Fig. 1.

IV. TEST RESULTS AND DISCUSSIONS

Table 3 provides the main results for the tested beams

A. Crack pattern and mode of failure

Fig. 3 shows the crack pattern for all the tested beams. Generally, similar behavior, regarding flexural and diagonal cracking, was recorded for all beams. Flexural cracking occurred at about 25% - 35% of P_u for beams in Group 1 and 18% - 34% of P_u for beams in Group 2.

The addition of steel fibers increased the tensile strength of concrete (as given in Table 1), and hence the increase in the values of flexural cracking load. Also, the addition of fibers greatly increased the values of the diagonal cracking loads by 60 – 80 % for the beams with 1.5% end-hooked steel fibers over those without fibers. The two types of steel fiber used in this experimental program almost had the same effect on the values of the tensile strength of concrete, and hence a little effect on both flexural and diagonal cracking loads.

The highest values were recorded for the reference beams without fibers (beams B0 and B1). Diagonal cracks which caused shear failure occurred at 62% - 88% of P_u for beams in Group 1 and 47% - 63% of P_u for beams in Group 2. It is clear that the absence of vertical stirrups (Group 1) reduced the beam resistance after diagonal cracking.

B. Effect of adding fibers to the beams on ultimate loads

Group 1: All beams failed in shear. The shear failure was either shear compression failure (beams B1, B3, and B11) or diagonal tension failure (beams B5, B7, and B9). The results indicate that all beams with the addition of steel fibers to the concrete mix achieved an ultimate load of 28% to 125% higher than that of the reference beam B1 without fibers, as shown in Fig.4. The two types of steel fiber used in this experimental program almost had the same effect on the shear strength of the beams. The shear strength of beams with corrugated steel fiber was 12% higher than that for beams with end-hooked steel fiber for V_f = 0.5 %, while it Was less by 7% for V_f =1%.

The ultimate load recorded for beam B0 with 6 mm stirrups and without fibers was achieved by adding only 0.5% steel fibers to beams B3 and B9 with end-hooked and corrugated steel fibers. The results also indicated that the shear strength of all beams with fibers was higher by 46%, 110%, 158%, 64%, and 95% for beams with V_f = 0.5%, 1%, 1.5%, 0.5% (corrugated), and 1% (corrugated) respectively, than that of the calculated shear strength according to the Egyptian code 2020 [15] for the reference beam B1 (calculated shear strength = 63 kN).

DOI: 10.21608/ERJENG.2023.187401.1145

Group 2: All beams, except B6 and B10, failed in shear. The results indicated that all beams with the addition of steel fibers resulted in an increase of the shear strength by 71%, 95%, and 55% for beams B2, B4, and B8, respectively, over that for the reference beam B0 without fibers, as shown Fig.5. In addition, beam B6 and B10, with 1.5% fibers, failed in flexure after the formation of the diagonal cracks. The high fiber volume fraction enhanced the shear strength of the beam and changed the brittle shear failure into ductile flexural failure. The failure load of beam B4 (with end-hooked steel fiber and V_f = 1.0%) was very close to the flexure failure. The behavior of this beam was ductile, and its shear strength was about twice that of the reference beam without fibers.

In terms of ultimate load, the efficiency of adding corrugated steel fibers to beams B8, and B10, was slightly less than that when using end-hooked fibers.

For all beams, the addition of fibers resulted in an increase of shear strength by 100%, 130%, and 80% for beams B2, B4, and B8, respectively, over the calculated shear strength according to the Egyptian code 2020 [15] for the reference beam (B0) without fibers (calculated shear strength = 74 kN).

C. *Effect of adding steel fibers on deflection and ductility of the tested beams*

Generally, the ductility of steel fiber reinforced concrete beams improved with an increase in the fiber volume fraction. The beams in Group 2 exhibited a better ductility at the same fiber volume fraction than the beams in Group 1. However, it is possible to obtain comparable performances in terms of ultimate strength by using steel fibers as shear reinforcement in an adequate dosage instead of stirrups, although a coupled use is more suitable because stirrups allow a greater deformation capacity beyond the elastic limit. Table 3 gives the ductility ratios for beams as the ratio between the deflection at the ultimate load (Δ_u) and the yielding load (Δ_y) obtained from the experimental program. The beam ductility increases, when this ratio increases in relation to 1.

Group 1: The reference beam B1 failed suddenly after the formation of the diagonal crack without going further sufficient deflection. The addition of steel fibers with volume fraction 0.5%, and 1% to the beams without stirrups had a little effect on both the load-deflection behavior and ductility values. However, for beam B7 with V_f = 1.5%, the ductility of the beam was slightly improved with ductility ratio 1.7 and the value of deflection at P_u was 3 times compared to the reference beam B1. Fig. 6 shows the load-deflection relationship under the load for group.

Group 2: The addition of steel fiber to beams in Group 2 significantly improved the beam ductility. For beam B4, the load-deflection behavior showed significant ductility with a ductility ratio equal to 5.5. In addition, for B6, and B10, the ductility ratio was very high equal to 9 and the values of deflection at P_u were about 12 times that for the reference beam B0 due to the ductile flexure failure. This behavior reflects a typical ductile behavior, and such ductile structural behavior is particularly needed in seismically active regions to avoid any eventual brittle and catastrophic failure. Fig. 7 shows the load-deflection relationship under the load for group 2.

D. *Effect of adding steel fibers on steel strains of the tested beams longitudinal tension steel*

Generally, it can be seen that the addition of steel fiber with different volume fraction did not have a significant effect on the yield load. In addition, the type of fiber did not affect the yield load. The yield load for all beams was fluctuating around 120 kN and is given in Table 3 for all beams. The load-steel strain relationship for beams in Groups 1 and 2 are shown in Figs. 8 and 9, respectively.

Stirrups

Generally, the strain in stirrups was small before the initial diagonal cracking because the tension was mainly resisted by concrete in this stage. When the diagonal crack occurred, the strain of the stirrup located close to the formation of the diagonal shear crack increased suddenly.

The results indicated that the load at first yield of stirrups for the end hooked steel fiber beams B2, B4, and B6 was increased by 34%, 51%, and 59%, respectively, than that for the reference beam B0.

DOI: 10.21608/ERJENG.2023.187401.1145

Journal of Engineering Research (ERJ)
Vol.7 – No. 1, 2023
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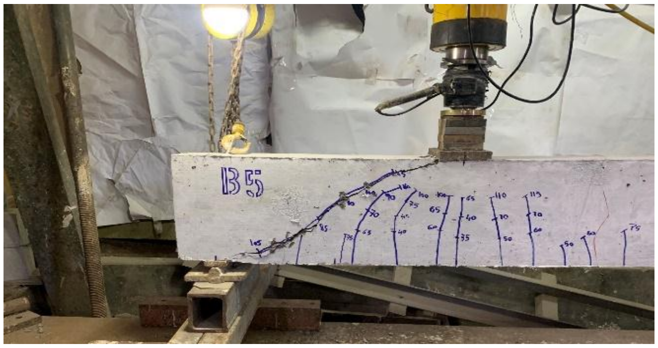
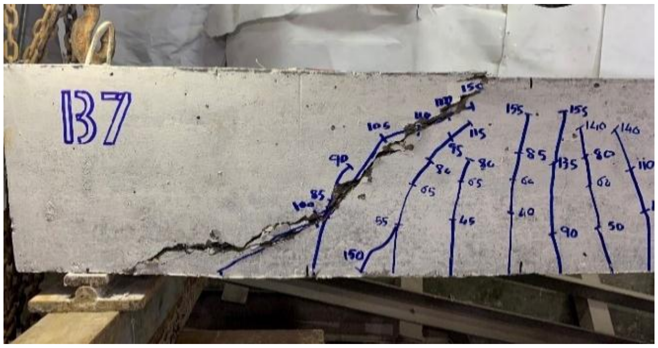
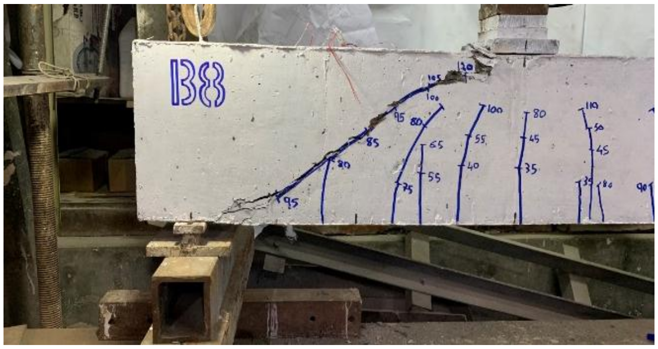
ISSN: 2356-9441 https://erjeng.journals.ekb.eg/ e ISSN: 2735-4873







DOI: 10.21608/ERJENG.2023.187401.1145

Journal of Engineering Research (ERJ)
Vol.7 – No. 1, 2023
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Figure 3. Crack patterns of beams at failure

Table 3. Test results

Beam	P_{cr}, kN	P_{crd}, kN	P_y, kN	P_{ys}, kN	P_u, kN	Δ_y; mm	Δ_u; mm	Ductility ratio Δ_u / Δ_y	Mode of failure
B1	25.0	63.0	NY	---	72.0	NY	4.1	----	Shear compression
B3	25.0	80.0	NY	---	92.1	NY	5.2	----	Shear compression
B5	35.0	85.0	113.4	---	132.1	5.3	7.3	1.4	Diagonal tension
B7	40.0	100.0	139.0	---	162.4	7.0	12.1	1.7	Diagonal tension
B9	30.0	80.0	103.5	---	103.5	6.5	6.6	1.0	Diagonal tension
B11	35.0	75.0	122.6	---	122.6	8.1	9.1	1.1	Shear compression
B0	30.0	55.0	NY	87.0	87.0	NY	5.6	----	Shear compression
B2	35.0	70.0	121.9	116.4	149.1	4.6	18.6	4.0	Shear compression
B4	30.0	100.0	129.0	131.3	169.4	6.6	36.5	5.5	Diagonal tension
B6	40.0	100.0	121.6	138.3	170.4	6.6	60.0	9.1	Flexural failure
B8	35.0	85.0	120.0	87.5	135.2	6.7	8.6	1.3	Shear compression
B10	35.0	90.0	133.0	125.8	159.8	7.2	65.0	9.0	Flexural failure

P_u; Ultimate (failure) load, P_{cr}; load at which first flexural crack was observed, P_{crd}; load at which first diagonal crack occurred, P_y; load at first yield of longitudinal tension steel, P_{ys}; load at first yield of stirrups, NY; steel not yielded, Δ_y; deflection at first yield of tension steel reinforcement, Δ_u; deflection at ultimate load, (Δ_u / Δ_y); ductility ratio.

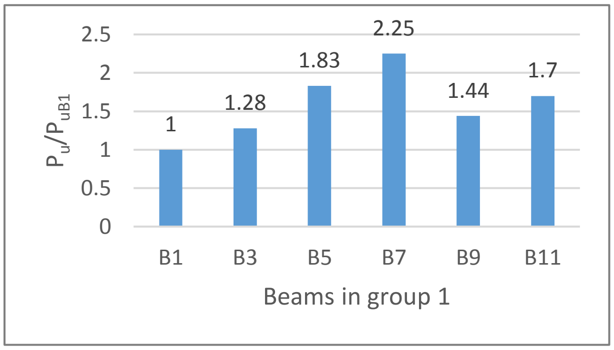

Figure 4. Ratio of Pu/PuB1 for beams in Group 1

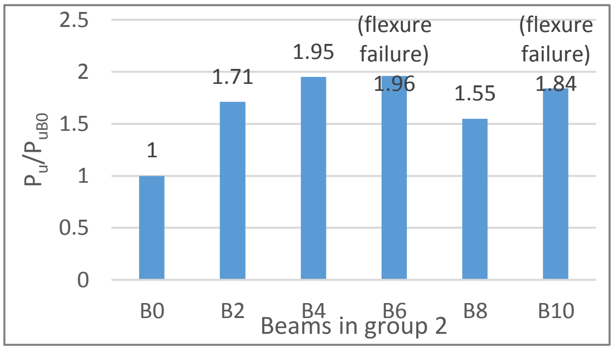

Figure 5. Ratio of Pu/PuB0 for beams in Group 2

DOI: 10.21608/ERJENG.2023.187401.1145

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Vol.7 – No. 1, 2023
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ISSN: 2356-9441 https://erjeng.journals.ekb.eg/ e ISSN: 2735-4873

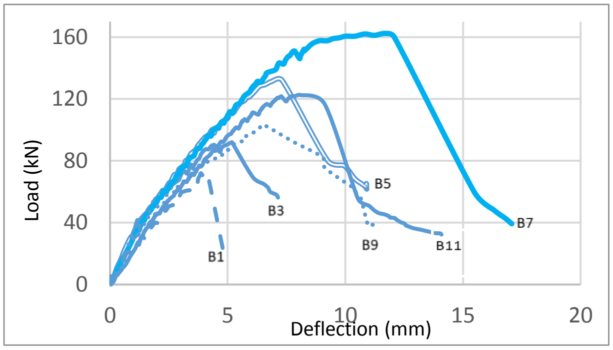

Figure 6. Load-deflection relationship for beams in Group 1 under load

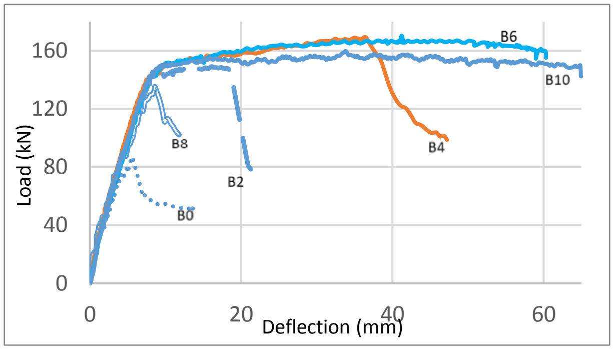

Figure 7. Load-deflection relationship for beams in Group 2 under load

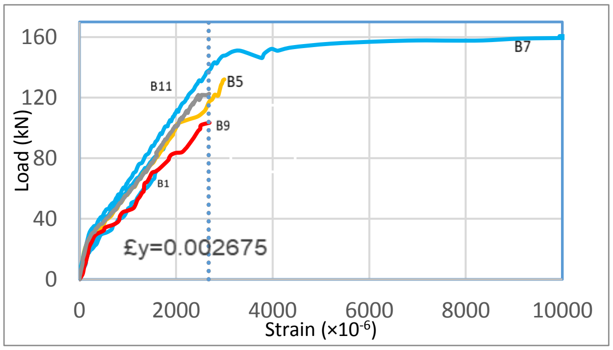

Figure 8. Load-Longitudinal tension steel strain relationship for Group 1

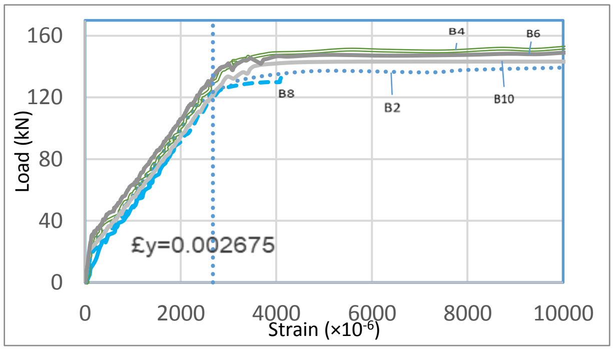

Figure 9. Load-Longitudinal tension steel strain relationship for Group 2

V. COMPARISON OF EXPERIMENTAL RESULTS WITH SUGGESTED FORMULAS FOR SHEAR STRENGTH OF FRC BEAMS

In this section, the shear strength calculated according to FIB code [16] and suggested by other researchers is compared to the experimental ultimate loads of the beams tested in this paper.

Most of the formulas found in the literature for the shear strength of FRC beams were based on test data of beams without shear reinforcement, therefore, the comparison presented in this paper is limited to beams in Group 1.

Table 5 gives the experimental ultimate shear stress, v_{uexp}, for all beams in Group 1 together with the shear strength, v_{uth}, as recommended and suggested by:

- FIB model code for concrete structures 2010 [16]
- Six equations proposed by Narayanan and Darwish (1987) [2], Shin et al. (1994) [3], Kwak et al. (2002) [4], Al-Ta'an and Al-Feel (1990) [17], Khuntia et al. (1999) [18], and Kara (2013) [13].

In Table 4, a summary of all equations used in the comparison is given.

The FIB 2010 [16] underestimates the contribution of fibers to the shear strength of beams without shear reinforcement compared to the contribution of fibers obtained experimentally, especially at higher content of fibers ($V_f \geq 1\%$); the average value of v_{uth} / v_{uexp} is 0.81. The calculated values of shear strength for beams with $V_f = 0.5\%$ and 1.0% are less by 5% and 27%, respectively, than that without fibers. As given in Table 5, the increase of V_f from 1% to 1.5% does not affect the calculated shear strength.

Generally, the formula proposed by Narayanan and Darwish (1987) [2] obtained good results for all beams. The average value of v_{uth} / v_{uexp} for beams with end-hooked steel fibers and corrugated steel fibers were 1.04, and 0.96, respectively. This formula slightly overestimated the shear strength of beams with end-hooked steel fibers and slightly underestimated that for beams with corrugated steel fibers. This difference may be due to the use of different values for the bond factor.

The formulas proposed by Shin et al. (1994) [3] and Kwak et al. (2002) [4] overestimated the shear strength of SFRC beams. The average values of v_{uth} / v_{uexp} for all beams were 1.15 and 1.27, respectively. These two formulas overestimated the contribution of concrete in shear strength, and this appeared clearly in the values of v_{uth} / v_{uexp} for the beam B1 without fibers which were 1.28, and 1.48.

Al-Ta'an and Al-Feel (1990) [17] proposed a formula that resulted in an overestimation of the shear strength with an average value of v_{uth} / v_{uexp} of 1.11. This overestimation may be due to the high values of the bond factor (D_f) which greatly increases the fiber factor (F).

DOI: 10.21608/ERJENG.2023.187401.1145

Journal of Engineering Research (ERJ)
Vol.7 – No. 1, 2023
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ISSN: 2356-9441 https://erjeng.journals.ekb.eg/ e ISSN: 2735-4873

Table 4. Model Code FIB and formulas proposed by some researchers

Code or researcher	Formula
Model Code FIB 2010 [16]	$v_u = \left[0.18\, k\, \langle 100\, \rho \left((1 + 7.5\, \frac{f_{ft}}{f_{ct}})\, f_c'\right)^{1/3} \rangle\right]$ where, $k = 1 + \sqrt{\frac{200}{d}} \leq 2$, $f_{ft} = f_{fts} - \frac{1.5}{2.5}\left(f_{fts} - 0.5\, f_{R3} + 0.2\, f_{R1}\right)$ $f_{fts} = 0.45\, f_{R1}$, $f_{R1} = 7.5\, (v_f\, \frac{L_f}{d_f})^{0.8}$, $f_{R3} = 6\, (v_f\, \frac{L_f}{d_f})^{0.7}$
Narayanan and Darwish (1987) [2]	$v_u = e\,(0.24\, f_{sp} + 80\, p\, \frac{d}{a}) + v_b$ where, $e = 2.8\, (d/a)$ and $D_f = 1.00$ *for end-hooked fibers and 0.75 for corrugated fibers,* $f_{sp} = \frac{f_{cu}}{20 - \sqrt{F}} + 0.7 + \sqrt{F}$, $F = \frac{L_f}{d_f}\, V_f\, D_f$, $v_b = 0.4\, \tau\, F$, *and* τ *is the bond stress* = 4.15 *MPa*
Shin et al. (1994) [3]	$v_u = 0.22\, f_{sp} + 217\, p\, \frac{d}{a} + 0.834\, v_b$ where $f_{sp} = \frac{f_{cu}}{20 - \sqrt{F}} + 0.7 + \sqrt{F}$, *and* $v_b = 0.41\, \tau\, F$
Kwak et al. (2002) [4]	$v_u = 3.7e(f_{sp})^{2/3}(p\frac{d}{a})^{1/3} + 0.8\, v_b$ where, $e = 3.4\, (d/a)$, $f_{sp} = \frac{f_{cu}}{20 - \sqrt{F}} + 0.7 + \sqrt{F}$, $v_b = 0.41\tau\, F$, *and* τ *is the bond stress* = 4.15 *MPa*
Al-Ta'an and Al-Feel (1990) [17]	$v_u = v_c + v_b$ where, $v_c = (160\, p\, f'_c)^{1/3}\, (\frac{d}{a})^{4/3}$, $v_b = 0.5\, \tau\, F$, *and* $D_f = 1.20$ *for end-hooked fibers and 1.30 for corrugated fibers*
Khuntia et al. (1999) [18]	$v_u = (0.167 \propto + 0.25F)\sqrt{f'_c}$ where, $\propto = 2.5\, (d/a)$ *and* $D_f = 1.00$ *for end-hooked and corrugated fibers*
Kara (2013) [13]	$v_u = \left(\frac{pd}{C_0 C_1 \left(\frac{a}{d}\right)}\right)^3 + \frac{F d^{1/4}}{C_2} + \sqrt{\frac{C_3 f'_c}{d}}$ where, C_0, C_1, C_2, *and* C_3 *equals 3.324, 0.909, 2.289, and 9.436 respectively, and* $D_f = 1.00$ *for end-hooked and corrugated fibers*

All values of shear stresses are in N/mm^2.

Table 5. Comparison between experimental results for beams in Group 1 and the formulas suggested by some researchers

Beam	v_{uexp} N/mm^2 (1)	v_{uth}; N/mm^2							v_{uth} / v_{uexp}						
		Model Code 2010	Narayanan and Darwish (1987)	Shin et al. (1994))	Kwak et al. (2002)	Al-Ta'an and Al-Feel (1990)	Khuntia et al. (1999)	Kara (2013)							
		(2)	(3)	(4)	(5)	(6)	(7)	(8)	(2)/(1)	(3)/(1)	(4)/(1)	(5)/(1)	(6)/(1)	(7)/(1)	(8)/(1)
B1	1.20	1.09	1.18	1.53	1.69	1.18	1.02	1.15	0.91	0.98	1.28	1.41	0.98	0.85	0.96
B3	1.53	1.46	1.72	1.97	2.18	1.77	1.34	1.55	0.95	1.12	1.29	1.42	1.16	0.88	1.01
B5	2.20	1.61	2.28	2.43	2.70	2.44	1.77	2.05	0.73	1.04	1.10	1.23	1.09	0.80	0.93
B7	2.70	1.69	2.76	2.82	3.10	3.07	2.17	2.50	0.63	1.02	1.04	1.15	1.14	0.80	0.93
B9	1.72	1.46	1.62	1.89	2.11	1.84	1.34	1.55	0.85	0.94	1.10	1.23	1.07	0.78	0.90
B11	2.04	1.61	1.98	2.19	2.42	2.51	1.77	2.05	0.79	0.97	1.07	1.19	1.23	0.87	1.00
Mean									0.81	1.01	1.15	1.27	1.11	0.83	0.96
Standard deviation									0.11	0.06	0.10	0.11	0.08	0.04	0.04
Coefficient of variation									13.5 %	5.9 %	8.7 %	8.7 %	7.2 %	4.8 %	4.2 %

v_{exp} (N/mm^2) = $\frac{V}{bd} = \frac{0.675 P_u}{bd}$, where b = 150 mm, and d = 270 mm

DOI: 10.21608/ERJENG.2023.187401.1145

The formula proposed by Khuntia et al. (1999) [18] greatly underestimated the contribution of steel fiber to the shear strength of reinforced concrete beams. The average value of v_{uth} / v_{uexp} for all beams was 0.83. This may be due to the low estimation of concrete contribution to the shear strength. Khuntia et al. (1999) [18] reported that when considering a shear strength reduction factor of 0.85, the predicted strength was found always to be conservative.

Kara (2013) [13] developed an equation for the shear strength of FRC beams using Gene Expression Programming (GEP is an algorithm that creates computer programs or models to solve problems). Very good results were obtained by using this equation for all tested beams in Group 1. The average value of v_{uth} / v_{uexp} was 0.96. One can conclude that this equation may predict the shear strength of FRC beams with very good accuracy.

VI. CONCLUSIONS

An experimental investigation on reinforced concrete beams provided with steel fibers was carried out. From the test results, the following conclusions can be drawn.

- The shear strength of FRC beams can be significantly increased by adding steel fibers. In addition, with large content of fibers, the brittle shear failure is changed into a ductile flexure failure. However, the type of steel fibers, either end-hooked or corrugated, almost had the same effect on the shear strength.
- For the beams without the conventional stirrups, the addition of fibers with volume content 0.5%, 1.0%, and 1.5% increased the value of diagonal shear cracking load by 27%, 35%, and 59%, respectively, over that of the beam without fibers. This increase in the value of shear cracking load is due to the increase in the tensile strength of concrete provided with steel fibers by similar ratios.
- The addition of end-hooked steel fibers to the beams without stirrups by content 0.5%, 1.0%, and 1.5% increased the ultimate shear strength of beams by 28%, 83%, and 126%, respectively over that for the beam without fibers. The value of the shear stress at the failure of the beam with 1.5% fiber content corresponds to using stirrups of 8 mm diameter with 150 mm spacing. Thus, adding steel fibers to the concrete mix may sufficiently substitute the use of conventional web reinforcement for post-shear cracking behavior.
- The shear strength for the beams with conventional stirrup and provided with end-hooked steel fibers of content 0.5% and 1.0% increased by 71% and 94%, respectively, over that for the beam without fibers. When fiber content was increased to 1.5%, a ductile flexure failure occurred. A ductile behavior was observed for beams with fiber content ≥ 1.0%.
- Narayanan and Darwish (1987) [2] and Kara (2013) [13] formulas predicted the shear strength of the tested beams without stirrups well. However, the fib Model Code 2010 [16] underestimates the contribution of fibers to the shear strength of the beams.
- This study may be useful for structural engineers for the calculation of the shear strength of reinforced concrete beams by replacing the large diameter stirrups spaced in small distances with steel fibers.

Suggestions for future research

- Different types of fibers, such as basalt, glass, and polypropylene fibers are needed to be studied.
- Develop an analytical model to fiber reinforced concrete (FRC) in compression and tension to be used in numerical modeling.

Funding: This research has not been conducted under any fund.

Conflicts of Interest: The authors declare that there is no conflict of interest.

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NOTATIONS

a = shear span, mm

a/d = shear span/effective depth ratio

b = width of the beam, mm

D_f = bond factor

d = effective depth, mm

d_f = diameter of fiber, mm

f_{cu} = cube compressive strength of concrete, MPa

f_c' = cylinder compressive strength of concrete, MPa

f_{ct} = tensile strength of concrete, MPa

f_{sp} = split cylinder strength of FRC, MPa

L_f = length of the fiber, mm

L_f / d_f = fiber aspect ratio

F = fiber factor equal to $(D_f \times \frac{V_f L_f}{d_f})$

P_{cr} = load at which first flexural crack was observed

P_{crd} = load at which first diagonal crack appeared

P_y = load at first yield of longitudinal tension steel

P_{ys} = load at first yield of stirrups

P_u = ultimate (failure) load

V_f = volume fraction of fiber, percent

v_u = shear stress corresponding to the shear strength of the beam

v_c = shear stress corresponding to diagonal cracking strength

v_b = vertical fiber pullout stresses along the diagonal crack

Δ_y = deflection at first yield of tension steel reinforcement

Δ_u = deflection at ultimate load

ρ = ratio of longitudinal tension reinforcement

τ = average fiber-matrix interfacial bond stress

DOI: 10.21608/ERJENG.2023.187401.1145