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SOME PARAMETERS AFFECTING SHEAR BEHAVIOR OF HIGH STRENGTH FIBER REINFORCED CONCRETE BEAMS LONGITUDINALLY REINFORCED WITH BFRP REBARS

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ABSTRACT

This research studies the shear behavior of high strength fiber reinforced concrete beams longitudinally reinforced with Basalt Fiber Reinforced Plastic (BFRP) bars with and without stirrups. Eight high – strength reinforced concrete beams were tested. Steel fibers and stirrups were used either separately or together as shear reinforcement. The test variables were steel fiber content **(V_f)%** with and without minimum shear reinforcement.

All beams were tested under a four point static loading up to failure to investigate the shear behavior of high strength fiber reinforced beams reinforced with BFRP rebars. The shear span-to-depth ratio (a/d) was kept constant at 2.5. Crack pattern and mode of failure, cracking and ultimate shear strength and mid-span deflection are presented to provide useful insights on the shear failure mechanism of such beams. The experimental study shows that addition of steel fiber improves cracking, ultimate shear strength and ductility of the tested beams, and transfers the mode of failure of these beams into a more ductile one.

The test results were compared with different proposed equations and design guidelines. Imam M. A, gave a reasonable equation to predict the shear strength of fiber concrete beams reinforced with BFRP bars with or without stirrups. Also the proposed equation predicted relatively well the ultimate shear strength of the experimental results than other predictions.

***Keywords**:* Steel Fiber Reinforced Concrete (SFRC) beams, Shear strength, BFRP bars, Deflection and Ductility of beams.

1. Introduction

Recently, Fiber-Reinforced Polymer (FRP) bars have been applied to mitigate the problem of corrosion in reinforced concrete structures. Basalt Fiber Reinforced Polymer (BFRP) bars are the newest types of FRP bars which have some advantages than others as lower cost, good bond to concrete and high resistance to fire. [2], [22]

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Because FRP bars have different properties than steel bars, the shear strength of concrete members longitudinally reinforced with FRP bars may differ from those of steel- reinforced ones. In reinforced concrete members, following the diagonal tension cracking, the concrete member resists the applied shear stresses by means of a number of mechanisms:

(1) uncracked concrete compression zone; (2) aggregate interlock; (3) the dowel action of longitudinal reinforcing bars; (4) the residual tensile stresses, which are transmitted directly across cracks; (5) arching action; and (6) the shear carried by the shear reinforcement. [6].

The contribution of first five components are lumped together and denoted as the concrete contribution to shear resistance (V_c) while, the latter is denoted as the contribution of the shear reinforcement to the shear carrying capacity (V_s).[1],[2],[3]

Due to the relatively low modulus of elasticity of FRP bars, concrete members reinforced longitudinally with FRP bars will develop wider and deeper cracks than those reinforced with steel bars. Deeper cracks decrease the contribution to shear strength from the uncracked concrete due to the lower depth of concrete in compression. Wider cracks, in turn, decrease the contributions from aggregate interlock and residual tensile stresses. Additionally, due to the relatively small transverse strength of FRP bars and relatively wider cracks, the contribution of dowel action may be negligible. Therefore, the shear capacity of concrete beams reinforced with FRP bars is lower than that reinforced with steel bars. [3], [4].

This draw back can be overcome through different methods as inclusion of fibers in high strength concrete (HSC). Fibers are used to boost the shear capacity of concrete or to replace, in part the vertical stirrups in RC structural members. Fiber reinforcement may also significantly reduce construction time and costs, especially in an era of high labor costs and possibly even labor shortage, since conventional stirrups require relatively high labor input to bend and fix in place. [7]

Fibers can be added to concrete which enhances the material properties such as compressive strength, modulus of elasticity, splitting tensile strength etc. Shear failure of a reinforced concrete beam occurs when the principal tensile stress within the shear span exceeds the concrete strength and a diagonal crack propagates through the beam web. This failure occurs usually without any warning due to the brittle nature of plain concrete. The randomly oriented discontinuous fibers bridge the crack which is developed in the concrete due to the applied load and provides some post cracking tensile strength. [5], [7].

The residual tensile stress depends on many factors such as shape, aspect ratio, volume fraction, and the surface characteristics of fibers [8], [9].

HSC is considered as a relatively brittle material and the post-peak portion of its stress-strain diagram almost vanishes and descends steeply with the increase in compressive strength. This inverse relation between strength and ductility is a serious drawback in the use of high strength concrete. A compromise between strength and ductility can be obtained by using discontinuous fibers. Addition of fibers to concrete makes it a homogeneous and isotropic materials and converts brittleness into a ductile behavior. When concrete cracks, the randomly oriented fibers start functioning, arresting both the randomly oriented micro-cracking and its propagation and thus improving strength and ductility [10].

Research on shear behavior of fiber reinforced concrete reinforced longitudinally by FRP bars has received less attention than that into their flexural behavior. Many reports published over the past 25 years [11-16] have considered the possibility of using fibers in reinforced concrete by assigning the functions of shear reinforcement to the fibers.

Lidia et al and Li, Ward, and Hazma [7], [17] done tests on rectangular simply supported beams containing a hooked end steel fibers with and without stirrups, subjected to two-point symmetrically placed vertical loads. The results showed that the inclusion of fibers in adequate percentage can change the brittle mode of failure characterizing shear collapse into a ductile flexural mechanism and the addition of fibers increases the first crack load and ultimate load. For 1% and 2% volume fibers, the ultimate load increased by 60% and 183% respectively.

Atif M. Abdel Hafez et.al (2004) [18] studied the shear behavior of high strength fiber reinforced concrete beams with and without stirrups by testing eighteen high strength reinforced concrete beams and concluded that, the presence of high percentages of steel fibers or/and stirrups transformed the mode of failure into a more ductile one and increased the number of diagonal cracks formed. Also the addition of steel fibers improves both shear strength and ductility of the tested beams.

Narayanan and Darwish [5] tested fiber-reinforced concrete (FRC) beams with crimped steel fiber at dosage rates of up to 3% by volume and found that the crack patterns developed in beams with FRC were generally similar to those in corresponding concrete beams reinforced with conventional stirrups. Fibers reduced the crack spacing to approximately a fifth of that in companion beams with stirrups, thus indicating a more uniform redistribution of stresses in beams made of FRC. They also concluded that at least 1% fiber by volume is needed to avoid shear failure and to change the mode of failure from shear to flexure. Beyond 1% fiber volume, little improvement in shear strength was noted.

The use of deformed steel fibers in place of minimum stirrup reinforcement is currently allowed in ACI Code Section 11.4.6 (ACI Committee 318, 2008) [1]. The benefits of using steel fiber reinforcement for shear resistance, however, have not been fully exploited yet, primarily due to lack of understanding of the role which steel fibers play on the shear behavior of beams with and without stirrup reinforcement.

In this paper, useful insights on the shear behavior of high strength fiber reinforced concrete reinforced longitudinally with BFRP bars will be discussed.

2. Experimental work

To assess the response of high strength fiber reinforced concrete (HSFC) beams longitudinally reinforced with BFRP bars under shear loading, the following studies were carried out.

- Response of fibrous concrete beams without shear reinforcement, and with volume fractions of fiber as 0.3%, 0.6%, and 1.2% (235.5 N/m3, 471 N/m3, and 942 N/m3) respectively.
- Behavior of steel fibers concrete beams with minimum shear reinforcement, and with volume fractions of fiber as 0.3%, 0.6%, and 1.2% of volume of concrete.

The experimental program consisted of eight beams in two series. The first series involved testing of four fibrous HSC beams, one of them (reference beam) without fibers and stirrups and the residual three beams were with volume fractions of fiber as 0.3%, 0.6%, and 1.2% respectively. The second series involved testing of four fibrous HSC beams with (Φ6@ 146 mm) as shear reinforcement. One of them (reference beam) without fibers, while the residual three beams with a volume fractions of fiber as 0.3%, 0.6%, and 1.2% respectively.

Detailed description of the specimens, the material properties, test set-up, instrumentation, test procedure, and measurements are presented in this section.

2.1. Test specimens

In the experimental program, tests were carried out on eight concrete beams with nominal cross-sectional dimensions of 150 x 200 mm with a total length of 2050 mm. All tested beams have 1600mm clear span and reinforced with the same flexural longitudinal reinforcement of BFRP bars of (3Φ8 mm). The beams were simply supported and subjected to two concentrated static loads (four-point bending). All beams was tested at a shear span-to-depth ratio of (a/d) = 2.5. The details of the tested beams are shown in Table (1) and Figs (1, 2).

2.2. Materials

Concrete mix design was made to produce high strength concrete having 28 day cubic compressive strength 70 MPa. Concrete mix properties are given in Table (2). Local natural sand, well-graded crushed basalt with nominal size of 10 and 20 mm, Ordinary Portland cement, additives as Silica fume and Addicrete BVF were used. Ribbed BFRP rods of 2000 mm length and 8mm diameter were used as a main flexural reinforcement. Hooked end Steel fibers with an aspect ratio (L/d) of 50 were also used. Table (3) shows the properties of the used steel fibers. The compressive strength results from the four cylinders and cubes tested in the study are presented in Table (1). Mild steel bars of 6 mm diameter were used as stirrups while 8 mm diameter was used as compression steel. The mechanical properties of BFRP bars and the mild steel bars are shown in Table (4).

2.3 Preparing test specimens and test procedure

Mixing was performed using a concrete tilting drum mixer. The time of mixing was about five minutes. Clean wood forms were used, and their inner sides were coated with oil before casting. Slowly steel fibers were added into the mixer to ensure that the steel fibers are uniformly distributed in the mixture.

Concrete was placed and compacted mechanically by internal electrical vibrator. After 24 hours, the wood forms were removed and the daily curing was started till the day before testing. All beams were simply supported and tested at 28 days age under four point static loads using the available testing machine (EMS 60-Ton). The mid – span deflection of the tested beam was measured using dial gage having an accuracy of 0.01 mm. The load was applied in increments of 5 kN, and was kept constant between two successive increments for about one minute to allow for reading of the dial gages and marking the crack propagation.

Table 1.
Details of the tested beams.

series	Beam No.	f_{cu} (MPa)	f_c' (MPa)	a/d	*Main Reinf.*	*Shear Reinf.*	*fiber volume V_f %*	*Top Reinf*
1	BF0	71	61.7	2.5	3φ8 *(BFRP) bars*	--	0	2Φ8 mm
	BF1	72.5	65.3				0.3	
	BF2	74	65.7				0.6	
	BF3	75.8	68.29				1.2	
2	BFS0	71	61.7			Φ6/146 mm	0	
	BFS1	72.5	65.3				0.3	
	BFS2	74	65.7				0.6	
	BFS3	75.8	68.29				1.2	

Table 2.
Properties of the concrete mixture.

Cement kN/m^3	Sand kN/m^3	Aggregate (A) <10mm kN/m^3	Aggregate (B) <20mm kN/m^3	Silica Fume kN/m^3	Addicrete (BVF) Liter/m^3	Water Litter/m^3
5	5.5	6	6	0.9	15	145

Table 3.
Properties of hooked end steel fibers.

Length (mm)	50
Diameter (mm)	1
Aspect ratio (L/d)	50
Ultimate Strength (MPa)	1050
Shape	

Table 4.
Mechanical properties of BFRP bars and the Mild steel bars.

Type of reinforcement	*Area (mm^2)*	*E (GPa)*	*f_y (MPa)*	*f_u (MPa)*
8 mm BFRP bar	50.24	55	N.A.	1150
8 mm mild steel bar	50.24	200	312	426
6 mm mild steel bar	28.26	200	294	411

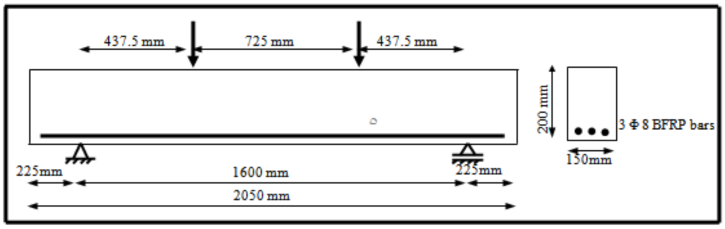

Fig. 1. Details of beams **(**BF0, BF1, BF2 and BF3**)**.

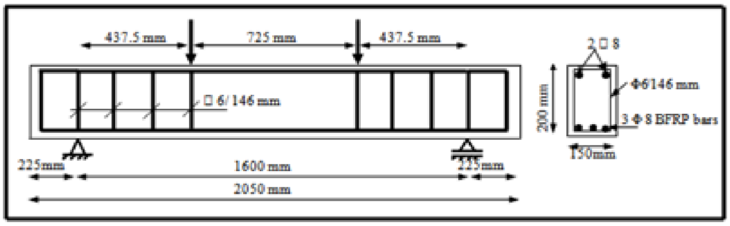

Fig. 2. Details of beams (BFS0, BFS1, BFS2 and BFS3).

3. Experimental results and discussion

3.1. Crack pattern and mode of failure

Only one critical diagonal crack was remarkable in each specimen. For beams with steel fibers only (BF1, BF2 and BF3), the initiation and propagation of cracks was observed visually with a magnifying glass. In these beams, the cracks were first initiated at the bottom fiber of the beam in the constant moment zone. As the load increased, new cracks were created along the beam and the formed cracks propagated towards the point of load application. The rate of cracks propagation was smaller than that of the reference beam BF0 due to the addition dosages of steel fibers in these beams, see photos 1 to 4 respectively.

A major improvement in cracking pattern, small discrete cracks were formed and the rate of extension and propagation of these cracks were very slow than that when a steel stirrups of Φ6@ 146 mm were added (beams BFS1, BFS2 and BFS3), photos 4 to 8 respectively. This means that the combination of steel fibers with stirrups led to better controlling of cracks.

when the steel fiber volume increased from zero to 1.2%, the failure mode changed from a catastrophic brittle shear compression failure to a ductile diagonal tension failure, however when the steel fibers incorporated with steel stirrups, the mode of failure changed from shear-compression failure to a more ductile diagonal – tension with bond failure. The appearance and propagation of horizontal crack from the terminal diagonal-tension shear crack along the longitudinal BFRP reinforcement (bond failure) in the final mode may be due to the low modulus of elasticity of BFRP bars, low percentage of stirrups (local dowel action in BFRP rebars) and due to the surface condition of the bars (not perfect adhesion). Beam (BF3) with 1.2% of fibers only did not exhibit obvious splitting along the BFRP reinforcing bars. This is attributed to the fact that fibers improved the confinement stress around the reinforcing bars and thus reduced splitting. Furthermore, it is visible that the inclination of the shear failure crack (angle of the shear crack plane with the beam longitudinal axis) for beams in these two series increased from 45^0 to be 65^0 approximately. All those are listed in Table 5.

Since the average crack width at failure (based on the visual observation) of the reference beams (BF0 and BFS0) were about 30 mm, this crack width decreased to be closer and thinner in beams (BF3 and BFS3) with crack width less than 3 mm when steel fibers increased to be 1.2%. This decrease in crack width led to an increase in number of cracks and decreased the spacing between cracks especially in beams in series 2. This due to the bridging effects provided by steel fibers with better blocked with the surround concrete provided by steel stirrups which give a closely spaced and thin or small cracks and enable better transmission of shear stress through the aggregate interlock than large, widely spaced and wide cracks given in reference beam (BF0, reinforced with low modules of BFRP bars only).

Also, the combination of steel fibers with steel stirrups allowing the tensile stresses to be transmitted across the cracks. All that results in less brittle shear failures with greater ultimate tensile strength and, more importantly, larger toughness and better energy absorption and ductility, see Table 5. During the testing of beam BFS0, the applied load reached to 75 kN and continued in increasing without any propagations of formed of cracks till failure. But increasing in the major crack width was noticed.

From the crack patterns and the modes of failure, at least (1 to 1.2) % fiber by volume is needed to avoid shear failure and to change the mode of failure from shear to flexure for beams reinforced with BFRP rebars. Also minimum web reinforcement must be added to avoid a catastrophic brittle shear failure. Furthermore, from Photos 2 and 6, the using of 0.3% steel fiber separately in beam BF1is not better in crack pattern than the using of (Φ6@ 146 mm = 0.26% volume) in beam BFS1.

Photos for series (1)

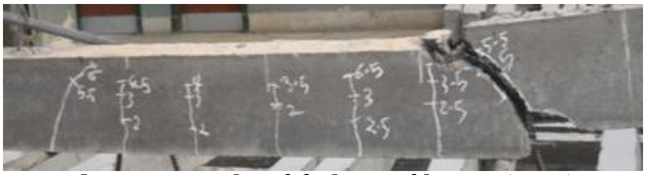

Photo 1. Mode of failure of beam (BF0).

Photo 2. Mode of failure of beam (BF1).

Photo 3. Mode of failure of beam (BF2).

Photo 4. Mode of failure of beam (BF3).

Photos for series (2)

Photo 5. Mode of failure of beam (BFS0).

Photo 6. Mode of failure of beam (BFS1).

Photo 7. Mode of failure of beam (BFS2).

Photo 8. Mode of failure of beam (BFS3).

Table 5.
Results of tested beams

Series	*Beam No.*	*Experimental observations*								*Mode of failure*
		p_{cr} *kN*	p_u *kN*	V_{cr} *kN*	V_u *kN*	*Slope angle* θ^o	Δ_{max} *(mm)*	Δ_{cr} *(mm)*	$\mu_D = \Delta_{max}/\Delta_{cr}$	
1	BF0	20	65	20	32.5	*45°*	25	11.8	2.11	S.C.F
	BF1	25	85	25	42.5	*45°*	29.5	10.7	2.75	D.T.F
	BF2	25	110	22.5	55	*60°*	30.8	9.5	3.24	D.T.F
	BF3	25	130	27.5	65	*60°*	31	9	3.44	D.T.F
2	BFS0	20	95	20	47.5	*45°*	27.7	11.3	2.45	S.C.F
	BFS1	30	105	27.5	52.5	*49°*	27.6	10.1	2.73	S.C.F
	BFS2	30	135	30	67.5	*61°*	31.3	9	3.48	D.T.F
	BFS3	30	150	35	75	*65°*	32.9	8.5	3.87	D.T. with B.F

** S.C.F = Shear Compression Failure, D.T. F = Diagonal tension failure, and B.F = Bond failure.*

3.2. Mid span deflection

The relationship between the shear load and the recorded deflection at mid-span for beams in series 1 is shown in Figure 3. As expected, the shear load-deflection curve for beams BF0, BF1, BF2, and BF3 was linear in the initial phase and the stiffness reduced gradually as the load was applied further. The linear behavior after cracking was noticed until failure although the steel fibers added to concrete. Due to the low modulus of elasticity of BFRP bars compared to steel bars, reference beam BF0 demonstrated wider cracks compared to others and consequently exhibited higher mid-span deflection. The increasing in steel fibers volume V_f % from zero to 1.2% led to decrease the central deflection measured for tested beam. This decrease appeared clearly in beam BF3 (with V_f % = 1.2%). At a certain shear load of 30 kN(equal to 92% shearing load in beam BF0), the value of decreasing was 30% when steel fibers volume V_f % increased to be 1.2%. Also from the Figure and Table 5, although the ratio of steel fibers volume increased from 0.6% to 1.2%, the ultimate mid -span deflection was at the same value of 31 mm approximately.

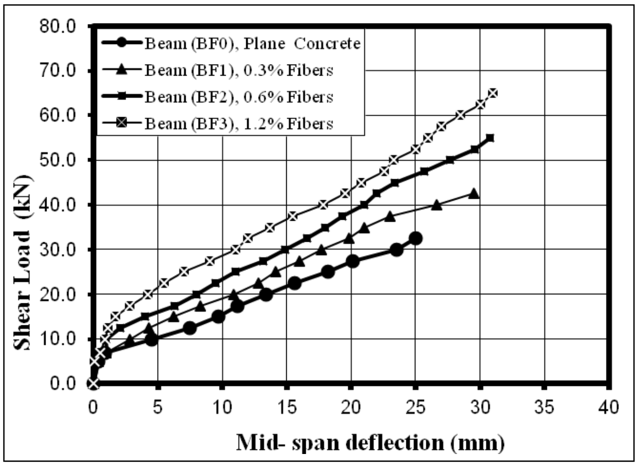

Fig. 3. Load – deflection relationships for beams in series 1.

When steel fibers were incorporated with vertical steel stirrups, the shear load versus mid - span deflections were figured in Fig 4. From the Figure, the shear load deflection in these series exhibited similar characteristics as previous. For all four beams, the shear load deflection relationship was bilinear in the first part up to flexural cracking was appeared (gross moment of inertia of the concrete cross section). The second part, post-cracking up to failure, represents the cracked beam with reduced moment of inertia. In this part, the flexural stiffness of the tested beams was dependent on the axial stiffness of the longitudinal BFRP rebars. For beams BFS1, BFS2, and BFS3, the addition of steel fibers to concrete in presence of steel stirrups (Φ6@ 146 mm = 0.26% volume) in shear zone and not only improve shear capacity enhancement but also the deformation characteristics. This improvement appeared when the ratio of steel fibers volume increased from 0.6% to 1.2%. This due to the enhancement of tension strength of concrete and the axial stiffness of the longitudinal BFRP rebars.

The increasing in steel fibers volume V_f % from zero to 1.2% led to decrease the central deflection measured for all tested beams. This decrease appeared clearly in beam BFS3 (with V_f %= 1.2%). At a certain shear load of 47.5 kN (equal to ultimate shearing load in beam BFS0), the value of decreasing was 34% when steel fibers volume V_f % increased to be 1.2%.

Figure 5 shows the relationship between beams (BF3 and BFS3) in terms of shear load – mid span deflection curves. From the Figure, the hybrid composite of 1.2% of steel fibers with 0.26% of steel stirrups had no effect on mid span deflection curve characteristics up to about 50% of the applied shearing load. But after that up to failure, the behavior of shear deflection characteristics was improved, this indicate that there is an increasing in the ductility of that beam (BFS3) than that in the beam (BF3).

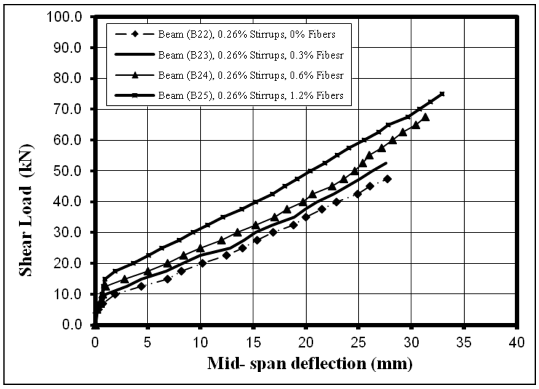

Fig. 4. Load – deflection relationships for beams in series 2, Part II.

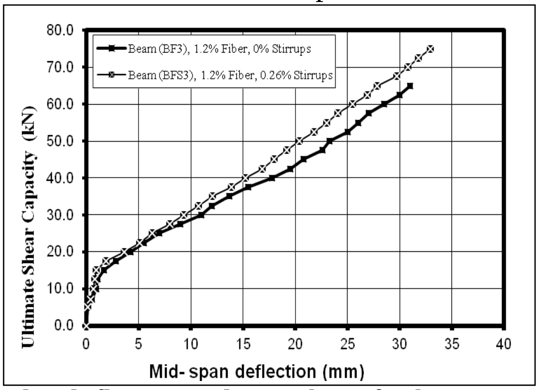

Fig. 5. Load – deflection relationships for beams BF3 and BFS3.

3.3. Cracking and ultimate shear capacity

Flexural cracking was initiated in the constant moment region where the flexural tension stress is highest and shear stress is zero. While the shear cracking load was initiated in the shear span between the applied load and the support when the major diagonal crack appears. The experimental shear cracking load was determined based on the visual observation of cracks during testing. Table 5 gives the flexural and shear cracking load for each tested beams. It can be noticed from the Table that in each series of tested beams, there is a difference in the flexural and shear cracking load. The flexural and shear cracking load increased with increase in steel fibers volumetric ratio's.

Table 5 and Figure 6 show the effects of volumetric ratio of hooked end steel fibers volume V_f *%* on ultimate shear capacity of beams reinforced longitudinally with BFRP bars in two series. Increasing steel fibers volume in two cases from zero to 1.2% volume fraction led to increase in ultimate shear capacity by approximately 62.5% in series 1 and 85% in series 2.

The increase in steel fibers volume from zero to 0.6% used in series 1, led to increasing the ultimate shear capacity of beams by 37.5%. While when volume increased from 0.6% to 1.2% and incorporated with (Φ6@ 146 mm) in series 2, the increase in ultimate shear capacity was approximately 50%.

When steel fibers volume increased from 0.6% to 1.2% in series 1, the increase in ultimate shear capacity was 18% this increase was about 25% when incorporated with vertical steel stirrups (Φ6@ 146 mm). all these remarks show that using steel fibers ratio greater than 1% has less effects on shear capacity when used separately or used with minimum stirrups. But using 1.2% steel fibers with stirrups not only improved the shear capacity but also enhanced the ductility of beams reinforced with BFRP bars. Shear capacity for beam BFS3 was less than the expected due to the diagonal tension with bond failure mode. The important notice from Table 5 and Figure 6 is that, the using of 0.3% steel fiber separately in beam BF1 is not better in shear capacity than the using of (Φ6@ 146 mm = 0.26% volume) in beam BFS0.

Finally, Test results of this study confirm that steel fibers significantly increase shear capacity of concrete especially when work in combination with conventional steel stirrups. Also, it confirms that 1.0 percent of steel fibers can replace a part of steel stirrups reaching moderately higher shear stresses at failure and improving crack propagation resistance showing higher ductility at failure. However, the steel stirrups can be placed and distributed in the required orientations and spaced in the required distances to withstand the design loads, while this can not be ensured when steel fibers is used instead, since steel fibers are randomly distributed in the concrete matrix and spread in different positions and orientations, which lead to the conclusion that steel fibers can not be used simply in place of conventional steel stirrups, it can be used in combination with steel stirrups to increase concrete ductility, help keeping the crack as small as possible and improve the shear capacity of concrete beams.

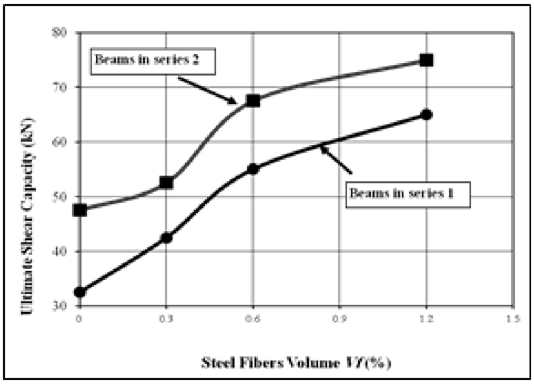

Fig. 6. Effect of steel fibers volume fracture V_f % on the ultimate shear capacity.

4. Comparison between experimental and the predicted ultimate shear strength

Many equations have already been proposed to estimate shear strength of concrete beams reinforced with FRP bars with and without stirrups, and also many have been proposed to estimate shear strength of high strength fiber reinforced concrete beams without stirrups. But non is proposed to estimate shear strength of fiber reinforced concrete beams longitudinally reinforced with FRP bars with or without stirrups. Four equations are selected to estimate shear strength of high strength fiber reinforced concrete beams longitudinally reinforced with FRP bars with and without stirrups, Modify-Zutty (1968)[21], Shin et al (1994)[19], M. A. Imam (1995)[20] and Narayanan et al (1986)[5].

In using the equations to predict the ultimate shear strength of fiber beams, splitting tensile strength (f_{spt}) of the concrete used is required and calculated according to [5] and [18], where:

$$f_{spt} = \frac{f_{cu}}{A} + B + C\sqrt{F}$$

$$A = 20 - \sqrt{F} \quad , \quad B = 0.7 \quad N/mm^2 \quad , \quad C = 1 \quad N/mm^2 \, , \; and \quad F = \left(\frac{L}{D}\right) V_f \, d_f$$

Where: A, B, C are - Non dimensional constant, F- Fiber factor and

L/D-Aspect ratio of fiber (L and D are length and diameter of steel fibers).

Current determination of the ultimate shear resistance of FRP reinforced concrete beams were mainly according to the existing formulas of beams reinforced with conventional steel reinforcement adopting some modifications to account for differences of physical and mechanical properties between FRP and steel bars. These formulas were proposed based on the traditional modified 45-degree truss model which considers the shear capacity of a reinforced concrete beam as the sum of the shear resistance of concrete contribution V_c and the shear reinforcement contribution V_s.

ACI 318-08 [1], The nominal shear strength of a steel – reinforced concrete cross section, V_n , is taken as:

$$V_n = V_c + V_s \qquad (1)$$

<u>Contribution of vertical steel stirrups by ACI -318 -08[1]:-</u>

$$V_S = \frac{A_v * f_y * d}{S} \qquad (2)$$

- For beams without stirrups the nominal shear strength is taken as:

$$V_n = V_c \quad (3)$$

- These proposed formulas are summarized in Table 6.

Table 6.
Proposed formula used in comparison.

Investigator	Predictive equation for ultimate shear strength [MPa]	Application
Modified Zutty [21]	$v_u = (0.7\sqrt{f_c'} + 7F)\frac{d}{a} + 17.2\rho\frac{d}{a} \quad (MPa)$	Beams with steel fibers
Shin et al. [19]	$v_u = 0.22 f_{spt} + 217\rho\left[\frac{d}{a}\right] + 0.34\tau F \quad (MPa)$	
Mahmoud A.Imam [20]	$v_u = 0.6\psi\sqrt[3]{\omega}\left[(f_c')^{0.44} + 275\sqrt{\frac{\omega}{(a\backslash d)^5}}\right] \quad (MPa)$ $\psi = \frac{1+\sqrt{(5.08/d_a)}}{\sqrt{1+d/(25d_a)}}$, d_a = Maximum aggregate size in mm. ω = Reinforcement factor = $\rho(1+4F)$	
Narayanan et al. [5]	$v_u = e[0.24 f_{spt} + 80\rho\left[\frac{d}{a}\right]] + 0.41\tau F \quad (MPa)$ Where : $e = 2.8\frac{d}{a} \quad for\ a/d \subseteq 2.8$ and τ- Average fiber matrix interfacial bond stress; τ = 4.15 (MPa)	

Comparison of the experimental results with Modified Zutty [21], Shin et al [19], Imam [20], and the method proposed by Narayanan et al [5] for beams with or without stirrups are shown in Table 7. From the Table, the steel fiber ratio significantly affects the experimental and predicted shear carrying capacity. The shear strength of the beams increase on increasing the steel fiber ratio V_f %. M. A. Imam [20] give a reasonable equation to predict the shear strength of fiber concrete beams reinforced with BFRP bars with or without stirrups, where the average value, standard deviation and the coefficient of variation are (0.9, 0.11, and 11.98) respectively.

Table 7.
Comparison between V_U *(pre/exp)* of ultimate shear capacity.

Beam N0.	V_U *(exp) kN*	V_U *(pre.) kN*				V_U *(pre/exp)*			
		Modified Zutty	Shin	Imam	Narayanan	Modified Zutty	Shin	Imam	Nara.
BF1	42.5	33	46	36.2	45.8	0.77	1.08	0.85	1.08
BF2	55	37	53	42.3	54.4	0.67	0.96	0.77	0.99
BF3	65	44	66	53.5	70.4	0.67	1.01	0.82	1.08
BFS1	52.5	52.9	65.9	56.1	65.7	1.01	1.25	1.06	1.25
BFS2	67.5	56.9	72.9	62.2	74.3	0.84	1.08	0.92	1.1
BFS3	75	63.9	85.9	73.4	90.3	0.85	1.15	0.98	1.2
Averg.						0.80	1.08	0.9	1.12
St.deviation						0.13	0.10	0.11	0.09
Coe. of var %						15.96	9.43	11.98	8.37

5. Proposed modification to predict the ultimate shear capacity

It is clear from the previous discussion that Imam [20] model can accurately predict the ultimate shear capacity of SFRC. In this study it is recommended to consider empirically the impact of longitudinally fiber reinforcement stiffness on the evaluation of shear strength. So Imam model is modified to the following form taking into consideration the effect of the modulus of elasticity of BFRP bars.

$$v_u = 0.6 \left[\frac{E_s}{E_f}\right]^{0.55} \psi \sqrt[3]{\omega} \left[(f_c^{'})^{0.44} + 275 \sqrt{\frac{\omega}{(a \backslash d)^5}} \right] \quad (MPa) \qquad (4)$$

From Table 8, it could be seen that the proposed equations in this study predicts relatively well the experimental results than other predictions.

Table 8.
Comparison between V_U *(pre/exp)* of ultimate shear capacity.

Beam N0.	V_U *(exp)* *kN*	V_U *(pre/exp)*				
		Modified Zutty	Shin	Imam	Narayanan	proposed
BF1	42.5	0.77	1.08	0.85	1.08	0.86
BF2	55	0.67	0.96	0.77	0.99	0.95
BF3	65	0.67	1.01	0.82	1.08	0.89
BFS1	52.5	1.01	1.25	1.06	1.25	0.95
BFS2	67.5	0.84	1.08	0.92	1.1	1.09
BFS3	75	0.85	1.15	0.98	1.2	1.03
Averg.		0.80	1.08	0.9	1.12	0.96
St.deviation		0.13	0.10	0.11	0.09	0.09
Coe. of var %		15.96	9.43	11.98	8.37	9.07

5. Conclusions

In view of the results obtained in this investigation, the following points have been concluded:

1- All tested beams were over-reinforced in flexure to ensure that shear failure occurs. However, the increasing of steel fibers volume from 0.3 % to 1.2% led to change the failure mode from shear to flexural – shear failure.
2- When the steel fiber volume increased from zero to 1.2%, the failure mode changed from a catastrophic brittle shear compression failure to a ductile diagonal tension failure and when the steel fibers incorporated with steel stirrups, the mode of failure changed from shear-compression failure to a more ductile diagonal – tension with bond failure.
3- The increasing in steel fiber volume from 0.3% to 1.2% led to decrease the maximum crack width at failure in the two series from 12mm to be 8mm approximately and the average numbers of cracks and spacing increased, this due to the fact that the presence of steel fiber in concrete bridge the cracks.
4- The addition of steel fibers not only improved the ultimate load capacity of the tested beams, but also increased the stiffness and hence reduced the mid-span

deflection at the same load level. This improvement is more pronounced in case of beams with steel fibers and stirrups.

5- When steel fibers incorporated with stirrups, small effects were noticed on mid-span deflection when 0.3% of steel fiber was used and when 1.2% of steel fiber was used. The effect of stirrups on mid-span deflection was noticed after 50% of the maximum applied load. This gives a notice that the effect of incorporated steel fibers with stirrups appears only with high volume of steel fibers.
6- At least (1 to 1.2) % fiber by volume is needed to avoid shear failure and to change the mode of failure from shear to flexure for beams reinforced with BFRP rebars. Also minimum web reinforcement must be added to avoid a catastrophic brittle shear failure.
7- The addition of steel fibers to concrete in presence of minimum value of steel stirrups (Φ6@ 146 mm = 0.26% volume) in shear zone not only enhanced shear capacity but also improved the deformation characteristics. Using steel fibers ratio greater than 1% has fewer effects on shear capacity when used separately or used with minimum stirrups. But using 1.2% steel fibers with stirrups not only improved the shear capacity but also enhanced the ductility of beams reinforced with BFRP bars.
8- Imam [21] gave a reasonable equation to predict the shear strength of fiber concrete beams reinforced with BFRP bars with or without stirrups.
9- The proposed equation to predict the ultimate shear strength of fiber concrete beams reinforced with BFRP bars with or without stirrups in this study predicted relatively well the experimental results than other researchers.
10- Additional experimental and theoretical work must be done to produce more reliable model for the evaluation the ultimate shear capacity.

6. Notation

A_f = Area of FRP reinforcement.
A_s = Area of steel reinforcement.
a/d = Shear span to depth ratio.
d = Depth of cross section.
E_f = Modulus of elasticity of FRP bars.
E_s = Modulus of elasticity of steel bars.
f_f = FRP tensile stress.
f_s = Steel tensile stress.
f_y = Yield steel stress.
f_{cu} = Cube concrete compressive strength.
f_c' = Cylindrical concrete compressive strength.
p_u = Load at shear failure.
n=Number of steel stirrups branches.
p_{cr}= Load at the first flexural crack.
S= Spacing between vertical stirrups.
V_{cr}= Shear cracking load.
V_U = Ultimate shearing load.
ε_{BFRP} = Tensile strain in BFRP bars.
μ_D = Ductility degree.
ρ_f = FRP reinforcement ratio.
ρ_v = Vertical stirrups ratio.
Δ_{max} = Maximum deflection.
Δ_{cr}= Deflection at cracking.

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بعض العوامل التي تؤثر على سلوك القص لكمرات خرسانة الألياف عالية المقاومة والمسلحة طوليا بأسياخ من ألياف البازلت

الملخص العربى

يتناول هذا البحث دراسة سلوك القص لكمرات خرسانة الألياف عالية المقاومة والمسلحة طوليا بأسياخ من ألياف البازلت في حال وجود أو عدم وجود كانات راسية في منطقة القص. ثماني كمرات من خرسانة الألياف والعالية المقاومة تم اختبارها في القص. ألياف من الصلب وكذلك الكانات تم استخدامهم منفصلين أو مجتمعين كتسليح للقص. المتغير الرئيسي في هذا البحث هو نسبة محتوى ألياف الصلب سواء في وجود أو عدم وجود الكانات. كل الكمرات تم اختبارها تحت تأثير الحمل الاستاتيكى حتى الانهيار حيث نسبة ذراع القص إلى العمق كان ثابتا = 2.5. نماذج الانهيار والشكل النهائي للانهيار وحمل القص عند التشريخ وعند الانهيار وكذلك الترخيم عند منتصف الكمرة تم تسجيلها حتى نلقى الضوء على آلية انهيار القص لمثل هذه الكمرات. النتائج المعملية أوضحت أن إضافة نسب من ألياف الصلب إلى الخرسانة يؤدى إلى تحسين في خواص التشرخ وأحمال القص القصوى وكذلك الممطولية مع تحويل شكل الانهيار النهائي إلى السلوك الأكثر ممطولية. وأن الكمرات المشتملة على كلا من ألياف الصلب والكانات الراسية كانت أكثر ممطولية من الكمرات التي بها كانات أو ألياف من الحديد الصلب فقط. تم مقارنة النتائج المعملية لقوى القص القصوى ببعض الصيغ المتاحة من الكودات أو من الأعمال السابقة والتي بينت أن معادلات الدكتور محمود إمام تعطى نتائج مقبولة للكمرات التي بها ألياف من الصلب مع وجود أو عدم وجود كانات راسية. وان قيم القص القصوى والمحسوبة طبقا للمعادلات المقترحة كانت أكثر قبولا من الآخرين.