Effect of axial force and fibre type on the shear behavior of high strength fiber reinforced concrete beams

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ABSTRACT. This study is part of a larger research work aimed to study the effects of fiber content, fiber type (corrugated shape and hooked-end), amount of web reinforcement and axial compression stress, on the shear behavior of high strength fiber reinforced concrete (HSFRC) beams. To the author's knowledge, the effect of applying axial compression forces, to the HSFRC beams, has not yet been studied. Nineteen simply supported HSFRC beams were subjected to axial compression forces and tested under two-point vertical loading for three values of shear span to depth ratio. It was found that the shear strength of beams subjected to axial compression stress level equals 0.1, is higher than that in the literature for beams tested without applying axial stress by a range of 22% -98%. Increasing the axial compression stress level to 0.2 led to an increase in the first crack load, ultimate load by 24% and 10%, a reduction in the deflection by (19-30%), compared with those subjected to axial compression stress level equals 0.1. In addition, a combination of web reinforcement and fibers resulted in a significant increase in the cracking and ultimate loads by 123 and 59%, respectively, over those of the reference beam. A new formula is proposed for predicting the experimental shear strength of HSFRC beams subjected to axial compression forces. The results obtained by the proposed formula are in better agreement with the test results when compared with the predictions based on the empirical equations proposed by other investigators.

Keywords: steel fibers, high strength concrete beams, hooked-end fibers, corrugated fibers, shear, prediction, and empirical equations.

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INTRODUCTION

High Strength Concrete (HSC) is considered to be a relatively brittle material because the post-peak portion of its stress-strain diagram descends deeply as compressive strength increases [1 and 2]. When added to concrete mixes, steel fibers distribute randomly through the mix at much closer spacings than conventional reinforcing steel and act to arrest cracking by decreasing the stress intensity factor at the tip of inherent internal cracks [3]. This leads to increasing the shear-friction strength of concrete and also improves the ultimate tensile strength and ductility because a lot of energy is absorbed in debonding and pulling out of fibers from the concrete before complete separation and failure of concrete occurs [3]. Swamy and Bahia [4] showed that fibers act as effective shear reinforcement, much like the legs of regularly spaced stirrups, and are more effective in arresting crack propagation and maintaining the integrity of the surrounding concrete. Ashour et al. [2] and Craig [5] showed that it is possible to replace stirrups partially or completely with fibers in beams of HSC under transverse loading to resist shear. The ACI Committee 544 [6] defined the FRC as a concrete with increased strain capacity, impact resistance, energy absorption, and tensile strength. It has been clearly shown that for beams reinforced with a fixed amount of minimum shear reinforcement, irrespective of the concrete strength, the reserve shear strength diminishes as the concrete strength gets higher [7 and 8]. Therefore, the minimum shear reinforcement for HSC either in the form of stirrups, fibers or both needs more investigation.

Despite that the behaviour of reinforced concrete (RC) beams in flexure and shear was examined in the literature using an independent test specimen without restraints, RC beams in real concrete structures are members of a frame structure and they behave differently from such idealized members because of the axial restraint imposed by adjacent members [9]. Based on experiments and analyses, researchers [10] have concluded that reinforced concrete member's characteristics, such as capacity and failure pattern in compression, are significantly different under restraint conditions. From a study performed by Yang et al. [9] it was shown that the flexural and shear behavior characteristics and the failure pattern of RC flexural members is governed by the intensity of axial restraints. Abdoun [11] studied the effect of axial compression forces on the behavior of HSC beams with web reinforcement. To date, an organized and comprehensive evaluation considering the effect of applying axial compression forces to the fiber reinforced HSC beams without web reinforcement, has not been attempted.

The aim of this research is to study the effect of varying the fiber type, fiber content and the axial compression forces on the shear behavior of HSFRC beams. All studied beams were subjected to axial compression forces and then tested by two-point transverse loading. The resulting first-crack loads and ultimate shear loads were compared with those of a plain concrete reference beam to assess the contribution of the fibers. A proposed formula was developed for prediction of shear strength of studied beams to a high degree of accuracy.

EXPERIMENTAL PROGRAMME

Preparation of Beam Specimens and Testing

Mix proportions for HSC used in this study are shown in Table 1. Steel fibers of varying amounts and types (see Table 2) were added during mixing of the concrete. Two types of fibers were used, namely, hooked-end and corrugated steel fibers of yield strength of 400 MPa. The aspect ratio of the two types of fibers was constant ($\ell/d_f = 50$ mm $/1$ mm $= 50$). Dimensions and details of specimens used in this research are shown in Table 2 and Figure 1.

It should be noted that all beams were over-reinforced in flexure to ensure shear failure. The tested beam specimens were subjected to axial compression force prior to testing by two-point transverse loading (shear span-to depth ratio, a / d = 2, 3 and 4). All beams were statically tested to failure in a single load cycle. A Linear Variable Differential Transducer (LVDT) was used to measure deflection, strains at bottom bars and stirrups from the electrical strain gauges through a computer-controlled data acquisition system.

Table 1 Mix Constituent Proportions for the Studied Beams

CHARACTERISTIC STRENGTH	PROPORTIONS, kg/m^3					
	Cement	Sand	Crushed Basalt	Silica Fume	Water	Superplasticizer Liter/ m^3
80 MPa	550	600	1250	55	150	23

a = 0.45 m for all beams except for B7, a = 0.30 m and B8, a=0.60 m
All beams contain steel fibers except B13-B16
N =0.2 f$_{cu}$ x Ac for Beams B4-B6, B11 and B12.
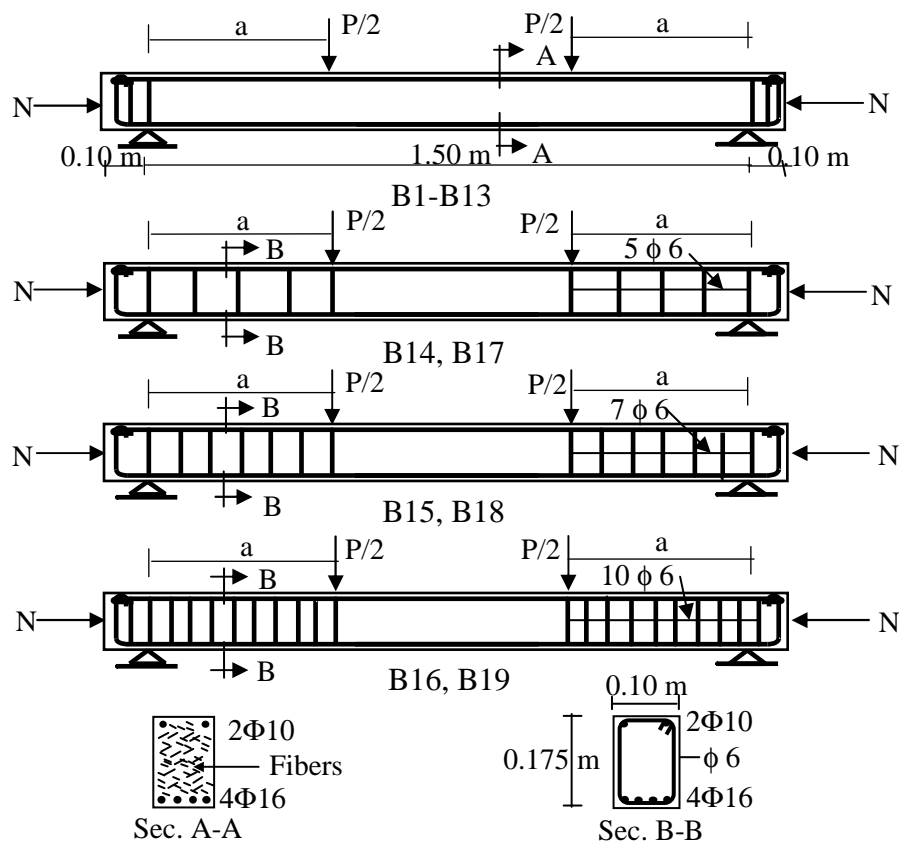N = 0.1 f$_{cu}$ x Ac for all other beams.

Figure 1 Dimensions, reinforcement details and loading of the studied beams.

EXPERIMENTAL RESULTS AND DISCUSSION

General Behavior, Crack Pattern and Failure Mode

Figure 2 shows the crack pattern and failure mode for all the tested beams. The first crack load, ultimate load capacity and modes of failure for the tested beams are listed in Table 3. Generally, the first crack for all beams occurred in the shear region perpendicular to the

direction of the maximum principal stress induced by pure shear. Despite that the type and amount of steel fibers did not change the mode of failure, they transformed the failure mode into a more ductile one, or in other words, they raised the value of the first crack and ultimate loads as shown in Table 3. For example, adding 0.5% fibers by volume resulted in increasing the cracking load and ultimate load for B1 by 14 and 17%, over those of the reference beam, B13. Increasing the fiber volume to 1.5% led to a further increase to cracking and ultimate loads for B3 by 41 and 48%, compared to those of the reference beam, B13. It was also observed that beams without web reinforcement had only a single diagonal crack on one end of the beam extending throughout the shear span (Beams B1-B13). In addition, Table 3 shows that the hooked-end fibers are slightly better than corrugated steel fibers in terms of raising the first crack load, increasing the capacity and ductility of studied beams. For example, Beams B1 and B2 (contains hooked-end fibers and subjected to axial compression stress level equals 0.1) had a first crack load, failure load and, in turn, ductility higher than those of Beams B9 and B10 (contains corrugated steel fibers), but the failure mode did not change. Balaguru and Shah [12] reported the superior properties of hooked-end fibers over the other steel fibers.

Table 2 Experimental Programme for Studied Specimens

BEAM SPECIMEN NUMBER	f_{cu}, MPa	AXIAL COMPRESSION STRESS $(N / f_{cu} A_c)$	TYPE OF STEEL FIBERS	VOLUME CONTENT OF FIBERS, v_f,%	SHEAR SPAN/ DEPTH RATIO a/d	WEB REINFORCEMENT RATIO, μ_v%
B1	90	0.1	Hooked-end	0.5	3	-
B2	91	0.1	Hooked-end	1.0	3	-
B3	90	0.1	Hooked-end	1.5	3	-
B4	84	0.2	Hooked-end	0.5	3	-
B5	77	0.2	Hooked-end	1.0	3	-
B6	76	0.2	Hooked-end	1.5	3	-
B7	84	0.1	Hooked-end	1.0	2	-
B8	79	0.1	Hooked-end	1.0	4	-
B9	85	0.1	Corrugated	0.5	3	-
B10	86	0.1	Corrugated	1.0	3	-
B11	79	0.2	Corrugated	0.5	3	-
B12	80	0.2	Corrugated	1.0	3	-
B13	78	0.1	-	-	3	-
B14	78	0.1	-	-	3	0.50
B15	79	0.1	-	-	3	0.75
B16	78	0.1	-	-	3	1.12
B17	84	0.1	Hooked-end	0.5	3	0.50
B18	80	0.1	Hooked-end	0.5	3	0.75
B19	82	0.1	Hooked-end	0.5	3	1.12

It was observed that the number of inclined cracks increased with the presence of web reinforcement, indicating an enhanced redistribution of internal forces (Beams B14-B19). The combination of fibers and web reinforcement (B17-B19) resulted in a significant increase in the cracking loads (81-123%) and ultimate loads (35-59%) over those of the reference specimen B13. This is in agreement with the findings of Johnson and Ramirez [7]. For Beams B14, the mode of failure was shear-compression, but adding steel fibers in B17 resulted in raising the first crack load and ultimate load by 20 and 8%, respectively.

Increasing the amount of transverse reinforcement in B15 resulted in propagation of flexural cracks in the beam but the mode of failure was shear. Adding fibers to the mix, B18 led to improving the shear behavior and changing of failure mode and the beam failed in flexure with crushing of concrete and yielding of compression steel in top of the beam. Further increase to the web reinforcement, B16, led to decreasing the cracks spacing, increasing the number of cracks and changing the failure mode to compression failure, since the tension zone was over reinforced. In addition, increasing the applied axial compression stress from 0.1 to 0.2 led to increasing the first crack load and ultimate load. For example, increasing the applied axial compression stress from 0.1 for B1, B2 and B3 to 0.2 for B4, B5 and B6 led to increasing the cracking loads by 24, 17 and 11% and ultimate loads by 10, 6 and 3%, for these beams, respectively. It is interesting to notice that the effect of increase in axial compression stress becomes less significant with the increase of percentage volume of fibers from 0.5% to 1.5%.
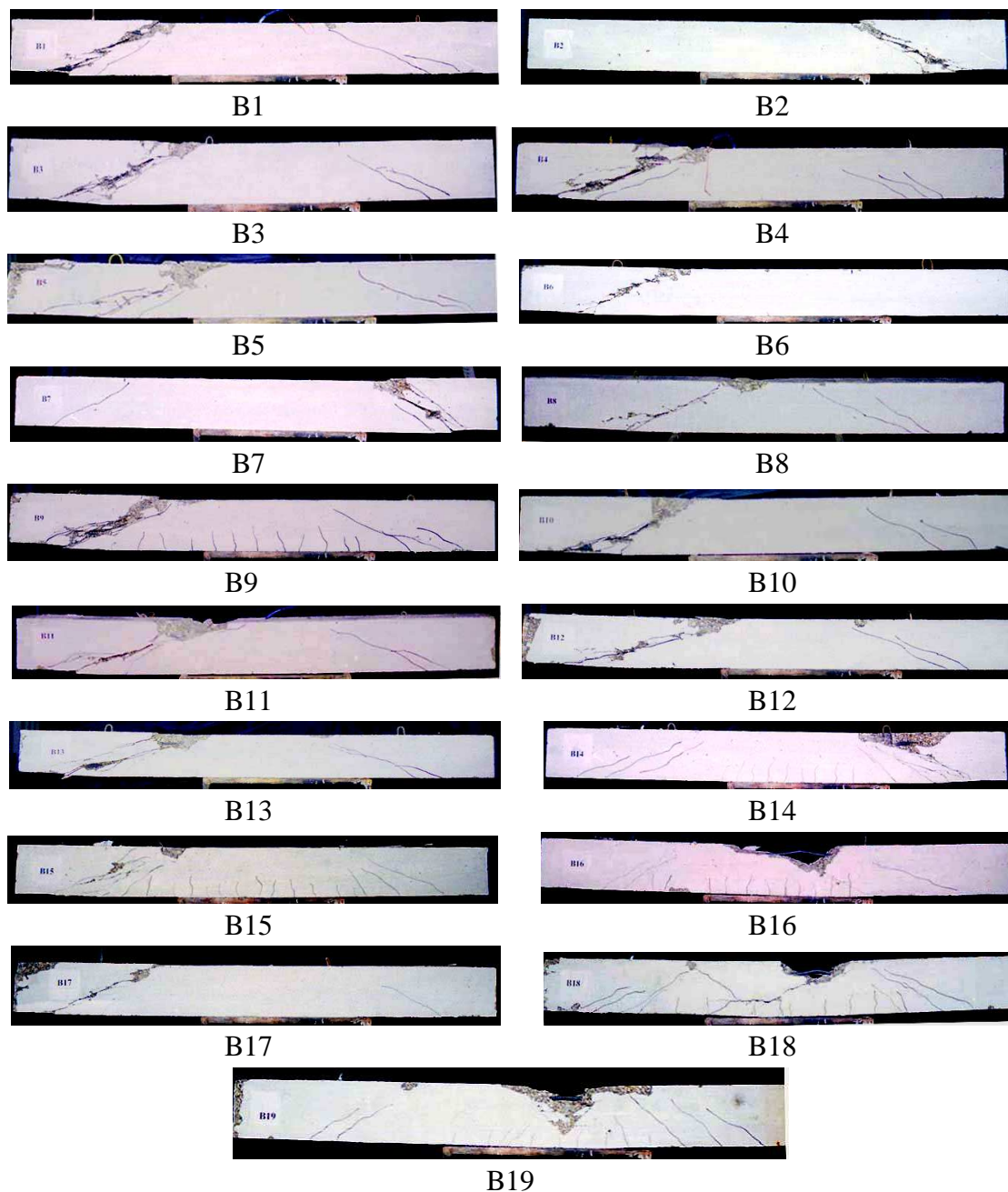

B1

B2

B3

B4

B5

B6

B7

B8

B9

B10

B11

B12

B13

B14

B15

B16

B17

B18

B19

Figure 2 Crack pattern and failure mode for studied beam specimens.

Table 3 Cracking, Maximum Shear Load, and Failure Mode of the Test Beams

BEAM	f_{cu}, MPa	a/d	FIBER TYPE & CONTENT, v_f,%	ACS	μ_v, %	P_{cr}, kN	P_u, kN	FAILURE MODE
B1	90	3	HE, 0.5	0.1	--	121	186	Shear
B2	91	3	HE, 1.0	0.1	--	132	200	Shear
B3	90	3	HE, 1.5	0.1	--	149	236	Shear
B4	84	3	HE, 0.5	0.2	--	150	205	Shear
B5	77	3	HE, 1.0	0.2	--	155	212	Shear
B6	76	3	HE, 1.5	0.2	--	166	244	Shear
B7	84	2	HE, 1.0	0.1	--	180	288	Shear
B8	79	4	HE, 1.0	0.1	--	93	152	Shear
B9	85	3	CR, 0.5	0.1	--	117	185	Shear
B10	86	3	CR, 1.0	0.1	--	130	194	Shear
B11	79	3	CR, 0.5	0.2	--	132	197	Shear-Compression
B12	80	3	CR, 1.0	0.2	--	157	201	Shear-Compression
B13	78	3	--	0.1	--	106	159	Shear
B14*	78	3	--	0.1	0.5	160	199	Shear-Compression
B15*	79	3	--	0.1	0.75	174	234	Shear
B16*	78	3	--	0.1	1.12	210	236	Compression
B17*	84	3	HE, 0.5	0.1	0.5	192	215	Shear
B18*	80	3	HE, 0.5	0.1	0.75	227	249	Compression
B19*	82	3	HE, 0.5	0.1	1.12	236	253	Compression

ACS = axial compression stress, P_u = ultimate load, P_{cr} = cracking load, HE= hooked-end fibers, CR = corrugated steel fibers.

* Beams with web reinforcement "stirrups"

PREDICTION OF SHEAR STRENGTH

Proposed Equation for Predicting Shear Strength Results

Based on the author's experimental results, the equation developed by Oh et al. [13] for normal strength FRC was modified to predict the experimental results in this investigation. In the formulation of the equilibrium requirements for a loaded FRC beam, the external and internal actions shown in the free body diagram of a part of the shear span of a simply supported FRC beam (Figure 3) is identified and the shear force, V_u can be written in its general form as

$$V_u = V_c + V_{ay} + V_d + V_{fy} \qquad (1a)$$

Where V_c is the shear force across the compression zone resisted by concrete, V_{ay} is the aggregate interlocking force (vertical component), V_d is the dowel action force, and V_{fy} is the vertical component of the fiber pullout force along the inclined crack, $V_{fy} = F_1 (h – c)/d$. The contribution of the aggregate interlocking was ignored in this study since it has been reported in the literature [14] that the crack plane in HSC is relatively smooth and passes through the aggregate instead of going around it, as in normal-strength concrete. Such a phenomenon results in a reduced contribution of aggregate interlocking in a diagonally cracked HSC concrete beam [14]. Thus the equation of shear strength was written as;

$$V_u = (10 \rho f_c' d / a_s)^{1/3} bd + A_v f_y d / s + F_1 (h – c)/d \qquad \text{for } a_s / d \geq 2.5 \qquad (1b)$$

$$V_u = (160 \, \rho \, f_c')^{1/3} \, (d / a_s)^{4/3} \, bd + A_v \, f_y \, d / s + F_1 \, (h - c)/d \quad \text{for } a_s / d < 2.5 \qquad (1c)$$

where

a_s is the shear span, mm
b is the breadth of beam section, mm
A_v is the area of stirrups, mm^2
s is the spacing of the stirrups, mm
f_y is the yield strength of the stirrups, MPa
F_1 is the ultimate force sustained by the steel fibers per unit area of crack at failure.
h is the total height of the beam, mm
c is the neutral axis depth, mm

(a) Free body diagram of part of the shear-span of a simply supported FRC beam [13].

(b) A photo showing the fibers at the surface of the diagonal crack of one of the tested beams in this investigation.
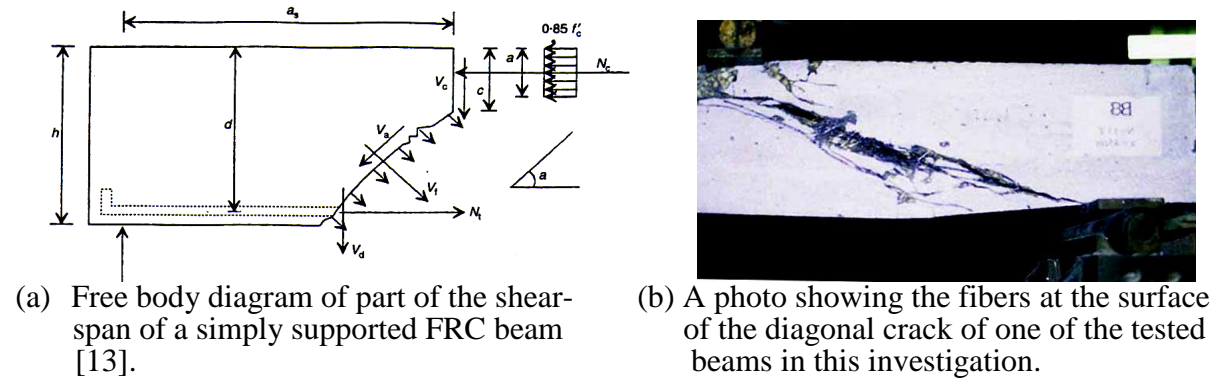
Figure 3 Contribution of concrete, fibers and stirrups in shear strength.

Four major modifications were made to Equation (1) in order to be applicable for HSFRC beams subjected to axial compression forces. Firstly, the contribution of steel fibers was modified to be as suggested by Narayanan and Darwish [15]. Secondly, the effect of axial compression forces, stated in the codes [16 and 17], was included in the proposed equation. Thirdly, after carrying out a regression analysis for the beams tested in this study, the multipliers 10 and 160 were changed to be 23 and 660 in order to reflect the behavior of HSC. Finally, the contribution of the web reinforcement "stirrups", V_{us}, was multiplied by a reduction factor, 0.9, since the steel fibers share the stirrups in resisting shear strength. Therefore the proposed equation becomes:

for $a_s / d \geq 2.5$

$$V_u = [(23 \, \rho \, f_c'd / a_s)^{1/3} \, b \, d + 0.9 \, A_v \, f_y \, d / s + 0.41 \, \tau \, F] \, (1 + 0.07 \, N / A_c) \qquad (2a)$$

and   for $a_s / d < 2.5$

$$V_u = [(660 \, \rho \, f_c')^{1/3} \, (d / a_s)^{4/3} \, b \, d + 0.9 \, A_v \, f_y \, d / s + 0.41 \, \tau \, F] \, (1 + 0.07 \, N/A_c) \qquad (2b)$$

where   N = axial compression force applied to the beam
         A_c = b d (cross sectional area of beam section)

Table 4 shows a comparison between the modified equations in the literature, which were originally proposed by Ashour et al. [2], Farahat [18], and Narayanan and Darwish [15], and the proposed equation in predicting the experimental results in this investigation. The equations in the literature were modified by multiplying their results by the factor (1 + 0.07 N / A_c) in order to include the effect of axial compression forces. This factor was included in the ACI Building Code equation [16] and the ECCS Code equation [17]. It can be seen from Table 4 that the equations developed by Ashour et al. [2], Farahat [18] and Narayanan and Darwish [15] improved greatly after including the effect of axial compression forces. The ratio of the experimental to the predicted shear strength by the modified equation developed earlier by Farahat [18] has a mean of 1.04 and a standard deviation of 0.14, while that of the

Narayanan and Darwish equation [15] has a mean of 1.1 with a standard deviation of 0.12 and Ashour et al. equation [2] predicted the results with a mean ratio of 1.18 and a standard deviation of 0.15. The proposed equation predicted the results very accurately with a mean of the experimental to the predicted results equals 1.0 and the standard deviation was 0.08 only. In order to assess the effect of axial compression forces applied to the studied beams, a comparison was made in Table 4 between the shear strength results in the current investigation and those tested by Farahat [18] and not subjected to axial compression forces. It can be seen that shear strength results for beams subjected to axial compression forces are higher than those tested without applying axial forces by a range of 22-98%.

Table 4 Comparison between the Proposed equation and Equations in Literature, modified to count for axial loading, in Predicting Shear Strength

BEAM	LEVEL OF AXIAL COMP. STRESS	f_{cu}, MPa	OBSERVED SHEAR STRENGTH, v_{uo}, Mpa	EXPERIMENTAL / PREDICTED SHEAR STRENGTH, v_{uo}/v_p			
				NARAYANAN AND DARWISH [15]	ASHOUR et al. [2]	FARAHAT [18]	PROPOSED Eq. (2)
B1	0.1	90	6.2 (3.33)	1.21	1.29	1.15	1.05
B2	0.1	91	6.7 (4.13)	1.15	1.15	1.04	1.01
B3	0.1	90	7.9	1.22	1.18	1.07	1.09
B4	0.2	84	6.8	1.02	1.1	0.98	0.90
B5	0.2	77	7.1	0.99	1.01	0.92	0.89
B6	0.2	76	8.1	1.02	1.0	0.92	0.93
B7	0.1	84	9.6 (7.85)	1.23	1.17	0.75	1.01
B8	0.1	79	5.1 (3.77)	1.0	1.28	0.98	0.91
B9	0.1	85	6.2	1.27	1.42	1.26	1.14
B10	0.1	86	6.5	1.17	1.27	1.14	1.08
B11	0.2	79	6.6	1.04	1.17	1.03	0.93
B12	0.2	80	6.7	0.94	1.02	0.91	0.86
B13	0.1	78	5.3 (2.67)	1.36	1.56	1.33	1.14
B14	0.1	78	6.6	1.15	1.26	1.13	1.05
B15	0.1	79	7.8 (4.13)	1.16	1.25	1.14	1.08
B16	0.1	78	7.9 (5.17)	0.97	1.04	0.96	0.94
B17	0.1	84	7.2	1.03	1.11	1.02	0.98
B18	0.1	80	8.3 (5.2)	1.08	1.15	1.07	1.05
B19	0.1	82	8.5 (6.0)	0.93	0.98	0.92	0.92
Mean				1.1	1.18	1.04	1.0
Standard Deviation				0.12	0.15	0.14	0.08

* Values in parentheses are results of beams tested by Farahat [18], not subjected to axial forces.

Validation of the Proposed Equation for Predicting Results from the Literature

The proposed equation was used for predicting other results in the literature in order to extend its validity for prediction of shear strength for beams of different shear span-depth ratios, different longitudinal and web reinforcement ratios. The prediction was made for beams tested by Swamy and Bahia [4], Shin et al. [19], Cho and Kim [20], Ashour et al. [2] and Farahat [18] beside the beams tested in this study. These beams had a range of concrete strength (44-101 MPa), different amounts of fiber content (0 to 2%), fiber aspect ratio (50 to 133), shear span-depth ratio (1.3 to 6), longitudinal reinforcement ratio (2.9-5.4%) and web reinforcement ratio (0-1.12%). Figure 4 shows the ratio of the experimental to predicted

results versus fiber content for 70 beams. It can be seen from the figure that the analytical predictions using the proposed equation are reasonably close to the test results of other researchers. Although the overall statistics are good, the equation is not conservative for a/d = 6 (Ashour specimens [2]) as shown in Figure 4. Cho and Kim [20] observed similar findings in their study. This may be attributed to the empirical formulation and the representation of more slender beam behavior.
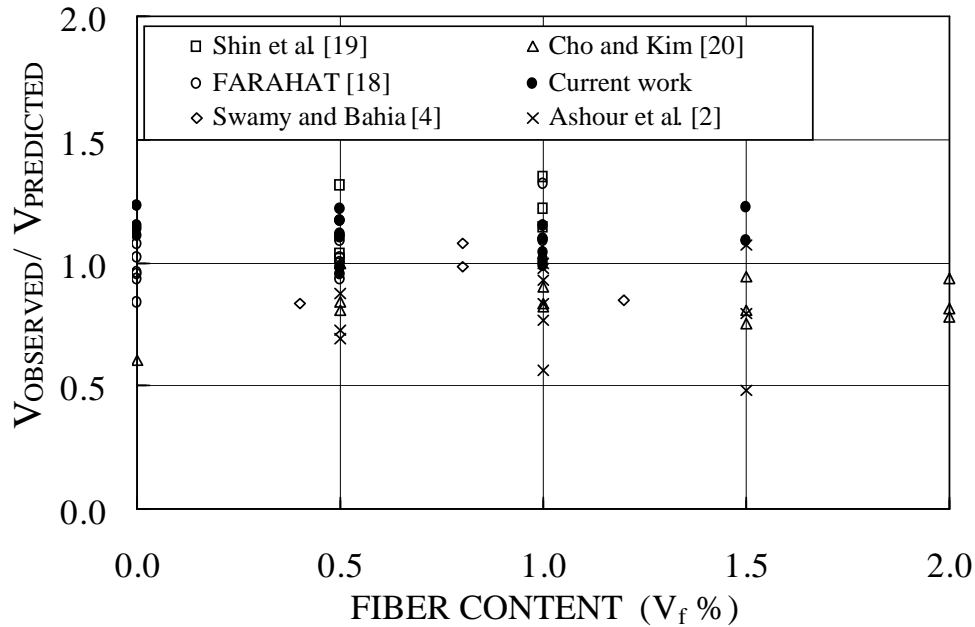

Figure 4 Validation of the proposed equation for predicting results of other tests.

CONCLUSIONS

A total of 19 HSFRC beams, containing longitudinal reinforcement and subjected to axial compression forces, were tested. Based on the experimental results and the analytical model developed in this research, the following conclusions were drawn:

1. Test results indicated that the addition of steel fibers enhanced initial stiffness, cracking loads, ultimate loads and, shear strength, and in turn, the ductility of the studied beams. Adding 0.5% fibers by volume resulted in increasing the cracking load and ultimate load by 14 and 17% over those of the reference beam. Increasing the fiber volume to 1.5% led to a further increase to cracking and ultimate loads by 41 and 48%, compared to those of the reference beam. Regardless of the failure mode, fibrous concrete beams eventually collapsed from the severely localized deformations at one or two major cracks.

2. It was found that fiber reinforcement can reduce the amount of shear stirrups required, and that a combination of web reinforcement and fibers resulted in obtaining the benefit of both high capacity and ductility. This combination resulted in a significant increase in the cracking and ultimate loads by 123 and 59% over those of the reference beam specimen. The hooked-end fibers are slightly better than corrugated steel fibers in terms of raising the first crack load, increasing the capacity and ductility of studied beams.

3. It was found that shear strength results for beams in the current investigation, subjected to axial compression stress equals 0.1, are 22-98% higher than those tested by Farahat [18] without applying axial stress. Increasing the applied axial

compression stress from 0.1 to 0.2 led to a maximum increase in the first crack load and ultimate load by 24 and 10%, and a reduction of the deflection by (19-30%) and it has almost the same effect as increasing the fiber content from 0.5 to 1% on the ultimate shear capacity of the tested beams. The effect of increase in axial compression stress level becomes less significant with the increase of percentage volume of fibers from 0.5% to 1.5%.

4. A proposed equation was developed to predict shear strength of HSFRC beams with and without stirrups and subjected to axial compression stress. The results obtained using this equation were in good agreement with the experimental results of the tested beams and other results reported in the literature for a practical range of concrete strength, different amounts of fiber content, fiber type, fiber aspect ratio, shear span-depth ratio (including deep beams), longitudinal reinforcement ratio and web reinforcement ratio. The results obtained by the proposed equation were in better agreement with the test results (mean of 1.0 and standard deviation of 0.08) when compared with the predictions based on the empirical equations proposed by other investigators.

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