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The shear strength of steel fiber-reinforced concrete beams

Resistência ao cisalhamento de vigas de concreto reforçado com fibras de aço

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Abstract

This research investigates the mechanical shear behavior of twelve reinforced concrete beams. The type of loading (normal or reverse), the presence or absence of steel fibers (30 kgf/m^3), and the concrete compressive strength (40MPa, 60 MPa, or 80 MPa) were the mains test variables studied. The beams had nominally identical cross-sections, effective depths, and longitudinal and transverse reinforcements. The loads were increased at 10 kN intervals until shear failure occurred, defined by the yielding of the first stirrup. The ultimate shear loads observed in these tests were compared to three empirical and semi-empirical formulas proposed in the literature. Based on the test results it could be concluded that concrete compressive strength has no significant influence on the reduction of ultimate shear load caused by reverse loading. Reverse-loaded beams with fibers had approximately the same ultimate shear strength as concrete beams without fibers subjected to normal loading, regardless of the compressive strength of the concrete.

Keywords: steel fiber; reinforced concrete; beam; reverse loading; shear strength.

Resumo

Este trabalho investiga o comportamento ao esforço cortante de doze vigas em concreto com adição de fibras de aço. As principais variáveis estudadas foram o tipo de carregamento (normal ou reverso), a presença ou a ausência de fibras de aço (30kgf/m^3) e a resistência do concreto à compressão (40 MPa, 60 MPa, ou 80 MPa). As vigas apresentavam seção transversal, altura útil e armaduras longitudinais e transversais nominalmente idênticas. Uma carga concentrada, no meio do vão da viga, foi aplicada em intervalos de 10 kN até a ruptura por cisalhamento, definida pelo escoamento do primeiro estribo em solicitação. A carga última de cisalhamento observada nos testes foi comparada com três formulas empíricas, e semi-empiricas, propostas na literatura. Baseando-se nos resultados dos testes, concluiu-se que a resistência à compressão do concreto não tem influencia significativa na parcela de redução da carga ultima de cisalhamento, promovida pela reversão do carregamento. Vigas sujeitas ao carregamento reverso e com fibras apresentaram, aproximadamente, a mesma resistência última de cisalhamento que as vigas sem fibras sujeitas ao carregamento normal, independentemente da resistência do concreto à compressão.

Palavras-chave: fibras de aço; concreto armado; viga; carregamento reverso; resistência ao cisalhamento.

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1. Introduction

Many studies have investigated the shear behavior of steel fiber reinforced concrete beams (Araúz [3]; Ashour et al. [4]; Cucchiara et al. [5]; Di Prisco and Romero [6]; Furlan Jr and de Hanai [7]; Parra-Montesinos [16], Swamy and Bahla [19]; Swamy and Balla [20]). Some authors have considered placing the burden of shear reinforcement on the fibers and several have found that adding steel fibers to a reinforced concrete beam increases its shear strength. Furthermore, a sufficient amount of fibers can suppress brittle shear failure in favor of more ductile behavior. The increase in shear strength depends not only on the amount of fibers, usually expressed as a fraction of the beam volume, but also on their aspect ratio and anchorage conditions. The fibers decrease the crack opening displacement and promote so-called alternative shear strength mechanisms, especially aggregate interlock and dowel action.

Narayanan and Darwish [11]; [12] observed that fiber-reinforced concrete beams and reinforced concrete beams with conventional stirrups develop similar crack patterns under very high shear stress, and concluded that fibers cannot entirely replace conventional shear reinforcement.

Several empirical expressions and analytical models have been proposed to evaluate the contribution of fibers to the ultimate shear strength (Mansur et al. [9]; Narayanan and Darwish [11]; Noghabai [13]; Oh and Lim [14]; Tan et al. [22]). This contribution depends mainly on three factors: the volume fraction of the fibers, the shape of the fibers, and the nature of the fiber-matrix interface. (The last one determines the resistance of the fibers to pullout.) However, no existing expression has yet been validated by a wide range of tests. In some cases, the calibration data even include the beams that failed by flexure or even by shear. The design procedures proposed for estimating shear strength need to be evaluated using a large collection of test results from beams that failed in shear.

However, only a few studies contain experimental data about shear behavior of fiber-reinforced beams submitted to reverse loadings, or even beams with conventional transverse reinforcement (Oliveira [15]; Paulay [17]; Wang et al. [23]). Paulay [17]) found that under reverse loadings, new cracks formed at an intersecting diagonal by cracks created during the previous loading (an example of this appears later in the paper). In this context, cracks covered the entire compression zone at the top of the beam and the residual deformation of the longitudinal reinforcement prevents the cracks to be fully closed. Thus, compared to a normal loading, the compression chord and aggregate interlock of a beam subjected to reverse loadings may contribute much less to the ultimate shear strength.

Recent studies carried out at the University of Campinas (Oliveira [15]) confirmed that reversion has an unfavorable effect on the shear resistance of reinforced concrete beams. In these experiments, the application of a reverse load reduced the ultimate shear strength of concrete beams by at least 50 per cent.

Design codes seldom consider alternative mechanisms (aggregate interlock, dowel action, arch action) to calculate the shear strength of reinforced concrete beams (e.g., ACI Committee 318 [2]). In some cases, they do not even refer the procedures for estimating the shear strengths of beams submitted to reverse loadings.

The reverse loading decreases the ultimate shear strength of reinforced concrete beams and adding the steel fibers increase its capacity. It stands to reason that a concrete beam with steel fibers could sustain reverse loads comparable to the normal shear loads sustained by normal concrete beams. This paper describes experimental measurements of reinforced concrete beams with steel fibers submitted to reverse shear loading. The ultimate shear loads recorded experimentally will also be compared to semi-empirical expressions proposed by Al-Taán & Al-Feel [1], Swamy et al. [21], and Sharma [18].

2. Materials and experimental program

2.1 Test program

These experiments test concrete beams of various compressive strengths (40 MPa, 60 MPa and 80 Mpa), both with and without steel fibers, under normal and reverse loading. Thus, each compressive strength test required four different tests, for a total of twelve beams.

The beam designations consist of several terms: an initial letter "I" (their cross-sectional form), the nominal concrete compressive strength in MPa, the steel carbon content (BC for low content and AC for high content), the amount of steel fibers (zero or 30 kg of fiber per m^3 of concrete), and the type of loading (N for normal or I for reverse). Beam I-80-BC30-I, for instance, has strength of 80 MPa and steel fibers of low carbon content. The amount of fibers was 30 kgf per cubic meter, and the beam experienced reverse loading.

The cross-sectional dimensions, effective depths, and longitudinal and transverse reinforcements of the beams were nominally identical. The areas of longitudinal and shear reinforcement were designed to obtain a premature shear failure; therefore, a stirrup always yields before a longitudinal reinforcement.

The beam specimens were 1800 mm long with the span length of 1550 mm and simply supported at both ends. A point load was applied at midspan in all specimens. The shear span *a* was 775 mm and the effective depth *d* was 178 mm, so the ratio *a*/*d* was 4.12 in all cases.

The longitudinal reinforcement consisted of six steel bars with diameters of 16.0 mm: three in the top layer and three in the bottom layer (ρ_l = 3.12%). The shear reinforcement consisted of vertical stirrups with diameters of 4.2 mm, spaced 15 centimeters apart (ρ_w=3.12%). Figure [1] shows the dimensions of the beams.

Figure 1 – Dimensions of the Beams

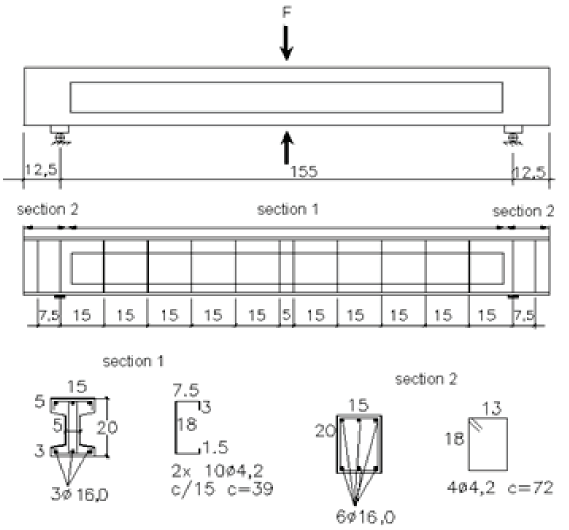
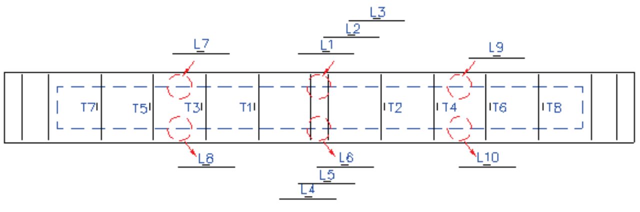


Figure 2 – Instrumentation of Beams



2.2 Test arrangment

A hydraulic jack of 500 kN capacity applied the loads through a rectangular plate attached to the beam. A load cell measured the real applied loads. In cases without reversion, only one of the chords received the load. The loads were applied through the jack with an increment of 10 kN until a shear failure occurred. For loading reversion cases, the jack was applied to both chords alternately in increments of 10 kN (i.e., 10 kN, 10 kN reversed, 20 kN, 20 kN reversed, and so on).

Electrical resistance strain gauges monitored strain in the steel. Each beam had strain gauges on eight stirrups (T1 up to T8) at middle height. Six extensometers were placed at midspan (L1 up to L6) along the longitudinal reinforcing bars, three in the top layer and three in the bottom layer. Two extensometers were also placed in the central bar, one on the top layer and one on the lower layer, placed at a distance equivalent to 1/4 of the beam span in relation to the support (L7 up to L10). Figure [2] illustrates the instrumentation of the longitudinal reinforcements and stirrups. Linear Variable Deflection Transducers (LVDT) measured out-of-plane deflections at midspan. The strain gauges, LVDTs and load cells were connected to a computerized data acquisition system and the data were taken in the range of one second during loading. For all beams, we observed and recorded the crack pattern after each load increment. The load was increased until shear failure occurred, meaning that a stirrup yielded while the longitudinal reinforcements remained intact.

2.3 Material properties

The concrete was made with Type I Portland cement. The coarse aggregates were crushed gravel with a maximum size of 19 mm and modulus of fineness (MF) of 6.23. The fine aggregates were natural river sand with a MF of 2.24. The addition of water-reducing admixture and silica fume (amount of 10% of the cement mass), improved the workability of the higher-strength concrete.

The low-carbon steel hooked fiber had length $L_f = 60$ mm, equivalent diameter $D_f = 0.8$ mm (aspect ratio $L_f/D_f = 66.7$), and a nominal tensile strength of 1115 MPa. The amount of steel fibers was 30 kgf/m^3 ($v_f = 0.4\%$) in each beam that contain them.

To better understand the behavior of the compressive strength and deformation capacity of the plain and fibrous concrete, six cylindrical specimens of each type with diameter 100 mm and height 200 mm were taken simultaneously with the preparation of the beams, permitting three independent tests of each property. The samples were covered with wet burlap and plastic foil for one week, then unwrapped and tested at 28 days old. Table [1] reports the mix designs and measured strengths of the three concretes.

Table 1 – Experimental mixtures

Mixture	Series 1	Series 2	Series 3
CEMENT (kg/m^3)	656	350	656
SILICA FUME (kg/m^3)	66	------	66
FINE AGREGATE (kg/m^3)	808	820	808
COARSE AGGREGATE (kg/m^3)	1234	1040	1234
WATER (l/m^3)	182	198	230
SUPERPLASTICIZER (l/m^3)	27.5	----	27.5
STEEL FIBERS (kgf/m^3)	0 - 30	0 - 30	0 - 30
w/c (WATER/CEMENT) (l/kgf)	0.29	0.59	0.35
$f'c$ (MPa)	82.0 - 80.1	41.2 - 40.3	60.5 - 63.1
$f't$ (MPa)	4.4 - 4.6	2,2 – 2,4	3.2 - 3.5

Based on tension coupon tests, the average modulus of elasticity, yield strength and specific yielding deformation of the longitudinal bars were 201 GPa, 573 MPa and 0.29% respectively.
The average modulus of elasticity, yield strength and specific yielding deformation of the vertical stirrups (web reinforcement) were 201 GPa, 682 MPa and 0.54% respectively. The web reinforcement ratio was 0.37%.

2.4 Shear strenght of steel fiber-reinforced concrete beams and the truss mechanism

For shear design purposes, the parallel chord truss is analogous to a web-reinforced concrete beam. First postulated by Mörsch [10], this old concept (the classical truss analogy) calls for stirrups as tension members and concrete struts running parallel to diagonal cracks, generally at 45 degrees to the beam axis. The flexural concrete compression zone and the flexural reinforcement form the top and bottom chords of the analogous pin-jointed truss and the equilibrium considerations are suffice to determine the forces in the truss. The predicted ultimate shear force V_u is equivalent to the maximum shear force V_s sustainable by the web reinforcement:

$$V_u = V_s = \rho_w f_{yw} bd \tag{1}$$

where *d* is the effective depth, *b* is the beam width, f_{yw} is the web reinforcement yield strength, and ρ_w is the steel ratio of the web reinforcement.
In experiments observing the stirrup load-stress behavior of concrete beams, Leonhardt and Walther [8] assumed that the web reinforcements bear only part of the ultimate shear load. A number of "alternative" mechanisms (aggregate interlock, longitudinal reinforcement dowel action, arch action) provide additional resistance, so the ultimate shear load should be expressed mathematically as follows:

$$V_u = V_c + V_s \tag{2}$$

where V_s is derived from the classical truss analogy and V_c includes all contributions from alternative mechanisms. In a similar vein, steel fibers contribute a third term to the equilibrium equation:

$$V_u = V_c + V_s + V_f \tag{3}$$

where V_c is the shear force resisted by alternative mechanisms in a reinforced concrete beam *without* fibers.
A fourth term, V_r, represents the negative contribution of reverse loading under identical conditions. Thus, the equilibrium condition becomes

$$V_u = V_c + V_s + V_f - V_r \tag{4}$$

Figure 3 – Detailed view of cracking in beam I80-BC30-I

for fiber-reinforced concrete beams and

$$V_u = V_c + V_s - V_r \tag{5}$$

for beams without fibers.

3. Results and discussions

3.1 Cracking

Initial flexure cracks always were formed along the bottom chord at midspan. The cracks had been regularly spaced, and their length increased when the load increased. Later, shear cracks formed near the quarter-span point. The beams eventually failed along a single shear crack.
In cases of reverse loading, two intersecting shear crack patterns were formed (Figure [3]).

3.2 Web reinforcement

All beams failed by shear and their ultimate shear loads correspond to the first load when a stirrup yielded. In all cases this occurred before any longitudinal reinforcement yielded.
Figures [4], [5], and [6] plot the shear force, V (F/2), versus stirrup stress, σ_{sw}, for each series. The stress data come from the most solicited stirrup on each beam.
Figures [7] and [8] show the same data for normally loaded and reverse loaded beams, comparing the beams of different compressive strengths.
In all cases, under small loads, the stirrup stress increases very slowly and the classical truss analogy is not relevant. The truss model is valid only after the beams begin cracking and the web reinforcement starts to tension. In that case, the

Figure 4 – Stirrup stress values for the 40 MPa beams

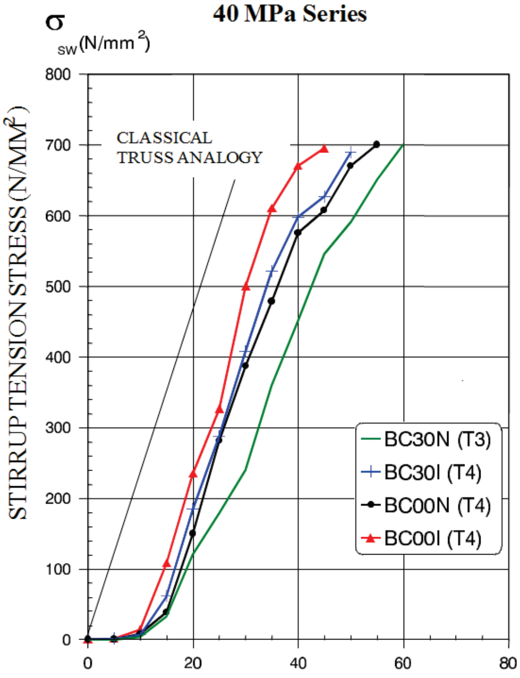


Figure 5 – Stirrup stress values for the 60 MPa beams

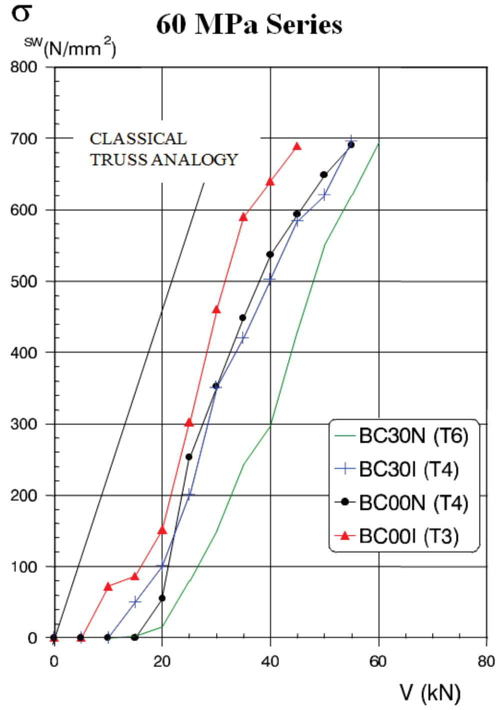


Figure 6 – Stirrup stress values for the 80 MPa beams

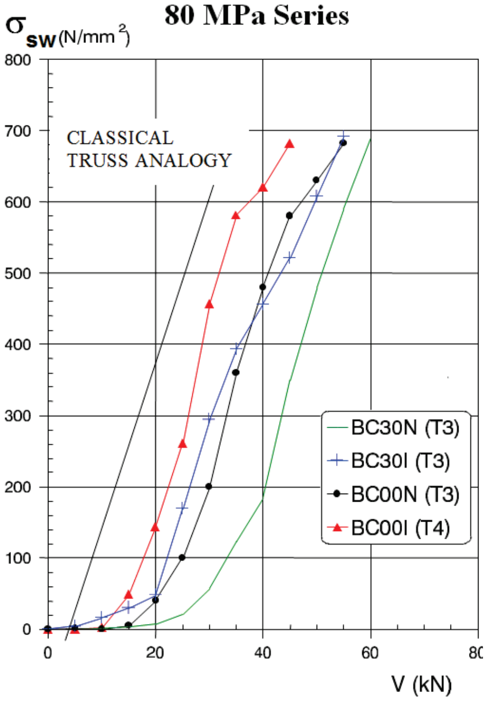
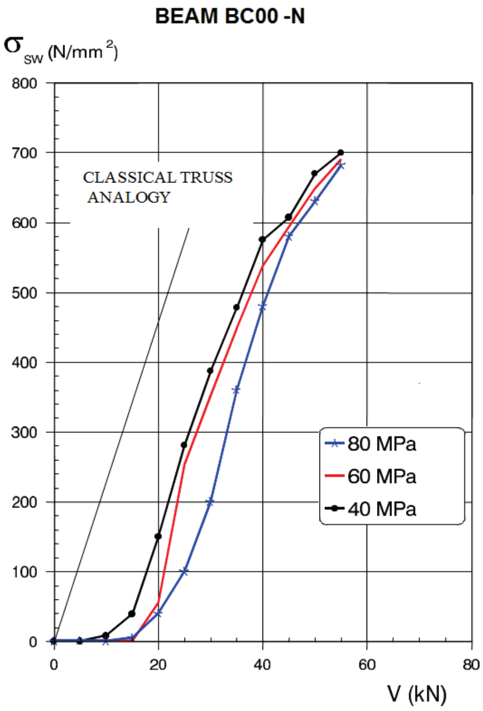


Figure 7 – Stirrup stress values for the BC00N beams



rate of increase approximately follows what is predicted by the classical truss analogy.

However, the stirrup tensions were never *higher* than the classical truss analogy prediction, even for beams subjected to reverse loadings. This fact confirms the point that some alternative mechanisms are at work even if the concrete compressive chord (arch action) and aggregate interlock are irrelevant. The longitudinal reinforcement pin effect (dowel action) is likely important.

Within each series, the type of loading and presence of fibers clearly had influenced the load-stress behavior of the beam. Figures [4], [5], and [6] fulfill expectations that the beam free of fibers subjected to reverse loading (BC00I) are closer to approximate the classical truss model than the beam free of fibers subjected to normal loading (BC00N). Furthermore, the beam with fibers subjected to normal loading (BC30N) has less similarity to the classical truss model than beam BC00N. These observations confirm that loading reversion has an unfavorable effect on the beam's ultimate shear load, while the fibers bring a favorable contribution.

Likewise, the addition of fibers restores some supporting capacity on reverse-loaded beams. Indeed, the stirrup stress values of beams with fibers subjected to reverse loading (BC30I) were similar to those observed in beams without fibers subjected to normal loading (BC00N).

Finally, the shear strength of a concrete beam subjected to reverse loading is lower than a similar beam subjected to normal loading. This decrease is important, but not large enough to match the values predicted by the classical truss analogy.

Figure [7] shows that normally loaded beams with higher compressive strengths have higher V_c contributions. Among beams subjected to reverse loading, however, this effect was not evident (Figure [8]).

Table [2] shows the ultimate shear force contributions (V_u, V_c, V_f and V_r) for each beam. V_s and V_c are calculated using equation 1 and equation 2 respectively. V_r, is the difference between beams of type “N” and type “I”. In the same way, V_f is the ultimate shear force difference between similar beams with and without fibers.

The favorable contribution of fibers is comparable to V_c in all cases. On average, V_f is 21% of V_c for beams subjected to normal loading and 26% of V_c for beams subjected to reverse loading.

The unfavorable contribution of loading inversion (V_r) is 28% of V_c for beams without fibers, and 23% of V_c for fiber-reinforced beams.

3.3 Ultimate shear strength – fiber-reinforcement concrete beams

This section compares the experimental values of V_u (=P_u/2) for beams with fibers to three expressions proposed in the literature (Al-Taán and Al-Feel [1]; Swamy et al. [20]; Sharma [17]).

The expression proposed by Al-Ta'an and Al-Feel [1] is based on a regression analysis of experimental data for 89 beams. Their result is reproduced below.

$$\nu_f = \frac{8.5}{9} k \quad \nu_f \frac{L_f}{D_f} \quad \text{(MPa)} \qquad (6)$$

where *k* is a factor reflecting the fiber's shape. For hooked fibers such as those used in the present research, Al-Ta'an and Al-Feel [1] propose the value *k* = 1.2.

Figure 7 – Stirrup stress values for the BC00N beams

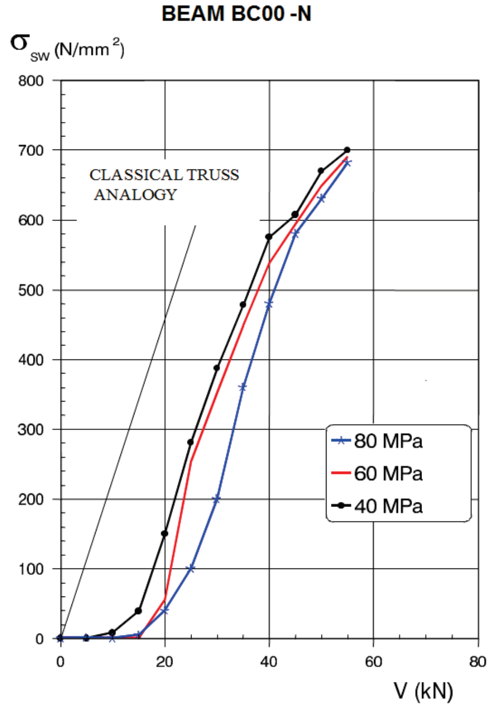


Figure 8 – Stirrup stress values for the BC00I beams

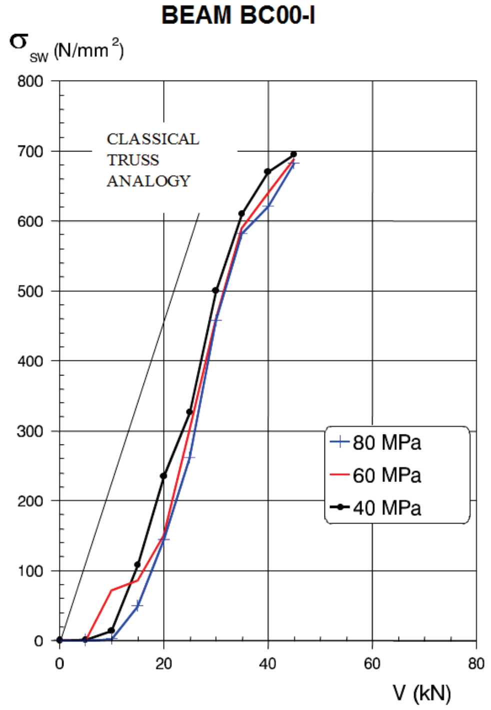


Table 2 – Experimental shear force

BEAM	V_u (kN)	V_c (kN)	$V_c - V_r$ (kN)	$V_c + V_f$ (kN)	$V_c + V_f - V_r$ (kN)	V_f (kN)	V_r (kN)
I80-BC00-N	55	33				-	-
I80-BC00-I	46		24			-	9
I80-BC30-N	61			39		6	-
I80-BC30-I	54				32	8	7
I60-BC00-N	54	32				-	-
I60-BC00-I	45		23			-	9
I60-BC30-N	60			38		6	-
I60-BC30-I	54				32	9	6
I40-BC00-N	49	27				-	-
I40-BC00I	41		19			-	8
I40-BC30-N	56			34		7	-
I40-BC30-I	48				27	7	8

Swamy et al. [21] evaluated the contribution of fibers in terms of the average fiber-matrix interfacial bond stress. Their result is

$$V_f = 0.37\ \tau\ V_f\ \frac{L_f}{D_f}\ \ (MPa) \qquad (7)$$

The value of 4.15 N/mm^2 was adopted for the parameter t in the absence of specific pullout tests on the fiber-reinforced concrete used in this investigation.

Finally, Sharma [17] derived empirical formula for the shear strength of fiber-reinforced concrete beams:

$$V_c + V_f = k'\ f_t{}'\left(\frac{d}{a}\right)^{0.25}\ \ (MPa) \qquad (8)$$

and

$$V_c = 0.166\ .\ \sqrt{f_c'} \qquad (9)$$

where κ´ is equal to 0.667 because f'_t is the indirect tensile strength determined by splitting tension tests.

Table [3] compares V_f. calculated with the three formulas proposed. The formula of Swamy et al. [21] comes closer to the experimental data. The difference between the three models is clearly significant. According to the results of table 3, the concrete compressive strength has little influence on experimental values of V_f, .Swamy´s [21] and Al-Taán and Al-Feel [1] proved these experimental results. It is interesting to note that amount of steel fibers, their aspect ratio, and their anchorage conditions were the same for all beams.

3.4 Ultimate shear strength – concrete beams subjected to reverse loading

Current design procedures (ACI Committee 318 [2]) for concrete beams subjected to reverse loading specify no contribution to the ultimate shear strength from the so-called alternative mechanisms (V_c=0). It means that beams subjected to reverse loading should be designed according classical truss analogy (V_c=0).

Figures 5 to 8 show the stirrup stress values for the beams. At no

Table 3 – Experimental and predicted results

Beam	Vf, (kN)			
	EXPERIMENTAL	PREDICTED		
		Al-Taan	Swamy	Sharma
I80-BC30N	6	2.7	3.7	6.2
I80-BC30I	8	2.7	3.7	6.2
I60-BC30N	6	2.7	3.7	3.1
I60-BC30I	9	2.7	3.7	3.1
I40-BC30N	7	2.7	3.7	0.8
I40-BC30I	7	2.7	3.7	0.8

time in these figures, the experimental stirrup tension exceed values predicted by the classical truss analogy (V_c=0). The unfavorable contribution of loading inversion (V_r) was significant (28% of V_c on average for beam without fibers and 23% for fiber-reinforced beams) but quite distant to 100% (V_c=V_r).

Thus, the current shear design procedures are very conservative for the beams tested in this study with reverse loading. It´s worth noting that all the results presented in this paper refer to the shear strength behavior of beams with a specific cross-section, 30 kg/m^3 of steel fibers, and a particular load increment.

4. Conclusions

In this paper the effectiveness of steel fibers on the shear capacity of concrete beams with normal or reverse load was checked. The main variable investigated, in addition to the effect of steel fibers and reverse load, was the influence of concrete compressive strength: 40 MPa, 60 MPa and 80 MPa.

A comparison between the experimental values of ultimate shear force and these values calculated by expressions proposed in the literature for beams with fibers showed that the formula of Swamy et al [21] comes closer to the experimental data.

According to the tests results, the concrete compressive strength has little influence on the ultimate shear force for beams with fibers. Swamy´s [20] and Al-Taán and Al-Feel [1] proved these experimental results.

For beams with reverse loading tested in this research, the current shear design procedures (V_c=0) showed very conservative. The unfavorable contribution of loading inversion (V_r) was significant (28% of V_c on average for beam without fibers and 23% for fiber-reinforced beams) but quite distant to 100% (V_c=V_r).

The results of this research showed that adding fibers can improve the shear capacity of load reverse beams. Concrete beams with steel fibers had shear strengths under reverse loading similar to the same beams loaded without fiber.

At last, it is important to note that overall more experimental research has to be done to get more information about optimizing shear behavior of load reverse beams. The effects of several variables involved in the shear behavior of concrete beams remain to be assessed, such as the longitudinal reinforcement ratio, the increment of reverse loading, the fiber content of the concrete, the type of fiber, and so on.

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