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The diagonal tension behavior of fiber reinforced concrete beams

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Abstract

This research studied the diagonal tension behavior of 16 beams reinforced with longitudinal bars and steel fibers. The variable parameters included the concrete compressive strength and the percentage of fibers (0%, 0.5%, 1.0% and 1.5% by volume). The beams were tested under static loads resulting in high diagonal tension stresses. The shear reinforcement was composed of stirrups instrumented with strain gages to detect the effect of the fibers on the strains. Research results indicate that as the fiber volume increases, the shear strength and the ductility of the beams increased, providing significantly higher shear strength than specified by the ACI-318 Code.

Keywords: Concrete; Reinforcement; Fibers; Diagonal tension; Shear; Strain; Stress; Beam

1. Introduction

The majority of experimental studies of the shear behavior of reinforced concrete beams have focused primarily on the determination of stresses at which concrete cracks, and the contributions of the concrete and stirrups to the shear strength of the beam. The application of steel fibers results in the improved ductility of reinforced concrete structural members such as beams and slabs [1,2]. Furthermore, steel fibers act as an additional shear reinforcement of concrete improving the stiffness, shear strength, shear toughness and resistance to diagonal cracking [3–6].

Fiber reinforced concrete (FRC) can be described as a composite material consisting of a concrete phase and a small portion of discrete and discontinuous fibers distributed and oriented randomly within the concrete matrix [7]. The design considerations for use of steel fibers in concrete with high and normal compressive strength are summarized in Refs. [8,9]. Combination of steel and non-metallic fibers was found to be extremely effective in FRC beams based in high-strength concrete [10].

The design criteria suggest that the stirrups must be placed to link the planes where the potential cracks are expected, however, at the high load levels this approach results in very small stirrup spacing. Therefore, an alternative reinforcement such as steel fibers would be effective in such case to resist the diagonal tension stresses. The investigation of steel fiber reinforced concrete beams with and without conventional stirrups demonstrated that the shear strength (corresponding to the first crack) had increased significantly due to the crack arrest effect of the fibers [11].

The effect of the steel fibers on the behavior of high-strength concrete beams and partially prestressed beams under high-diagonal tension stresses was investigated [12–15]. That work resulted in the analytical and empirical equations for the shear strength of these beams. The effectiveness of steel fibers to enhance the shear strength in flanged sections of beams has been reported [16]. It was concluded that the addition of fibers can effectively control the deflections, strains and rotations induced by the shear. Additional works investigated the effect of cyclic loads [17], direct shear [18] and punching shear [19,20] on the performance of FRC beams.

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2. Research significance

The present work describes the behavior of FRC beams with stirrups subjected to high shear stresses. The main objective of this study was to determine the contribution of steel fibers, used as partial replacement of stirrups. Tests on investigated FRC beams have demonstrated the advantageous effect of fibers in concrete beams subjected to high shear stresses. It was demonstrated that the load at the first crack and the ultimate strength of the beam were enhanced. The reported results can have valuable implications for the design and application of concrete elements composed of FRC.

3. Experimental program

3.1. Experimental setup

The experimental program included the test of 16 reinforced concrete beams with dimensions of $2000 \times 150 \times 250$ mm ($79 \times 6 \times 10$ in.). The beams were designed to fail in diagonal tension. All beams were reinforced with three No. 16 longitudinal bars located at an effective depth, $d = 216$ mm (8 1/2 in.), and plain wire stirrups of diameter 6.35 mm (1/4 in.). The steel fibers of 25 mm (1 in.) length were used at different volumes (V_f), 0%, 0.5%, 1.0% and 1.5%. Two "twin" beams were cast for each dosage of fiber and concrete compressive strength combination.

Fig. 1 shows the experimental setup and the locations of strain gages on two stirrups at their mid-height. The strain gages were placed at the assumed critical distance in shear, with an additional strain gage mounted on the longitudinal bars at a mid-span location. Beams were cast and vibrated in accordance with ASTM C 192 [21]. All beams were tested at 28 days by applying two concentrated loads at a distance of 500 mm (20 in.) from the supports (Fig. 1). Based on the prior experience, this type of loading provides the high shear stresses toward the extremes of the beams [22,23]. The cracks and the cracking patterns visible on the surface of the FRC beams (with the width from 0.1 mm) were detected with naked eye or magnifying glass and marked. The notations used in this work are according to ACI-318 Code [24].

3.2. Materials

The materials used in this research were portland cement type CPC 30R complying to ASTM C150. Crushed limestone aggregates were from Nuevo Leon, Mexico with a maximum size of 12.7 mm (1/2 in.) and a gradation in accordance with ASTM C 33. Fine aggregates were also crushed limestone with maximum size of 4.75 mm (ASTM sieve No. 4). Potable water was used for concrete preparation and curing. Yield strength of the longitudinal steel reinforcement bars (ASTM A615) and plain wire stirrups was 420 MPa (60 ksi) and 330 MPa (48 ksi), respectively. Steel fibers were deformed slit sheet according to ASTM A820. Fig. 2 shows the tension test results for the No. 16 bars and the plain wire.

3.3. Concrete mixture proportioning

Several concrete mixtures were tested at different W/C and different aggregate proportions following the recommendations of ACI-318 Code [24]. The final concrete mixtures and corresponding test results are presented in

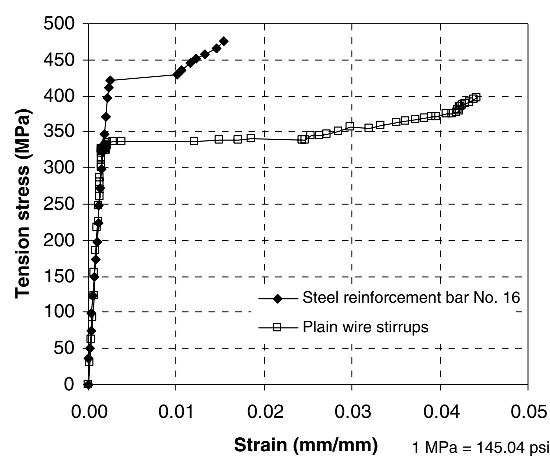

Fig. 2. Tension test results of the steel reinforcement.

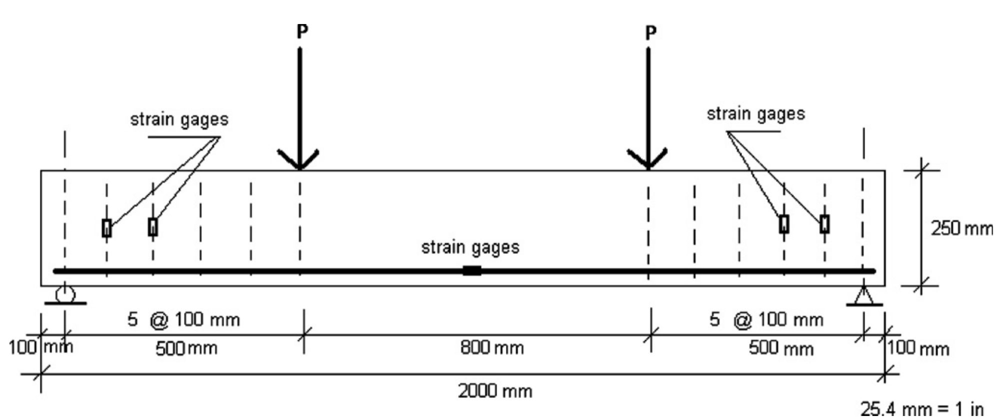

Fig. 1. Arrangement of the reinforcement and locations of the strain gages.

Table 1
Concrete mixture proportioning

Materials	Mixture proportions (kg/m)^3							
	A-0.0	A-0.5	A-1.0	A-1.5	B-0.0	B-0.5	B-1.0	B-1.5
Cement	334	334	334	334	227	227	227	227
Water	184	184	184	184	193	193	193	193
Fine aggregates	689	684	679	674	968	961	955	948
Coarse aggregates	1136	1128	1120	1112	919	913	906	900
Fibers	–	39	78	117	–	39	78	117
W/C ratio	0.55	0.55	0.55	0.55	0.85	0.85	0.85	0.85
Compressive strength, (MPa) (ksi)	36.7 (5.3)	37.2 (5.4)	36.9 (5.4)	35.8 (5.2)	18.7 (2.7)	19.7 (2.9)	18.3 (2.7)	18.8 (2.7)
Slump (mm) (in.)	150 (5.9)	130 (5.1)	100 (3.9)	80 (3.1)	160 (6.3)	110 (4.3)	120 (4.7)	60 (2.4)

1 kg/m^3 = 1.69 lb/yd^3; 1 MPa = 0.145 ksi.
Notation: A or B designates the beam group with $f'_c = 36.7$ MPa and 18.9 MPa, respectively, and the fiber volume fraction is identified by the numbers from 0.0 to 1.5.

Table 1. Totally, eight different concrete mixtures were used, half with a W/C = 0.85 and an average $f'_c = 18.9$ MPa (2.7 ksi) and another half with a W/C = 0.55 and an average $f'_c = 36.7$ MPa (5.3 ksi). The selected W/C and strength levels are common to concrete structural elements in Mexico. Therefore, the experimental variables were the fiber volume fraction and an average concrete compressive strength. Duplicate "twin" beams were cast for each experimental node.

3.4. Mixing, casting and curing of concrete

The mixing concrete was made in a 90-l (3.18 ft^3) conventional mixer. First, the fine and coarse aggregates were mixed with complete amount of the absorption water to achieve the aggregates saturated surface dry (SSD) condition. Then the cement and the design amount of water were added to the mixer; this process was followed by one minute mixing, one minute of rest and one minute of additional mixing. The fibers were randomly added during the second period of mixing. After mixing, the concrete slump was measured and concrete was cast in the steel molds and compacted with an internal electrical vibrator. Concrete was continuously cured by ponding water on the top of the molds until the age of seven days. Following this period, the beams were de-molded, sealed by water based curing compound and tested at the age of 28 days.

4. Test results and discussion

Test results of the investigated beams are shown in Table 3 and Figs. 3–5. Shear behavior of beams (i.e. the stresses in longitudinal reinforcement and stirrups) was analyzed for different fiber volume fractions at two concrete compressive strength levels.

Table 2
Nominal shear strength according to ACI 318 code for the reference beams

Beam type	f'_c (MPa)	V_c (kN)	F_y (MPa)	V_s (kN)	V_n (kN)
A	36.7	39.0	330.0	45.1	84.1
B	18.7	32.2	330.0	45.1	77.3

1 MPa = 145.04 psi; 1 kN = 224.73 lb.

Table 3
Loads (P) corresponding to crack formation and shear strength of investigated beams

Beam type	Load at first shear crack, (kN)	Load at first flexure crack, (kN)	Shear strength, (kN)
A-0.0-1	32.6	32.6	87.8
A-0.0-2	46.1	46.1	91.0
A-0.5-3	46.1	30.7	90.9
A-0.5-4	46.1	30.7	92.8
A-1.0-5	61.9	46.4	98.0
A-1.0-6	51.6	30.9	90.3
A-1.5-7	51.6	30.9	96.5
A-1.5-8	56.7	36.1	97.7
B-0.0-1	30.9	30.9	65.5
B-0.0-2	30.9	36.1	63.7
B-0.5-3	36.1	20.6	85.1
B-0.5-4	41.3	20.6	74.8
B-1.0-5	51.6	25.8	93.2
B-1.0-6	46.4	20.6	90.3
B-1.5-7	46.4	30.9	100.6
B-1.5-8	51.6	30.9	98.0

1 kN = 224.73 lb.
Notation: A or B designates the beam group with $f'_c = 36.7$ MPa and 18.9 MPa, respectively, the middle numbers from 0.0 to 1.5 are related to fiber volume fraction; and the additional number identifies each beam within the set.

4.1. Nominal shear strength

The nominal shear strength of the reference reinforced concrete beams without fibers can be obtained using the ACI 318 Code [24]. For elements exclusively under shear and flexure, the shear strength of reference beams (V_c, in kN) is

$$V_c = \left(\sqrt{f'_c} + 120\rho_w \frac{V_u d}{M_u}\right)\frac{b_w d}{7} \tag{1}$$

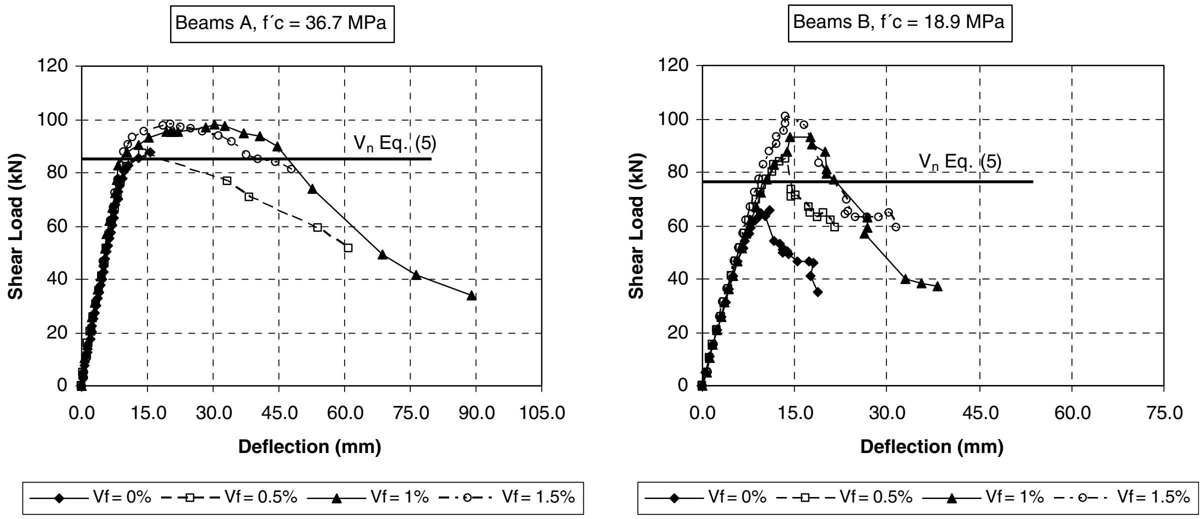

Fig. 3. Strength and ductility as a function of concrete strength and volume of fibers.

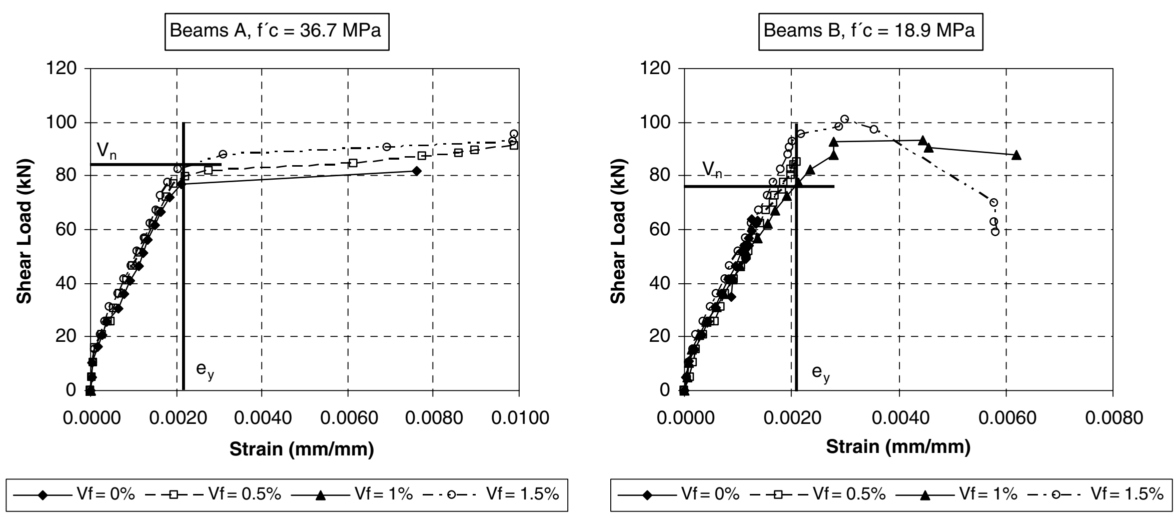

Fig. 4. Strains in the longitudinal reinforcement as a function of concrete strength and volume of fibers.

where

$$V_c \leqslant 0.3\sqrt{f'_c}b_w d \tag{2}$$

and

$$\frac{V_u d}{M_u} \leqslant 1.0 \tag{3}$$

The nominal shear strength carried by the stirrups (V_s) is defined as

$$V_s = \frac{A_v f_y d}{s} \tag{4}$$

Table 2 summarizes the results of the nominal shear strengths (V_n, in kN) of the reference beams which is

$$V_n = V_c + V_s \tag{5}$$

4.2. Effect of steel fibers

As it was expected, the incorporation of fibers improves the toughness of the composite [23]. Fig. 3 shows that FRC beams exhibit higher ductility and higher shear strength when compared to the reference beams. The group A of beams demonstrates up to two-fold improvement of the ductility vs. the group B. However, the main effect of fiber reinforcement was related to the improvement of the shear strength as the volume fraction of fibers increased. The group B beams with $V_f = 1.5\%$ showed the shear strength increase of 54% vs. the reference beams, and for the group A beams with $V_f = 1.5\%$, the increase was 12%. For the A and B beams with $V_f = 1.5\%$, the test shear strength of the FRC beams was higher than that assumed by the ACI-318 Code nominal shear strength, by 17% and 30%, respectively. In these calculations the strength reduction factor, $\phi = 0.75$ was not used for the design.

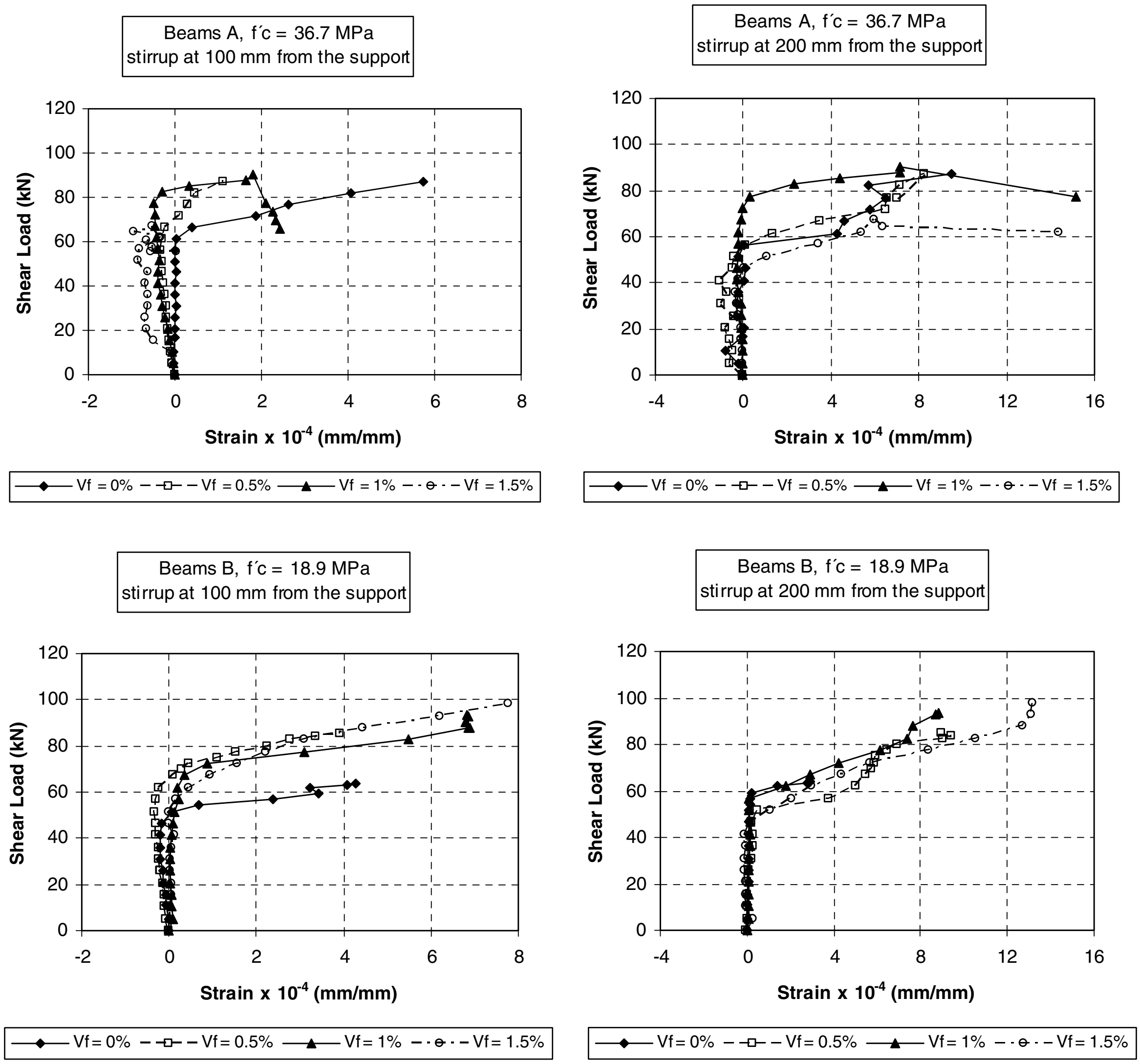

Fig. 5. Effect of the fiber volume on the strains in stirrups.

It was confirmed that the addition of fibers reduces the width of diagonal tension cracks, improving the transmission of shear load and redistribution of the stresses between the concrete matrix, fibers and stirrups. On the other hand, it can be observed that the increase in concrete compressive strength provides only 9% improvement of nominal shear strength.

It was demonstrated that the strains in the longitudinal bars increased as the V_f increased. Test results presented in Fig. 4 indicate that with rise of V_f, the shear load required to attain the yield strain of longitudinal reinforcement was also increased. This behavior was mainly observed for the beams with lower concrete strength ($f_c' = 18.9$ MPa), when the reference beams failed without yielding of the longitudinal reinforcement. The longitudinal reinforcement yielded in all beams with higher concrete strength ($f_c' = 36.7$ MPa) prior to their failure in shear, as shown in Fig. 4. This could be explained by the improved bonding between the fibers and the concrete matrix, resulting in the enhancement of ductility. In both cases, the important effect of the addition of fibers is in the improvement of ductility, as shown in Fig. 3. It can be observed that for concrete with $f_c' = 36.7$ MPa, the longitudinal reinforcement in beams with $V_f > 1.0\%$ reached the ultimate strain of three times greater than that of the reference beams (Fig. 4).

The strains in the stirrups shown in Fig. 5 indicate that prior to cracking of the beams, the stresses are relatively low, and, in most cases, are in compression. After cracking, the stresses in the stirrups increased. The effect of the fibers on corresponding strains is small, even through for beams with $f_c' = 18.9$ MPa higher shear strength was observed at the increased V_f (Fig. 5). This behavior can be attributed to the location of the strain gages, since in all tested beams the diagonal cracks did not occur at the exact position of the gage.

With increase in the volume of fibers the number of cracks also increases, yet resulting in a significantly reduced crack width (Fig. 6). The load level at first shear crack increases in all beams with increase in fiber content.

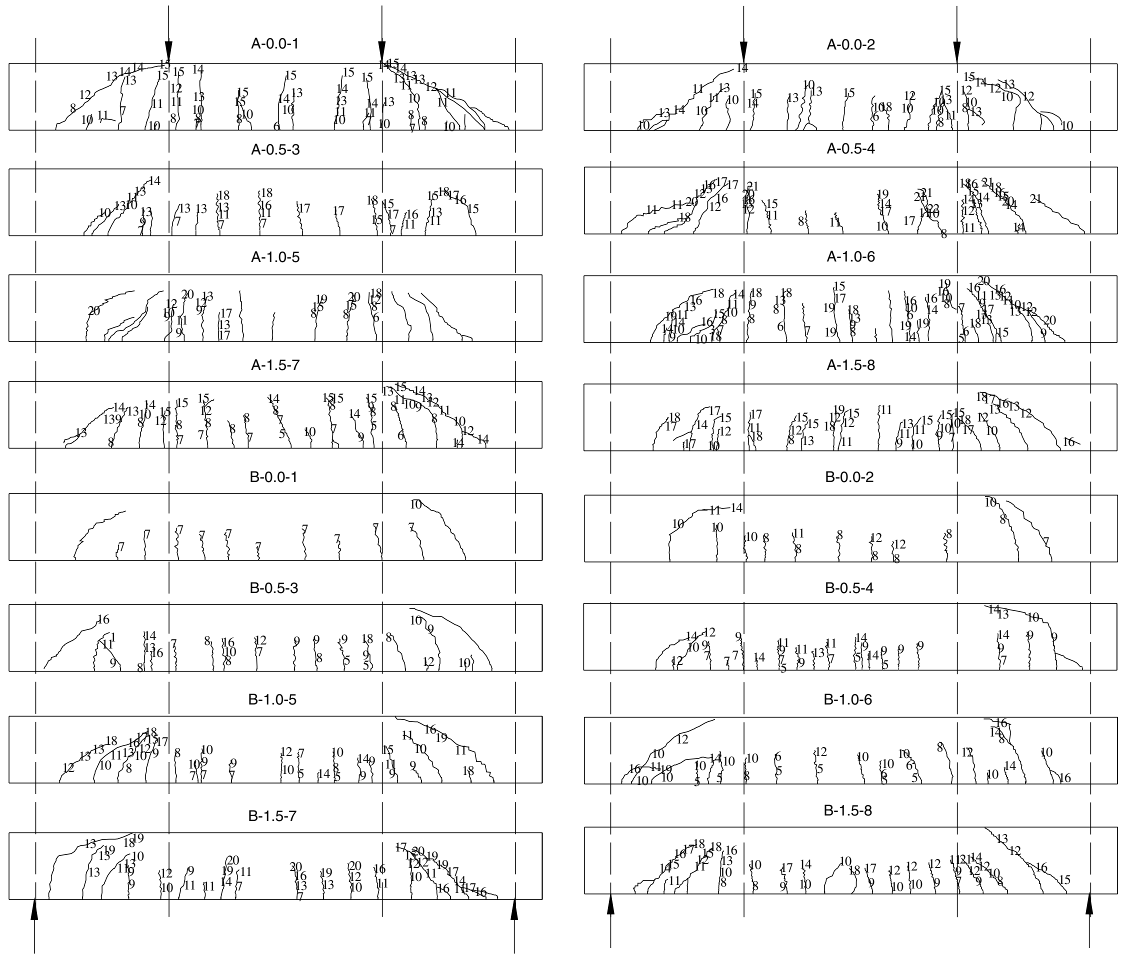

Fig. 6. Cracking patterns of the investigated beams. *Notation*: 1. The values next to the crack represent the number of loading steps (where an average load incrementing step was 5 kN). 2. The vertical dashed lines show the zone where the stirrups were located.

However, the first cracks in flexure appeared at the same load levels for all investigated beams. Therefore, the compressive strength or fiber content had little effect on this parameter. Importantly, the addition of fibers was very effective to hinder the shear crack formation; this effect is somehow improved for the composites based on concrete of higher compressive strength (Table 3).

The failure of the beams occurred in the concrete compression zone when the diagonal tension cracks propagated to the compression zone bridging the opposite zones of load application (Fig. 6).

5. Conclusions

Based on the results of the experimental work, the following conclusions were made:

1. The application of steel fibers as an additional reinforcement allows a substantial increase of the shear strength and the ductility of FRC beams vs. the reference beams.
2. The presence of fibers increases the load level at which the longitudinal reinforcement yields.
3. The main effect of the steel fibers is related to the increase of the beam's shear strength, the increase in the load level corresponding to the first shear crack, and therefore, improved shear behavior when compared with the reference beams with stirrups.
4. The shear strength of the fiber reinforced concrete beams with fiber volume of 1.5% is about 30% higher than the nominal design capacity computed by the ACI 318 Code.
5. Increased fiber volumes allow the development of multiple cracking in all investigated beams; smaller crack widths were detected for beams with higher concrete compressive strength due to denser concrete matrix, better bond to the fibers and also due to the load transfer across the cracks.

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