Fibrous Reinforcing System to Increase the Shear Resistance of High Strength Concrete

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Abstract. The available research has evidenced that discrete steel fibers can increase significantly the shear resistance of High Strength Concrete (HSC) structural elements when High Strength Fiber Reinforced Concrete (HSFRC) is designed in such way that fiber reinforcing mechanisms are optimized. In general, the increase of the concrete compressive strength is associated to an increase of its compactness, resulting benefits in terms of durability, but a strong concern emerges related to the integrity of this material, since it fails in a too brittle mode when submitted to high temperatures. To contribute for the knowledge about the benefits provided by discrete steel fibers when added to HSC applied to laminar structures, an experimental program composed of slab strips submitted to shear loading configuration was carried out. Uniaxial compression tests with cylinders of 150 mm diameter and 300 mm height, and bending tests with 600×150×150 mm^3 beams were executed to assess the compression and bending behavior of the developed HSFRC. To evaluate the influence of the percentage of fibers in the shear resistance of laminar structures, three point loading tests with slab strips of 800×170×150 mm^3 dimensions were performed. Taking the obtained experimental results, the applicability of the formulation proposed by RILEM TC 162-TDF was evaluated. Test results showed that, even with relative low dosages of steel fibers, the increment in shear resistance was significantly increased. The main obtained results in the research program are presented and discussed in this paper.

Introduction

The application of steel stirrups in concrete elements of shallow or hollow cross section or in thin wall elements, mobilize significant labor time, resulting in important financial charges. Moreover, in reinforced concrete (RC) buildings in zones of high seismic risk, the density of shear and confinement reinforcement may difficult to obtain the desired concrete quality. These are some of the reasons that justify the research effort that has been done on the possibility of replacing, totally or partially, steel stirrups by steel fibers [1-3].

Casanova [1] concluded that steel fibers may substitute significant percentages of stirrups, especially when HSC is used, once the fiber reinforcement mechanisms are more effectively mobilized. This research has also concluded that the beam depth has a remarkable influence on the fiber reinforcement performance, since the higher the beam depth was, the less efficient were the steel fibers.

In the present work, a fibrous system was selected to be an effective alternative to the steel stirrups for the shear reinforcement of HSC laminar structures, and to provide the necessary mechanisms to avoid the explosive failure mode that occurs when HSC are exposed to high temperatures. This fibrous system is composed of steel and polypropylene (PP) fibers: the first ones to provide the necessary shear resistance and energy absorption capacity to the material and the second ones to create, after have been burnt, a network of micro-channels in the concrete microstructure for the escape of the water vapor.

Experimental program

The selection of a nonmetallic type of fiber for the developed concrete was part of an experimental research program previously carried out by Lourenço et al [4]. Two kg of Duro-Fibril PP fiber (length, l_f, equal to 12 mm) per m^3 of concrete was used in the entire research program.

In a preliminary experimental program, dosages of steel fibers (Q_f) ranging from 60 to 90 kg per m^3 of concrete were adopted. Eight different compositions of HSC were developed, varying the dosage of fibers (60, 75 and 90 kg/m^3). The hooked ends steel fibers have a commercial denomination of DRAMIX® RC 80/60 BN. This fiber has l_f = 60 mm, a diameter, d_f, of 0.75 mm, an aspect ratio (l_f / d_f) of 80 and a yield stress of 1100 MPa. After the results of this experimental program, the dosage of 90 kg/m^3 was abandoned, due to economical reasons (the compositions would not be competitive) as well as for lack of concrete workability. Therefore, the six distinct HSC compositions indicated in Table 1 were selected for the present experimental program.

Series designation	**f_{cm} (MPa)**	**Steel fibers (kg/m^3)**	**PP fibers (kg/m^3)**
fcm50_NoFibres	50	0	2.0
fcm50_FC60	50	60	2.0
fcm50_FC75	50	75	2.0
fcm70_NoFibres	70	0	2.0
fcm70_FC60	70	60	2.0
fcm70_FC75	70	75	2.0

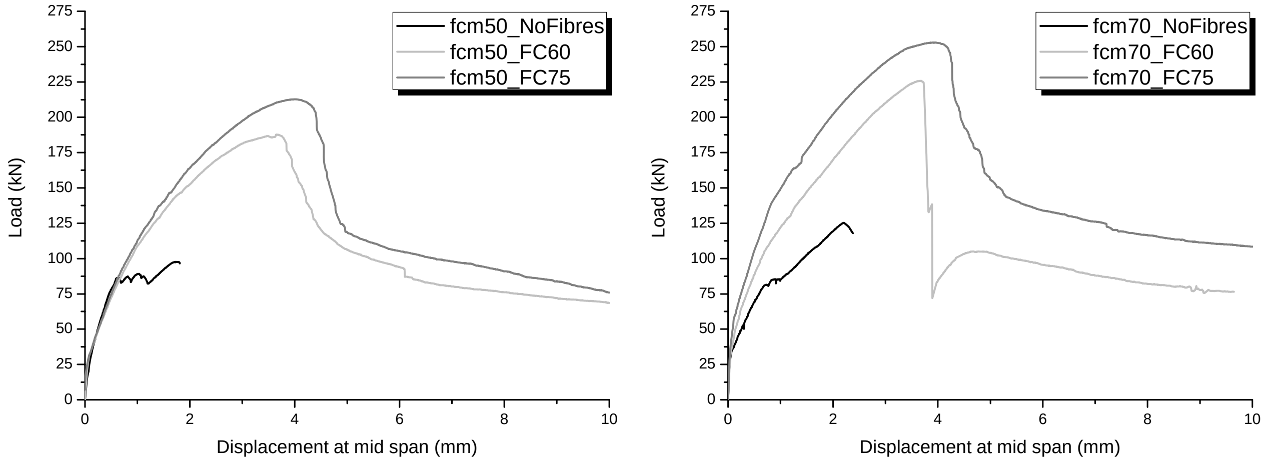
Table 1: Compositions of HSC designed to the experimental program (f_{cm} = average concrete compressive strength)

For each composition three cylinders (150 mm diameter and 300 mm height), three cubes (150×150×150 mm^3) and four prismatic specimens (600×150×150 mm^3) were casted and tested to evaluate the compression and bending behavior of the developed concrete compositions. To evaluate the influence of the fiber percentage in the shear resistance of HSC elements, three point loading tests (see Fig. 1) in slab strips (800×170×150 mm^3) were performed (distance between supports equal to 720 mm). For each composition, four slab strips were casted, two of them including ordinary longitudinal reinforcement (2Φ20 to assure shear failure) and two without ordinary reinforcement, to serve as reference. A total of twenty-four slab strips were casted and tested.

Figure 1: Three point loading tests in slab strips

Results

The load-displacement curves obtained from the three point loading tests carried out with the slab strips with ordinary longitudinal reinforcement are present in Fig. 2. Table 1 includes the force at a deflection corresponding to the serviceability limit state (L/400 with L being the span length in mm), F_{ELUt}, and the maximum force, F_{max}, registered in the tests.



a) f_{cm} = 50 MPa

b) f_{cm} = 70 MPa

Figure 2: Load-displacement curves series with ordinary longitudinal reinforcement

To estimate the contribution of fiber reinforcement at serviceability and at ultimate limit states, the values of the following ratio was determined

$$I_F = \frac{F_{Qf} - F_{ref}}{F_{ref}} \times 100 \tag{1}$$

where F_{Qf} is the force of the slab strip made by a fibrous composition and F_{ref} is the slab manufactured with the corresponding plain concrete. When these force values correspond to F_{ELUt}, it is evaluated the I_F for the serviceability limit state analysis, $I_{F(ELUt)}$, whereas the I_F for the ultimate limit state analysis, $I_{F(max)}$, is obtained when the maximum forces are used in the evaluation of (1). The obtained values for $I_{F(ELUt)}$ and $I_{F(max)}$ are indicated in Table 2, from which it can be concluded that fiber reinforcement provided a contribution for the load carrying capacity of the slabs, at deflection corresponding to the serviceability limit state analysis, ranging from 43% up to 72%, while for the maximum load the fiber reinforcement effectiveness varied from 80% up to 118%.

Series	**F_{ELUt}**			**F_{max}**		
	Q_f = 0 kg/m^3	**Q_f = 60 kg/m^3**	**Q_f = 75 kg/m^3**	**Q_f = 0 kg/m^3**	**Q_f = 60 kg/m^3**	**Q_f = 75 kg/m^3**
fcm50	97.35	146.06	154.83	97.66	187.50	212.73
fcm70	112.10	160.29	192.36	125.23	225.82	252.90

Table 1: Values for the F_{ELUt} and F_{max}

Series	**$I_{F(ELUt)}$ (%)**		**$I_{F(max)}$ (%)**	
	Q_f = 60 kg/m^3	**Q_f = 75 kg/m^3**	**Q_f = 60 kg/m^3**	**Q_f = 75 kg/m^3**
fcm50	50.04	59.05	91.99	117.84
fcm70	42.98	71.59	80.33	101.96

Table 2: Fiber reinforcement effectiveness indexes for serviceability ($I_{F(ELUt)}$) and ultimate ($I_{F(Max)}$) limit state analysis

RILEM TC 162-TDF approach

According to the formulation proposed by RILEM TC 162-TDF committee [5], the shear resistance of a concrete element reinforced with steel stirrups, steel fibers and ordinary longitudinal reinforcement is given by:

$$V_{Rd3} = V_{cd} + V_{fd} + V_{wd} \tag{2}$$

where V_{cd} represents the concrete contribution for the shear resistance:

$$V_{cd} = \left[0.12\, k \left(100\, \rho_\ell \, f_{ck} \right)^{\frac{1}{3}} + 0.15\, \sigma_{cp} \right] b_w \, d \;\; [\mathrm{N}] \tag{3}$$

$$k = 1 + \sqrt{\frac{200}{d}} \;\; (d \text{ in mm}) \text{ and } k \leq 2, \tag{4}$$

$$\rho_\ell = \frac{A_{s\ell}}{b_w \, d} \leq 2\% \tag{5}$$

with $A_{s\ell}$ being the cross section area of the tensile longitudinal reinforcement, b_w is the minimum width of the web cross section, d is the effective depth of the cross section,

$$\sigma_{cp} = \frac{N_{sd}}{A_c} \;\; [\mathrm{N/mm^2}] \tag{6}$$

where N_{sd} [N] is the axial force due to applied external load and pre(pos)-stress (compression is assumed positive) and A_c [mm^2] is the area of the cross section.

The contribution of steel fibers, V_{fd}, is determined by

$$V_{fd} = 0.7\, k_f \, k_l \, \tau_{fd} \, b_w \, d \;\; [\mathrm{N}] \tag{7}$$

where k_f is a factor taking the contribution of the flanges in a T cross sections,

$$k_f = 1 + n \left(\frac{h_f}{b_w} \right) \left(\frac{h_f}{d} \right) \leq 1.5 \tag{8}$$

with h_f [mm] and b_f [mm] being the heigh and width of the flanges, respectively,

$$n = \frac{b_f - b_w}{h_f} \leq \min(3; \; \frac{3\, b_w}{h_f}) \tag{9}$$

This contribution is simulated by τ_{fd}, that can be determined by two different parameters:

$$\tau_{fd} = 0.12\, f_{eqk,3} \;\; [\mathrm{N/mm^2}] \tag{10a}$$

or

$$\tau_{fd} = 0.12\, f_{Rk,4} \;\; [\mathrm{N/mm^2}] \tag{10b}$$

where $f_{eqk,3}$ and $f_{Rk,4}$ are the equivalent and the residual flexural tensile strength parameters determined under the recomendations of RILEM TC 162-TDF [6].

In (1), V_{wd} represents the contribution of steel stirrups or inclined bars,

$$V_{wd} = \frac{A_{sw}}{s} 0.9\, d \, f_{ywd} \left(1 + \cot g\alpha \right) \sin\alpha \;\; [\mathrm{N}] \tag{11}$$

where A_{sw} is the cross section area of the arms of the steel stirrup, s is the distance between consecutive stirrups, f_{ydw} is the design yield stress of the stirrup and α is the inclination of the shear failure crack (assumed 45°). In the present experimental program $V_{wd} = 0$.

According to this formulation, the contribution of steel fibers for the concrete shear resistance was evaluated. The obtained values are included in Table 3.

Series	*fcm* (kN)	*fck* (kN)	*Vcd* (kN)	$\tau_{fd,1}$ [1] (MPa)	$\tau_{fd,2}$ [2] (MPa)	V_{fd} [1] (kN)	V_{fd} [2] (kN)	V_{Rd} [1] (kN)	V_{Rd} [2] (kN)	SF,1 [3]	SF,2 [3]
fcm50_NoFibres	41.74	33.74	26.35	-	-	-	-	26.35	-	1.85	-
fcm50_FC60	46.58	38.58	27.56	1.06	0.92	15.19	13.11	42.76	40.67	2.20	2.31
fcm50_FC75	48.10	40.10	27.92	1.42	1.24	20.34	17.65	48.25	45.57	2.21	2.34
fcm70_ NoFibres	66.39	58.39	31.64	-	-	-	-	31.64	-	1.98	-
Fcm70_FC60	65.73	57.73	31.52	1.47	1.25	21.02	17.81	52.44	49.33	2.14	2.28
Fcm70_FC75	66.08	58.08	31.59	1.71	1.55	24.39	22.13	55.98	53.72	2.25	2.35

Considering $\tau_{fd} = 0.12 f_{eqk,3}$ [N/mm^2]; (2) Considering $\tau_{fd} = 0.12 f_{Rk,4}$ [N/mm^2]; (3) Ratio between V_{exp} and $V_{Rd(1)}$ (or $V_{Rd(2)}$).

Table 3: Contribution of steel fibers to the concrete shear resistance

Conclusions

According to the Standard Method proposed by RILEM TC 126 – TDF, steel fibers present a significant contribution to the increase of shear resistance of laminar structures: the smaller value of the safety factor in series reinforced with fibers was 2.14, which represents an increase of 114% in the shear resistance.

A fiber dosage of 60 kg of steel fibers per m^3 of concrete allowed a remarkable contribution for the shear resistance of high strength concrete laminate structures, proving that relative small fiber dosages can replace, partially or totally, conventional shear reinforcement in this type of structures.

All series reinforced with steel fibers showed high ductility and load carrying capacity in the post-cracking phase, revealing that this type of reinforcement is effective for both serviceability and ultimate limit state analysis.

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