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Shear resistance of concrete reinforced with ultra-high strength steel fibres

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Abstract

In order to evaluate the performance of high strength concrete reinforced with Dramix 5D 65/60 BG fibres, with non-deformable hook and ultra-high tensile strength, 24 beams were subjected to shear, with different fibre content (0, 15, 30 and 50 kg/m^3), with and without stirrups in the shear span. In a second test campaign, 18 of those beams were tested again in the opposite end, with a variable shear span/effective depth (*a*/*d*) ratio in order to evaluate the influence of this parameter in the shear crack pattern and shear resistance. A probabilistic approach was followed to derive the corresponding design value of the shear strength (a procedure herein named by Design Assisted by Testing, DAT), which was then compared with the design shear strength determined according to recommendations of RILEM, EHE and FIB. Test results of both campaigns showed a significant increase in shear strength in relation to beams without fibres. Besides that, the design values of the shear strength derived from test results (DAT) were considerably higher than the design shear resistance provided by design codes.

Keywords: Fibre reinforced concrete; shear resistance; experimental analysis.

1. Introduction*

The development of new guidelines and normative recommendations defining the bases for structural design with fibre reinforced concrete (FRC), as well as the evolution of fibres in terms of material properties and geometric characteristics (able to provide improved structural performance), constitute a great opportunity to extend the use of steel fibre reinforced concrete (SFRC) beyond its traditional applications.

The total or partial replacement of stirrups by steel fibres in concrete beams allows reducing the time spent in the preparation and execution stages, and to simplify the arrangement of the reinforcement in beams with high steel density. However, this kind of solution still lacks confidence from designers and contractors.

Several studies conducted over the last years showed the fibres' capacity of enhancing the shear strength of concrete beams, with or without stirrups, by increasing the crack bridging stresses across the critical shear cracks, thereby controlling their opening and allowing the occurrence of smeared instead of localized cracks [1-6]. One of the parameters that strongly influences the behaviour of FRC subjected to shear is the type of fibres used in the concrete mix. Furlan and Hanai [5] tested steel and polypropylene FRC beams in shear and noted that steel fibres are more effective due to its higher modulus of elasticity. Cuenca *et al.* [1] studied the shear behaviour of self-compacting SFRC beams with varying concrete compressive strengths and types of fibres and concluded that the later substantially affects the shear behaviour, even if design code formulas indicate similar contributions. According to Ferreira [7], even similar fibres with the same

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commercial designation but from different producers may have different performance in the residual tensile behaviour of the concrete.

This work evaluates the shear performance of 140×260×2200 mm beams with high strength concrete reinforced with Dramix 5D 65-60 BG [8]. With this type of fibres, the pull out mechanism that determines the residual tensile strength of the SFRC is substituted by a mechanism where the fibre is firmly hooked to the matrix and the residual tensile strength is governed by the fibre elongation. The main experimental findings are discussed and compared with the proposals of design code recommendations [9,10,11].

2. Experimental Programme

Twenty four beams were cast with high strength concrete reinforced with different dosages of fibres (0, 15, 30 and 50 kg/m^3). The following control tests were made at 28 days: compressive strength, f_c [12], Young modulus, E_c [13], tensile splitting strength, $f_{ct,sp}$ [14], direct tension strength, f_{ct} [15], tensile flexural strength, $f_{ct,fl}$ [16] and residual flexural strength, f_L, f_{R1}, f_{R2}, f_{R3} and f_{R4} [17]. The average values for the concrete mechanical properties are summarized in Table 1 (the subscript *m* stands for average value).

Table 1. Concrete properties.

Mixture	*A* (0 kg/m^3)	*B* (15 kg/m^3)	*C* (30 kg/m^3)	*D* (50 kg/m^3)
f_L (N/mm^2)	-	7.53	7.42	7.83
f_{R1} (N/mm^2)	-	3.04	6.21	11.15
f_{R2} (N/mm^2)	-	3.78	8.21	12.87
f_{R3} (N/mm^2)	-	4.11	8.36	10.51
f_{R4} (N/mm^2)	-	4.03	7.76	9.99
$f_{ctm,fl}$ (N/mm^2)	7.20			
$f_{ctm,sp}$ (N/mm^2)	3.80	5.35	5.60	6.30
f_{cm} (N/mm^2)	77.1			
f_{ctm} (N/mm^2)	4.7			
E_{cm} (N/mm^2)	43375			

The flexural reinforcement, designed to avoid bending failure, is the same for all beams and consists in four 20 mm steel bars. The stirrups and the top longitudinal reinforcement are made with 6 and 10 mm bars, respectively. In order to assess the shear strength of beams without stirrups in the shear span, half the beams tested in campaign 1 lack the dashed stirrups represented in Fig. 1. Table 2 shows the main properties of the employed steel bars (average values). In the first test campaign, 24 beams were subjected to a point load with an *a*/*d* ratio equal to 2.7 (Fig. 1). Each configuration was tested thrice and is labelled with 2 characters: *1* or *2* for beams with or without stirrups in the first campaign's shear span, respectively, and a letter depending on the fibre content (*A*, *B*, *C* or *D* for fibre contents of 0, 15, 30 or 50 kg/m^3, respectively).

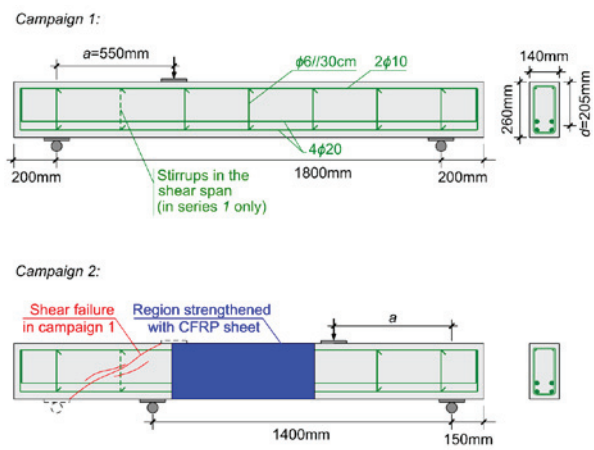

Fig. 1. Specimen's geometry and test layout in campaigns 1 and 2.

Table 2. Steel properties.

Property/Diameter	6 mm	10 mm	20 mm
Yield stress (N/mm^2)	377.4	531.7	544.1
Tensile strength (N/mm^2)	455.3	597.9	643.2

Some of the beams tested in the first campaign were tested again (campaign 2) in the opposite end, with a variable distance *a* between the applied load and the support axis (Fig. 1). This distance was set to vary the parameter *a*/*d* between 2.7 (the same as in campaign 1), 3.0 and 3.3. Note that all the beams have stirrups in the second campaign's shear span, as shown in Fig. 1. Results from campaign 2 are labelled with *.

In order to avoid failure in the opposite end, which was severely cracked due to the first test campaign, this segment was strengthened with two sheets of carbon fibre (having a fibre weight of 400 g/m^2 each, in the main direction). The concrete age at the time of the tests was 31±3 days for campaign 1 and ~18 months for campaign 2. The tests were conducted in the facilities of the university laboratory LEMC.

3. Experimental Results

Table 3 shows the experimental shear strength, V_R, for all the tested beams. Beam *1C*#1 test result is not available due to an error in the acquisition system during the experiment. The tests demonstrated the fibres' capacity to control the opening of the critical