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

José Gomes[a], Carlos Sousa[b, *], Mário Pimentel[b], Ana Maria Proença[a], A. Serra Neves[b]

[a]LEMC, Faculty of Engineering (FEUP), University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
[b]CONSTRUCT-LABEST, Faculty of Engineering (FEUP), University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal

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

* Corresponding author.
E-mail address: cfsousa@fe.up.pt (C. Sousa)

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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).

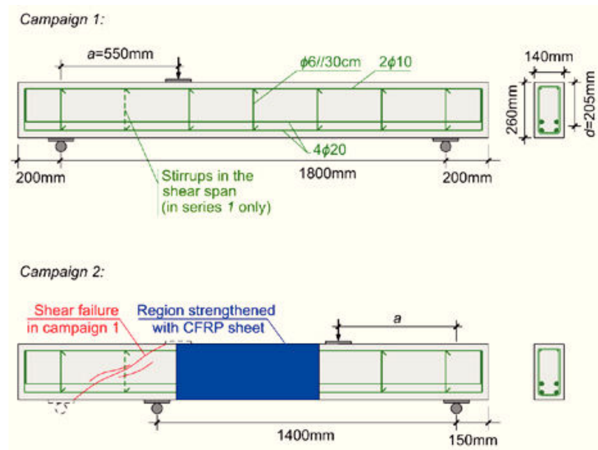

Fig. 1. Specimen's geometry and test layout in campaigns 1 and 2.

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 shear crack, which led to a considerable improvement of the beam ductility. This fact contributed to a significant rise in the shear strength for increasing fibre dosages.

Table 3. Shear resistance for all the tested beams.

1: Beams with stirrups	V_R (kN)	*a*/*d*	2: Beam without stirrups	V_R (kN)	*a*/*d*
Mixture *A* (without fibres)					
1A#1	138.2	2.7	*2A*#1	109.3	2.7
1A#2	140.0	2.7	*2A*#2	97.2	2.7
1A#3	135.3	2.7	*2A*#3	118.2	2.7
1A#1*	118.0	2.7	Average	108.2 (CV:10%)	
1A#2*	133.5	2.7			
2A#1*	144.7	3.0			
2A#2*	123.3	3.3			
2A#3*	110.0	3.3			
Average	130.4 (CV: 9%)				
Mixture *B* (15 kg/m^3)					
1B#1	127.0	2.7	*2B*#1	126.0	2.7
1B#2	137.6	2.7	*2B*#2	159.8	2.7
1B#3	146.6	2.7	*2B*#3	153.9	2.7
1B#1*	170.6	2.7	Average	146.6 (CV:12%)	
1B#2*	165.3	2.7			
2B#1*	175.9	3.0			
2B#2*	149.6	3.3			
2B#3*	149.2	3.3			
Average	152.7 (CV:11%)				
Mixture *C* (30 kg/m^3)					
1C#1	n.a.	2.7	*2C*#1	145.5	2.7
1C#2	172.4	2.7	*2C*#2	143.8	2.7
1C#3	185.4	2.7	*2C*#3	141.0	2.7
1C#1*	153.3	3.3	Average	143.4 (CV:2%)	
1C#2*	175.3	3.3			
2C#1*	154.1	3.3			
Average	168.1 (CV:8%)				
Mixture *D* (50 kg/m^3)					
1D#1	200.1	2.7	*2D*#1	176.8	2.7
1D#2	192.4	2.7	*2D*#2	176.8	2.7
1D#3	201.4	2.7	*2D*#3	180.1	2.7
1D#1*	203.3	2.7	Average	177.9 (CV:1%)	
1D#2*	236.4	2.7			
1D#3*	194.4	3.0			
2D#1*	197.4	3.0			
2D#3*	217.7	3.0			
Average	205.4 (CV:7%)				

As regards the beams with stirrups (series *1*), the adoption of 15, 30 and 50 kg/m^3 of fibres resulted in an increment of shear strength of 17.1, 28.9 and 57.5%, respectively, compared to beams without fibres. For beams without stirrups (series *2*), the respective increase was more significant (35.5, 32.5 and 64.4%).

The difference between the average shear strength of beams from series *1* and *2* ranged between 22.2 kN (mixture *A*) and 27.5 kN (mixture *D*), which corresponds to the expected contribution of the stirrups to the shear strength, the exception occurred for mixture *B* (with a difference of only 6.1 kN). The experimental results in Table 3 show that the shear strength of beams *1B*#1 and *1B*#2 was much higher in campaign 2 than in campaign 1, with the same test conditions, and that the shear strength of beams *2B*#2 and *2B*#3 was even higher in campaign 1, without stirrups in the shear span, than in the second campaign, with stirrups. These results may be justified with an uneven distribution of fibres in the beam or a less favourable orientation of fibres in the shear span in some tests.

For the others mixtures, the average shear resistance obtained in the second test campaign didn't change significantly relatively to the first one. However, it was observed that the shear strength is slightly reduced in tests performed with an *a*/*d* ratio of 3.3.

The development of the shear crack pattern in beams without fibres, regardless of the ratio *a*/*d*, mainly consists in the emergence of a crack in the middle of the web that extends towards the nearest support and load application point. The crack opens as the load increases. In Fig. 2, where the shear crack pattern is shown for representative beams, one can see that, in SFRC beams, the deformation is not localized in a single crack, owing to the fibres capacity to transmit tensile stresses across the cracks. The number of cracks tends to increase for higher fibre contents.

4. Prediction of Shear Strength

Fig. 3 presents the average and the design value derived from the test results, for all the test series. The design value (labelled with DAT as justified before) was derived according to the proposals of the EN 1990 [18], considering a resistance sensitivity factor $\alpha_R = 0.8$, a target reliability index $\beta = 3.8$, a normal distribution of the studied variable, and assuming a known coefficient of variation, CV, equal to 12% (a conservative estimate based on the available test results). In that figure, the test results are compared with the design shear strength values recommended by RILEM [9], EHE [10] and *fib* [11]. These results were calculated considering a characteristic concrete compressive strength of 70 MPa and class S235 steel for stirrups. The characteristic residual flexural strength values were determined based on the bending test results, considering a known variation of the average equal to 25%, as admitted by the EN 14845-2 [19]. A detailed calculation of the design shear strength according to the design codes can be found in [6].

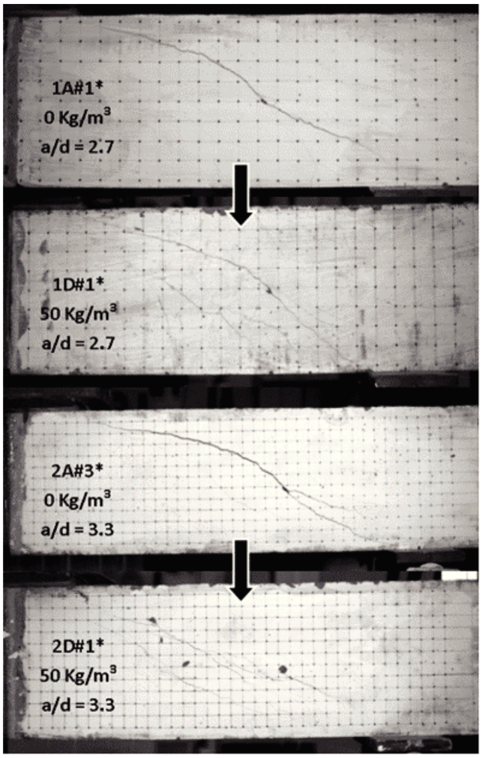

Fig. 2. Shear crack pattern at failure.

For all test series, the average experimental shear strength was considerable higher than the resistance estimates provided by design codes. The ratio between that average experimental strength and the design code values ranged between 2.6 and 3.2 (RILEM), 2.8 and 3.8 (EHE) and between 2.3 and 3.0 (Model Code 2010).
Besides that, the design value derived from the experimental strength values (DAT) is also considerably higher than the code recommendations, which means that the code provisions are on the safe side, but may be too conservative for the specimens and materials considered in the present study. This conservatism is accentuated by the use of high strength concrete and a high rate of longitudinal reinforcement. An upper limit for f_c, lower than the value considered in the present work, is imposed by EHE [10] and *fib* [11]. Besides that, an upper limit of 0.02 is set, in the adopted codes, for the reinforcement ratio, a value which is exceeded in the present tests.

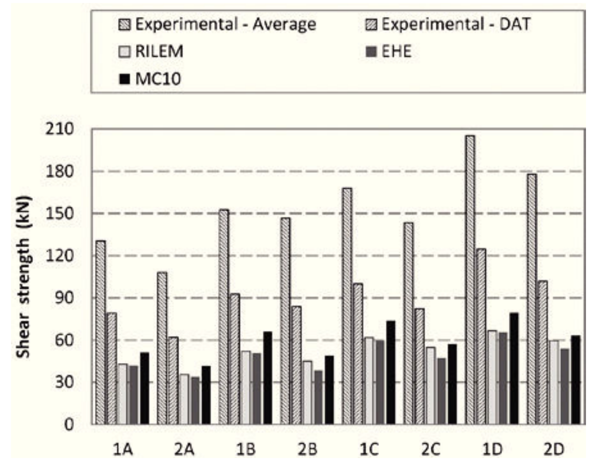

Fig. 3. Average experimental results in the first and second test campaign and shear strength based on design codes.

5. Conclusions

The experimental tests performed in this study have shown the capacity of Dramix 5D 65/60 BG fibres, combined with high strength concrete, to control the opening of the critical shear crack. A significant increase in the shear strength was obtained for increasing fibre dosages.
Besides that, in FRC beams, the deformation was not localized in a single crack, which led to a considerable improvement of the beam ductility.
By comparing the experimental results for beams with or without stirrups, it was found that the difference was compatible with the estimated beneficial contribution provided by the stirrups only.
As expected, the average experimental shear strength was considerably higher than the resistance estimates provided by design codes (RILEM, EHE and *fib*), for all the test series. By comparing the code recommendations with the design value derived from the experimental strength values, it was concluded that the code provisions are on the safe side, but are too conservative for the specimens and materials considered in the present study. This conservatism is accentuated by the use of high strength concrete and a high rate of longitudinal reinforcement.

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