

MULTIDIRECTIONAL DOUBLE PUNCH TEST TO ASSESS THE POST-CRACKING BEHAVIOUR OF FRC

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ABSTRACT

Several authors have shown the direct influence of the orientation of the fibres on the residual strength of the material. From a design-oriented perspective, the anisotropy due to the dispersion and orientation of fibres has to be taken into account when characterizing the mechanical behaviour of the material. However, the wide variety of tests currently used for the characterization of fibre reinforced concrete (FRC) only allow a unidirectional characterization (without considering the orientation of the fibres in the matrix). In order to overcome this drawback, a complete characterization of the fibres orientation together with its structural contribution in the cracked section is required. Considering the above, this paper proposes the use of the double punch test on cubic samples (so called multidirectional double punching test or MDPT test) as an alternative to conventional characterization tests. Due to the specimen shape in a single procedure an estimation of the fibre orientation efficiency can be obtained, establishing a link between the mechanical properties of FRC with the fibre orientation. Thereby, this paper represents a meaningful contribution to provide a step towards the development of a rational and design-oriented constitutive model for real-scale structures.

Keywords: Multidirectional Double Punch Test, Fiber reinforced concrete, Characterization

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1. INTRODUCTION

Several authors have shown the direct influence that the orientation and distribution of the fibers have on the residual strength of the material [1-3]. The anisotropic orientation of fibres in the hardened-state is the final result of the different stages (fresh-state, the concrete pouring, the geometry of the formwork, the type of vibration and the production method) that FRC passes through from mixing to hardening [4, 5].

For this reason, authors such di Prisco et al. [6], claim that in a design oriented perspective, the strong anisotropy due to the dispersion and orientation of fibres has to be suitably taken into account when characterizing the mechanical behaviour of the material. However, all the design recommendations and codes [7-11] for the FRC are based on an inverse approach and do not consider the dispersion and orientation of the fibers. In fact, these recommendations and codes retrieve the constitutive equations from the results of a unidirectional characterization test, which in a way means adopting the common and erroneous assumption of isotropy, that is, the fibers are oriented evenly in all directions. This approach leads to an apparent inconsistency in the design of real structures, since characterization test specimens are not representative of the real fibre orientation in the structure.

In order to overcome this drawback, a complete characterization of the fibers distribution and orientation together with its structural contribution in the cracked section is required. Considering the above, this paper presents the use of the double punch test on cubic samples (multidirectional double punching test or MDPT test) as an alternative to the conventional characterization tests [12]. Furthermore, the shape and size of the specimen allows obtaining information regarding the fibre orientation indirectly from the behaviour of the material.

2. DESCRIPTION OF THE MDPT CHARACTERIZATION TEST

The MDPT is an indirect tensile test developed by Pujadas et al. [12] to assess the toughness and residual tensile strength of FRC considering the distribution and orientation of fibers. In this test two steel cylindrical punches arranged concentrically above and below a FRC cubic specimen (with 150 mm of edge) transmit the load applied by the plates of the press that approach each other at a constant relative rate (Figure 1a). The diameter of the punches is 1/4 the diameter of the inscribed cylinder (37.5 mm) and its height 24 mm. Unlike the Barcelona test [13], in the MDPT the control is not performed by the TCOD chain or circumferential extensometer (due to the cubic geometry of the specimen, see Figure 1b). Instead the test control is performed by the position of the loading plate [14]. The rest of the test parameters are the ones defined in the Barcelona test [15].

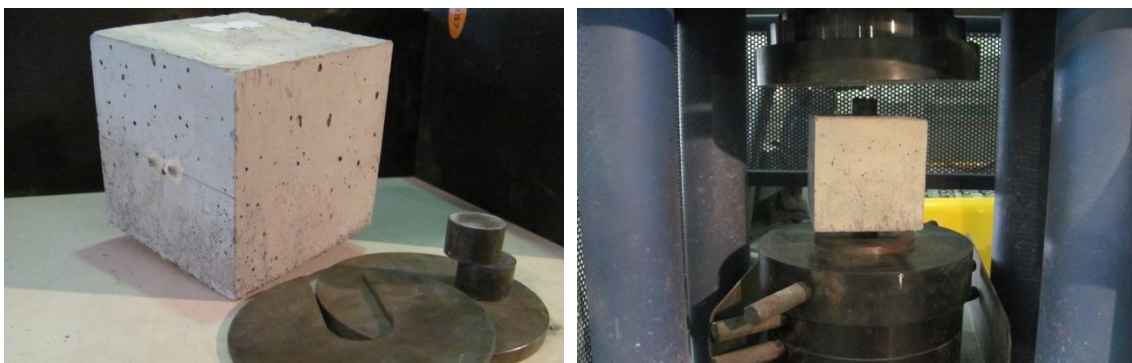


Figure 1. a) Dimensions and b) test set up of the multidirectional (MDPT)

During the test, the specimen undergoes three different phases depending on its integrity and on the resistant mechanism. The Stage 1 (Figure 2a) coincides with the initial application of load. The radial internal stress generated is resisted by the concrete matrix that presents no major cracks. Once the stress

reaches the tensile strength of the material, the specimen enters Stage 2. The upper and lower wedges are abruptly formed. According to several authors, these wedges present a conical shape with a diameter equal to that of the punches used in the test [13-17].

Between 2 and 4 major cracks appear, dividing the specimen in parts that are kept together by the fibres bridging the cracks (Figure 2b). As the cracks stabilize, the Stage 3 begins, following a kinematic mechanism that involves sliding between the conical wedge and the fragmented specimen, as illustrated in Figure 2c.

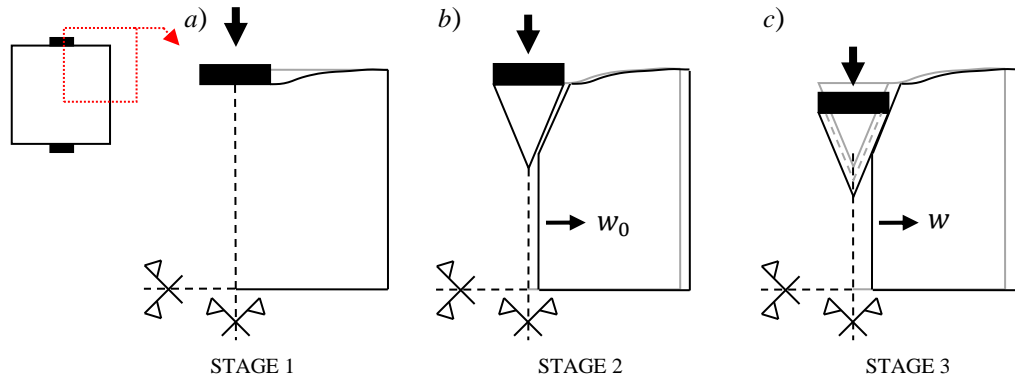


Figure 2. Stages of the MDPT test: a) stage 1; b) stage 2 and c) stage 3

During this stage the debonding and pull-out of the fibres dissipate more energy, which leads to a significant increase in toughness [18]. The alignment of the fibres according to the generated stresses (in the perpendicular plane to the loading direction) improves the post-cracking response due to an increased number of effective fibers crossing the crack and an improved pull-out behavior of those fibers with low angles of inclination in relation to the cracking plane.

Based on this principle and considering that the post-cracking residual strength is proportional to the average orientation of the fibers [4, 19], three different post-cracking behaviors (curves F- δ) associated with three loading directions may be obtained.

3. EXPERIMENTAL PROGRAM

3.1. Materials and mixtures

Taking into account that the post-cracking response of FRC is significantly influenced by the main characteristics of its components, different fiber types and contents should be analyzed. In order to assure a complete and balanced validation of the test, a wide range of FRC in terms of fibre type and fibre content was considered.

This work investigated different steel and plastic fiber reinforced concrete (SFRC and PFRC, respectively). Two different fibers macrofibers plastics (PF), and Dramix® RC80/50BN with circular cross-section and hooked ends (SF). Additional characteristics of this fibre are summarized in Table 1.

Table 1. Characteristics of the fibres (data provided by the manufacturer)

		PF	SF
Length (L)	[mm]	48	50
Diameter (d)	[mm]	-	0.62
Aspect ratio (L/d)	[-]	-	83
Tensile strength (f_f)	[MPa]	550	1270
Modulus of elasticity (E)	[GPa]	10	210
Number of fibres per kg	[fibres]	>35000	8100

In Table 2 the dosages used in this experimental campaign are defined (designated with the code: *PF/S1*, *PF/S2*, *PF/S3*, *SPF/S1* and *SF/S2*).

Table 2. Composition of FRC mixtures (in kg/m³)

		<i>PFRC</i>			<i>SFRC</i>	
<i>Material</i>	<i>Characteristics</i>	<i>PF/S1</i>	<i>PF/S2</i>	<i>PF/S2</i>	<i>SF/S1</i>	<i>SF/S2</i>
Gravel (6/15 mm)	Granite	520	520	520	520	520
Gravel (2,5/6 mm)	Granite	400	400	400	400	400
Sand (0/3 mm)	Granite	500	500	510	510	510
Cement	CEM I 52,5 R	400	400	350	350	350
Filler	Marble dust	260	260	300	300	300
Water	-	170	170	178	178	178
Superplasticizer	Adva® Flow 400	12	12	12	12	12
Fibres	Table 1	5	7	9	40	60

The average results at 28 days for the compressive strength (f_{cm}) and modulus of elasticity (E_{cm}) of each batch are presented in Table 3 as well as the coefficient of variations (CV). The table also shows the limit of proportionality (f_L) and the residual flexural tensile strengths (f_{R1} , f_{R2} , f_{R3} and f_{R4}) corresponding to the CMOD of 0.05 mm, 0.50 mm, 1.50 mm, 2.50 mm and 3.50 mm, respectively.

Table 3. Characterization of the FRC mixtures (f_{cm} , E_{cm} , f_L and f_{Ri})

	<i>PFRC</i>						<i>SFRC</i>			
	<i>PF/S1</i>		<i>PF/S2</i>		<i>PF/S3</i>		<i>SF/S1</i>		<i>SF/S2</i>	
	<i>Media</i> [MPa]	<i>CV</i> %	<i>Media</i> [MPa]	<i>CV</i> %	<i>Media</i> [MPa]	<i>CV</i> %	<i>Media</i> [MPa]	<i>CV</i> %	<i>Media</i> [MPa]	<i>CV</i> %
E_{cm}	31150	1.69	31930	1.61	32000	0.74	24300	1.65	31599	1.09
f_{cm}	52.15	1.52	54.64	0.82	46.40	2.44	37.87	1.09	54.30	1.51
f_L	4.38	0.71	5.14	8.71	4.82	7.71	3.73	8.57	3.72	-
$f_{R,1}$	1.82	13.22	3.59	9.20	3.56	8.47	4.62	12.15	6.40	-
$f_{R,2}$	2.01	9.36	4.66	7.05	4.70	6.05	5.09	13.77	6.12	-
$f_{R,3}$	2.11	8.72	5.14	6.50	5.19	4.81	5.10	15.91	6.24	-
$f_{R,4}$	2.08	10.75	5.17	6.43	5.23	5.17	4.87	14.08	6.47	-

For each of the five batches, three types of cubic specimens (150 x 150 x 150 mm) were tested in this experimental program: (1) cubic specimens casted in cubic moulds (CUB), (2) cubic samples cut from prismatic beams at 150 mm of the edge of the beam (CUT1) and (3) cubic samples obtained also from prismatic beams by cutting at 75 mm and 225 mm from the edge of the beam (CUT2).

For this study, the z axis corresponds to the casting direction and the x axis, in the case of the cubic samples, corresponds to the larger dimension of the beam. The analysis of the results is completed with 6 casted cylindrical specimens (150 x \varnothing = 150 mm) for the Barcelona test (BCN), according to [15].

3.2. Test procedure

The test procedure for the MDPT is the same as for the Barcelona test [15], previously described. For the experimental purposes of this paper, the test was considered completed when the piston displacement is at least 4 mm after the cracking of the specimen. The use of a cubic specimen allows three different loading conditions (directions X, Y and Z axis), activating different groups of fibers in each case. Thereby, a different toughness and residual tensile strength may be obtained in each loading direction (see Fig. 3). Two specimens of each series and types were tested in each of the X, Y and Z axes.

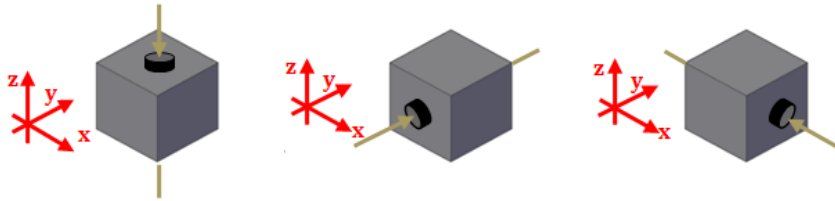


Figure 3. Scheme of the MDPT methodology [12]

4. ANALYSIS OF THE RESULTS

4.1. Influence of the shape of the specimen.

The procedure adopted in this section is to compare the results obtained in the Barcelona test with the results obtained in the CUB specimens loaded in the same direction than de BCN test (z axis or casting direction). Figure 4 shows the global results for both test for the series CUB_PF/S1; CUB_PF/S2 and CUB_SF/S1.

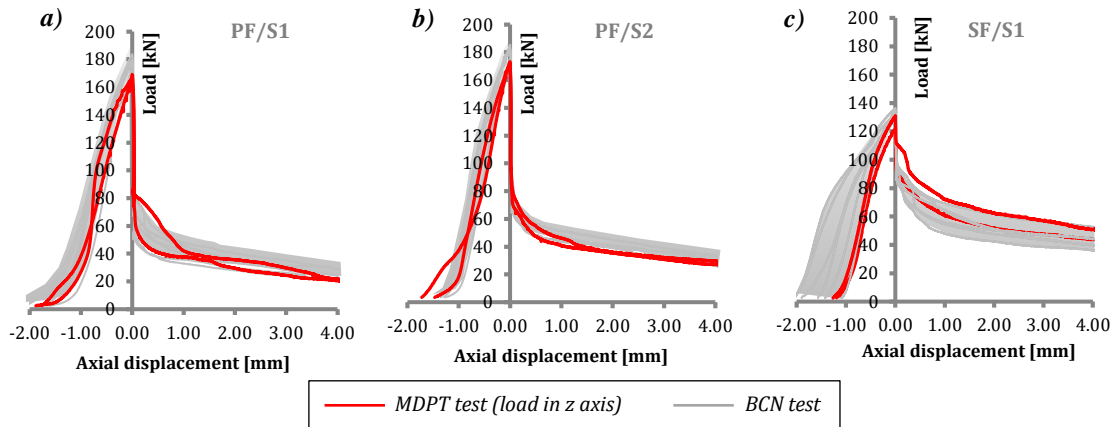


Figure 4. Comparison of the Multidirectional test results loaded in z axis and the Barcelona test results for the series a) PF/S1 b) PF/S2 c) SF/S1 [12]

The results presented in Figure 4 show that the MDPT load-axial displacement curves for the Z loading direction (in red) perfectly fit the results obtained with the BCN test (in grey). Thus highlighting the equivalent mechanical behavior of both test.

4.2. Sensibility of the test to the material anisotropy

4.2.1. CUB specimens (molded)

Figure 5 represents the experimental *load-axial displacement* (δ) curves obtained for the CUB specimens of the series CUB_PF/S1; CUB_PF/S2 and CUB_PF/S3 (representing each of the three amounts of PF fibres used, 5 kg/m³, 7 kg/m³ and 9 kg/m³ respectively). In each graph, the experimental curves are grouped according to the loading direction. In order to avoid confusions, the results of the MDPT method are depicted in terms of load-displacement curves taking the cracking as the origin

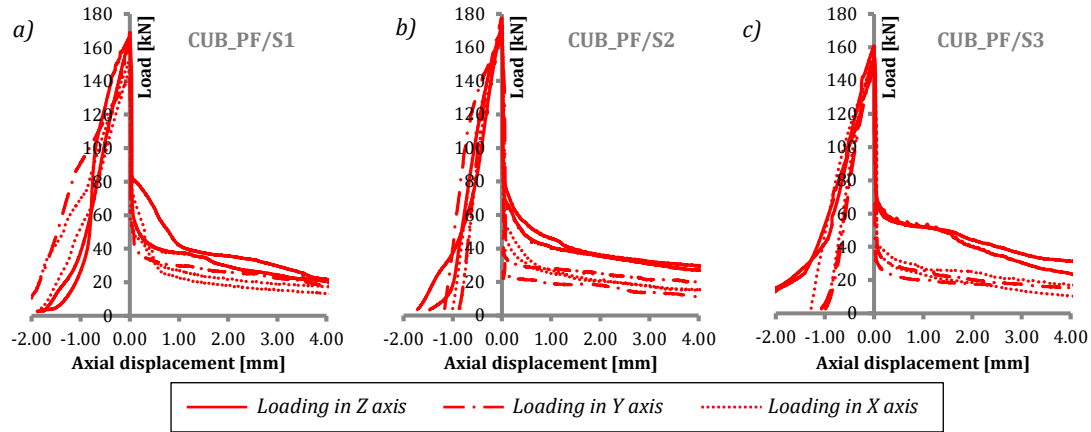


Figure 5. Load-axial displacement curves a) CUB_PF/S1; b) CUB_PF/S2 and b) CUB_PF/S3 [12]

In the results, an initial nonlinear tendency attributed to the casting imperfections and inherent instabilities of the test setup for low load levels is observed in the first stage of the test. Once the coupling between the specimen and the press has taken place, the curve clearly shows an almost linear tendency up to the cracking of the concrete.

Once the concrete has cracked, the fibres exert a "bridge" effect between the divided specimens, allowing a controlled formation of cracks and leading to ductile behavior. However, as FRC is an anisotropic material, the fibers do not provide an identical reinforcement in all directions. Consequently, different post-cracking behaviour of cubic specimens are obtained when loading in the Z, Y and X axis. Higher residual strengths ($F_{R;\delta=2\text{ mm}}$) are obtained for the series with larger fiber dosage, especially when loading in the Z direction. As an example, for the latter direction, $F_{R;\delta=2\text{ mm}}$ values of 32.59, 35.72 and 42.15 kN were obtained for the PF dosages of 5, 7 and 9 kg/m³ respectively, and 57.24 and 72.18 kN for the series with 40 and 60 kg/m³ of SF. Leading to the expected conclusion that the test is sensitive to the amount of fibers. However, for the CUB specimens studied in this section, such outcome cannot be observed in the Y and X load values as, in which the post-cracking fiber contribution is so small that the differences when increasing the dosage are unnoticeable (due to the low number of fibers actively oriented to bridge the cracks in these cases). Nevertheless, the load obtained in X and Y is consistently 60%-70% (average) the value obtained when loading in the Z direction.

4.2.2. CUB specimens (molded)

In this section, a comparison between the results of the molded cubic specimens (CUB) and the cut prismatic specimen (CUT1 and CUT2) is presented. Figure 6 show the experimental curve of the series PF/S3 in terms of load-axial displacement and load-axial displacement respectively.

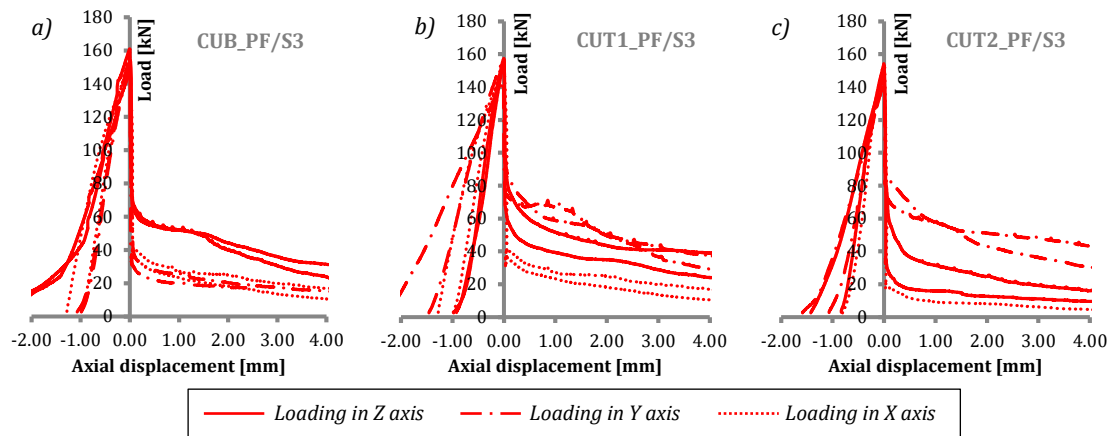


Figure 6. Load-axial displacement curves a) CUB_PF/S3; b) CUT1_PF/S3 and b) CUT2_PF/S3 [12]

The results of Figure 6 show that unlike the results of CUB specimens presented in section 4.2.1, the CUT specimens present lower values of load in the post-cracking stage when the specimens are tested in the X axis. That means that compared to the CUB specimens, in the specimens cut from beams (CUT1 and CUT2) there is another preferential orientation: the alignment of fibres along the X axis (along the length of the beam).

Such outcome is particularly true for the specimens CUT2 (see Figure 6c) since the fibre alignment of fibres along X axis is around 20% higher than along Y axis. Nevertheless, the specimens CUT1 exhibit a different behaviour due to the wall-effect provided by the side of the beam that was not cut (see Figure 6b). This local phenomenon distorts the results of the preferential alignment of fibres along X axis by increasing the percentage of fibres along Y axis. Hence, the percentage of both axes is very similar.

5. CONCLUSIONS

One of the main drawback of the conventional post-cracking characterization tests is the impossibility to suitably take into account the strong anisotropy of FRC due to the dispersion and orientation of fibres. To overcome this drawback, a new characterization test so called MDPT was presented in this paper. Based on the results of this study, the following conclusions may be derived:

- The MDPT represents an efficient alternative to the conventional characterization test. No specific instrumentation is required for its execution (only a conventional press and two metal punches) and the cubic configuration has the advantage of being able to quantify the structural contribution of the fibers in each of the directions of the three Cartesian axes
- The MDPT allows a complete characterization of post-cracking behavior of the FRC, considering the influence of the fiber orientation in the assessment of the toughness and the residual tensile strength of the material. Likewise, the test could be applied to define de coefficient K, proposed by the Model Code, thus having the missing link between the mechanical behaviors and fiber orientation obtained in the characterization tests with the expected of the material at the structural level is missed.
- The results herein presented indicate that the MDPT method shows the influence of fibre orientation in the post-cracking behaviour of FRC, detecting preferential orientations due to the geometry of the specimen and the walls of the moulds are detected.

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