Quality Control Test for SFRC to be Used in Precast Segments

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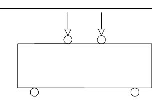
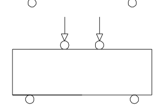
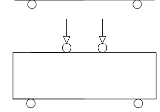
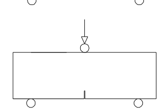
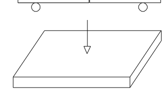
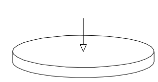
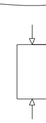
ABSTRACT

Current methods to measure tensile strength and toughness in Steel Fiber Reinforced Concrete (SFRC) show a considerable scatter. That scatter makes difficult the quality control, in particular when such properties are taken into account in the evaluation of overall strength of the precast tunnel lining segments, as in the case of the Line 9 of the subway in Barcelona. In order to improve the material assessment procedure, the Double Punch Test (DPT) has been recovered for the quality control of the tension behavior of SFRC. Results of an initial feasibility research are presented, showing a significant reduction of the scatter in the values of the tension strength and in the toughness. Other advantages shown by this test are: (1) the reduced size 150x150 mm of the cylindrical specimens, compared with those used in beam test, and (2) the use of a conventional compression press controlled by displacement.

1. INTRODUCTION

The application of Steel Fiber Reinforced Concrete to structural members is nowadays experiencing a significant growth. Much research has been done to take into account the benefits of the inclusion of steel fibers in the capacity of structural members under shear and normal stresses. However, the implementation of SFRC on the actual construction works also requires a test to assess the quality of the material. It is specially needed to assess the tension behavior of SFRC. To that purpose, standards include the beam test: ASTM C-1018, NBN B 15-238, RILEM TC 162-TDF, and for SFR Shotcrete, the test is performed in panels: EFNARC and Round Determinate Panel (Bernard, 2001) (Table 1).

Table 1. Specific failure surface in SFRC tension tests.

TEST	CONFIGURATION	FAILURE SURFACE (cm^2)	ESPECIFIC FAILURE SURFACE
Beam ASTM C-1018		10x10 = 100	0,0286
Beam NBN B 15-238		15x15 = 225	0,0133
Beam EFNARC		7,5x12,5 = 93,8	0,0182
Beam RILEM		15x12,5 = 187,5	0,0152
Panel EFNARC		8x(32,5x10) = 2.597,7	0,0722
Round Determinate Panel		3x(40x7,5) = 900	0,0238
DPT		3x(7,5x15) = 337,5	0,1274

All these tests demand specific moulds to produce the specimens which are much heavier than those used for compression. In addition, the beam test always presents an uncomfortable scatter of its results when applied to normally low fiber contents. It is known that this scatter, in terms of tensile strength and toughness, is determined by the number of fibers actually bridging the crack. During the quality assessment of building works the scatter encountered in the results produced by the beam tests makes very difficult to define a threshold to take decisions.

Such problem has arisen during the construction of the precast tunnel lining segments of the L9 of the Barcelona's subway. This project is considered to be record-breaking with 12 m diameter TBM-excavated tunnel of about 40 km length. Reinforced concrete rings of Section 4 of the line content, according to the design, 25 or 30 kg/m3 of steel fibers plus 60 kg/m3 of conventional reinforcement.

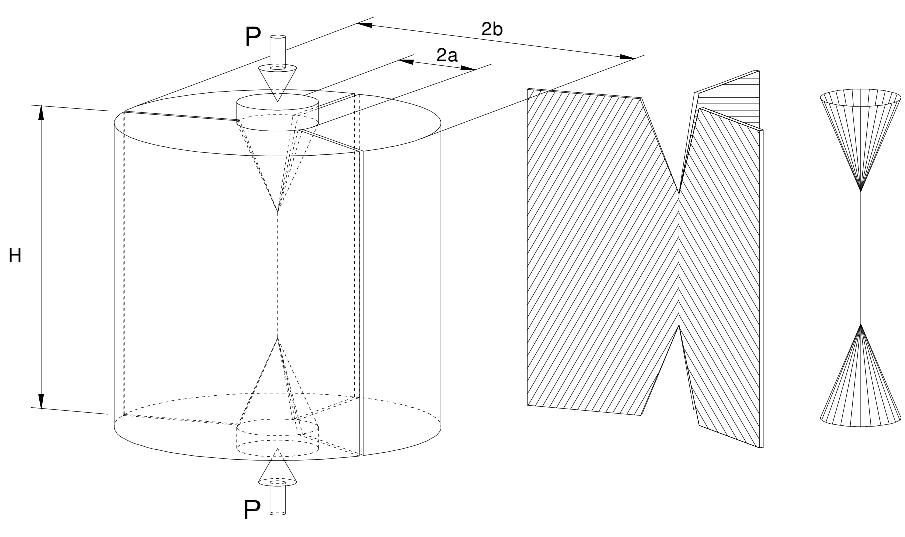
In order to improve material assessment procedure, the Double Punch Test (DPT), that was developed thirty years ago, has been recovered for the quality control of the tension behavior of SFRC. In a first attempt to appraise its capability, twenty samples were tested using Double punch test. The results showed: (1) a significant reduction of the scatter in terms of the tension strength and in those of toughness, (2) sharp dependence on the fiber contents of the concrete. Other advantages that show DPT are: (1) the cylindrical specimens are of reduced size 150x150 mm and (2) a conventional compression press controlled by displacement can be used.

In this paper, the description of the test, its advantages in the case of SFRC and the results of a preliminary campaign with its analysis and discussion are presented.

2. DOUBLE PUNCH TEST PROCEDURE

Barcelona test for fiber reinforced concrete (FRC) is the adaptation of the DPT, used to determinate the tensile strength of plain concrete. DPT was developed in the 1970's as an alternative to the widely spread Brazilian one, that allows to indirectly measure the tensile strength of concrete. Since Chen (1970) presented DPT, notable research effort has been devoted to it. However, it did not become a standard as the Brazilian indirect tension test, probably because the latter was already well established and easier to perform.

In this test, a concrete cylinder is placed vertically in a uniaxial compression press with two steel circular punches centered, that transmits the compression force, at the top and bottom surfaces of the cylinder (Figure 1).



(a) Double-punch test arrangement (b) Failure surfaces

Figure 1. Double-punch test arrangement, mechanism of failure and failure surfaces.

Several approaches have been developed to evaluate the indirect tensile strength from the double-punch test. Chen (1970) derived an expression applying the limit analysis of perfectly plastic material:

$$f_t = \frac{P}{\pi\left(1.2bH - a^2\right)} \tag{1}$$

where P is the applied load at failure, H the height of the specimen, b is the radius of the cylinder and a is the radius of the punch.

Chen and Yuan (1980) proposed another approach, which reduces the value of expression (1) by 25%, by applying the Finite Element Method assuming that the concrete of the cylinder is a linear elastic, plastic strain-hardening and fracture material:

$$f_t = \frac{0.75P}{\pi\left(1.2bH - a^2\right)} \tag{2}$$

Bortolotti (1988) derived also an approach assuming a modified Coulomb failure criterion for concrete and compared its results with those obtained in the experiments published by Chen:

$$f_t = \frac{P}{\pi\left(bH - a^2 \cot\alpha\right)} \tag{3}$$

where α is derived from the internal friction angle of concrete.

Marti (1989) derived an expression applying the Bazant's non-linear fracture mechanic approach:

$$f_t = 0.4\frac{P}{4b^2}\sqrt{1 + \frac{2b}{\lambda d_a}} \tag{4}$$

where λ is a constant which depends on the material (varying from 37 to 68 for concrete) and d_a is the maximum aggregate size. In deriving expression (4), it was supposed that b/h was equal to 1, as recommended by Chen. These expressions are derived from equilibrium equations in terms of displacements' functions and applying the virtual work principle in the kinematics of the failure drawn in Figure 1, that shows the scheme of the test and its typical failure.

Recently, Wei and Chau (2000a, 2000b) derived an approach for stress analysis within a finite isotropic elastic solid cylinder under the double punch test. The paper (Wei and Chau, 2000b) presented the influence of the geometric ratios and the Poisson's modulus. The tensile strength yield by their approach agrees with those achieved analytically and experimentally by Chen and with those obtained by the Bortolotti's expression (3) by $a/b > 0.25$.

3. EXPERIMENTAL CAMPAIGN

The aforementioned research appraises the feasibility of the double-punch test in determining the tensile strength of plain concrete. However, almost no research has been devoted to its extension to SFRC. Probably, that is due to the different degree of use and development between both, plain concrete and SFRC.

A research group in the Department of Construction Engineering at the Technical University of Catalonia was commissioned, by the public company responsible of the design and constructions of the new L9 of the subway in Barcelona, to look for topics of research that could improve the construction of such a line. In that frame, it was proposed to use derive a test, named Barcelona, as an alternative to the four point beam bending test.

The experimental research was designed to analyze the effect of varying some significant parameters. Table 2 shows the selected parameters and Table 3 summarizes the tests carried out, distinguishing between the origin of the concrete: from the plant of precast segments at Can Zam or from the plant at Gorg, which present different strength and different volume of fibers and type of fibers. Can Zam SFRC presents a compression strength of 50 N/mm^2 and contents 30 kg/m^3 of fibers 50 mm long with a diameter of 1 mm (aspect ratio of 50). Gorg SFRC presents a compression strength of 40 N/mm^2 and contents 25 kg/m^3 of fibers 50 mm long with a diameter of 0.75 mm (aspect ratio of 66.7). In addition, the specimens 150 mm height correspond to a half of a 300 m height sample. A set of twenty cylindrical 300 mm height specimens were required to perform the experimental program.

Table 2: Test variables.

Variable	Values	Observations
Punch diameter	38 mm	$\O_{specimen} = 3 \cdot \O_{punch}$
	50 mm	$\O_{specimen} = 4 \cdot \O_{punch}$
Slenderness of the specimen	2 (300 mm height)	
	1 (150 mm height)	Two specimens obtained from cutting one of 300 mm
Loading speed	0,75 mm/min.	Height speed
	0,5 mm/min.	Medium speed
	0,25 mm/min.	Low speed
Eccentricity of the load (punches)	No eccentricity	Tested on 150 mm height specimen
	One punch 5 mm eccentric and the other one centered (1ecc.)	
	5 mm eccentric both punches (2ecc.)	
Position of the molded face of the specimen	Molded face (bottom half) or cut face (upper half) on the lower punch (pos.1)	Tested on 150 mm height specimen
	Cut face (bottom half) o finished face (upper half) on the lower punch (pos.2)	

Table 3 shows the adopted combinations of values of the selected variables that were been tested. As summarized in Table 2, three different options were simulated in relation with the eccentricity to appraise the sensitivity of the test to errors in the placement of the specimen on the press. The radiuses of the punch were selected in the range recommended by previous experiences.

4. ANALYSIS OF TEST RESULTS

Table 4 shows the results achieved in the tested set of specimens. Failure loads of the pairs of 150 mm height specimens, obtained by cutting a 300 mm one, are in most of cases almost identical. 300 mm height specimens present a failure load of about 25% to 35% larger than those of 150 mm. Also in those higher samples, radial cracks didn't achieve the total height as normally occurred in 150 mm height samples (Figure 2). This fact implies a different behavior at failure.

Results were not sensitive to the position of the molded or cut face during the test. Testing speed didn't significantly affect failure loads. Only some increase is noticed in Can Zam samples. It was also verified that normal working eccentricities have no noticeable effect.

The scatter (12%) that shows the experiments in terms of failure loads is significantly lower than those obtained in beam tests with similar fiber contents which actually are about 20% to 25%.

Table 3. List of tests.

Ø punch	H specimen	Speed mm/min	Eccentric.	Position	Number of specimen Zam	Gorg
50 mm	300 mm	0,50	No		1 + 9	7 + 9
38 mm	300 mm	0,50	No		7 + 8	1 + 8
38 mm	150 mm	0,50	No	1	10 u+b	10 u+b
38 mm	150 mm	0,75	No	1	3 u+b	6 u+b
38 mm	150 mm	0,25	No	1	4 u+b	2 u+b
38 mm	150 mm	0,50	1 ecc.	1	5 u+b	3 u+b
38 mm	150 mm	0,50	2 ecc.	1	2 u+b	4 u+b
38 mm	150 mm	0,50	No	2	6 u+b	5 u+b

Note: *u* and *b* are used to mean upper half and bottom half.

Table 4. Failure loads, energy and number of radial cracks.

Origin	Øpunch (mm)	Nº spec	Height (mm)	Test. speed mm/min	Eccent. (mm)	Pos.	P (kN)	Energy (J)	Radial cracks
Can Zam	50	1	300	0,50	0	1	314	364	4
		9	“	“	“	1	328	351	3
	38	7	“	“	“	1	222	460	3
		8	“	“	“	1	232	394	3
		10	150 b	“	“	1	186	174	3
			150 u	“	“	1	193	205	3
		3	150 b	0,75	“	1	207	178	3
			150 u	“		1	208	226	2
		4	150 b	0,25	“	1	177	206	3
			150 u	“	“	1	170	194	3
		5	150 b	0,50	1 p 5	1	188	232	2
			150 u	“	“	1	188	302	3
		2	150 b	0,50	2 p 5	1	179	207	3
			150 u	“		1	200	266	4
		6	150 b	0,50	0	2	191	285	4
			150 u	“	“	2	188	245	3
Gorg	50	7	300	“	“	1	285	325	3
		9	“	“	“	1	190*	549*	4*
	38	1	“	“	“	1	220	235	2
		8	“	“	“	1	231	202	2
		10	150 b	“	“	1	175	219	4
			150 u	“	“	1	184	188	3
		6	150 b	0,75	“	1	168	90	2
			150 u	“	“	1	166	150	2
		2	150 b	0,25	“	1	168	128	2
			150 u	“	“	1	133	108	2
		3	150 b	0,50	1 p 5	1	176	163	3
			150 u	“	“	1	176	163	4
		4	150 b	0,50	2 p 5	1	168	103	3
			150 u	“		1	163	175	3
		5	150 b	0,50	0	2	156	128	2
			150 u	“	“	2	152	112	2

Note: u and b are used to mean upper half and bottom half.

5. CONCLUSIONS

The use of the DPT is proposed for the quality control of SFRC in precast tunnel lining segments. The experiments show a reduced scatter in terms of failure load and energy, of about 12%.

The parametric analysis showed that testing velocities of 0.25 to 0.50 mm/min are appropriate and the Φ38 mm punches (one fourth of the specimen's diameter) present lower scatter. Because of that, 0.50 mm/min testing velocity and 38 mm punches have been selected to perform the test. In addition, normal working errors (eccentric placing of the punches) presented no noticeable effect in the results. Also, inverting the position of the molded face vertically didn't affect the results. More consistent results were achieved using 150 mm height specimens.

Figure 2. Tested 150 and 300 mm height samples.

These encouraging results deserve a further research effort to achieve a better understanding of the mechanics involved in the double punch test and to standardize it as a quality assessment tool for the tension properties of SFRC: tensile strength and toughness.

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