Fracture Mechanics of Concrete Structures
Proceedings FRAMCOS-3
AEDIFICATIO Publishers, D-79104 Freiburg, Germany

STUDY OF THE POST-PEAK BEHAVIOR OF CONCRETE IN THE SPLITTING-TENSION TEST

S. Carmona
Dept. of Public Works, Universidad Técnica Federico Santa María, Valparaíso, Chile
R. Gettu and A. Aguado
Dept. of Construction Engineering, Universitat Politècnica de Catalunya, Barcelona, Spain

Abstract
The Brazilian test method for evaluating the splitting-tensile strength of concrete is modified to obtain the entire pre- and post-peak response of the specimen. Results are given for different sizes of high strength concrete specimens and specimens of concretes incorporating steel fibers.
Keywords: Splitting-tension, fracture, concrete, brazilian test

1 Introduction

Since the behavior of concrete under tension is interesting in terms of materials engineering and characterization, several experimental procedures have been proposed for this purpose. In this work, a modified methodology for the Brazilian splitting (or the splitting tension) test of a cylinder is presented with the objective of determining the post-peak response of the specimen in a stable and satisfactory manner. The splitting test is popular mainly because the cylinder is a routinely fabricated specimen. Moreover, the testing procedure is quite simple, and has been specified in several recommendations and standards (e.g., ASTM C 496, 1992; RILEM, 1994). In general, a cylinder (normally of 150 mm diameter) is subjected to compressive loading along a diametrical plane. The load is applied with strips of cardboard or wood between the specimen and the plattens, under load control. The test terminates at the peak load, with a catastrophic failure of the specimen. The maximum tensile stress is calculated (assuming line loads and a uniform distribution of tensile stresses) from the peak load, as $f_t = 2P/\pi b d_c$, where f_t is the tensile strength, P is the maximum load, b and d_c are the specimen thickness and diameter, respectively.

It should be noted that the tensile strength obtained from the splitting test depends on the diameter of the specimen (Bažant et al., 1991; Tang et al., 1992; Rocco et al., 1997; Bažant and Planas, 1998). However, the use of a standard diameter circumvents this problem, as in compression tests. The result is not necessarily a material property but, nevertheless, a reliable value that can be used for comparison and design.

Furthermore, for fiber reinforced concretes (FRC) the conventional test is not very objective since crushing due to the concentrated compressive loads and large deformations across the crack can lead to a progressive increase in the contact area between the platten and the specimen. Consequently, the load continues to increase even after the cracking of the matrix and after the crack has completely developed. In such cases, the tensile strength cannot be obtained without appropriately modifying the test configuration. Another motivation for altering the methodology is for obtaining the post-peak load-displacement response that can be used for some applications as in the quantification of the toughness of FRC.

In the present paper, minor modifications are made to the test method, which allow the determination of the complete response of the specimen. Tests have been performed on high-strength concrete (60 MPa) specimens of four different sizes, and on fiber-reinforced concrete specimens.

2 Proposed test procedure

Normally, the diameter of the test specimen is chosen as 150 mm so that the standard cylinder may be utilized. The specimen length can be three to five times the fiber length or the maximum aggregate size, whichever is larger. This ensures a representative volume and minimizes wall effects. The length is restricted in order to reduce asymmetries in the loading and cracking.

The loading setup is modified to avoid the increase in contact area during the test. Two steel bars are placed between the loading plattens and the specimen so that the contact width is always constant. For the 150 mm

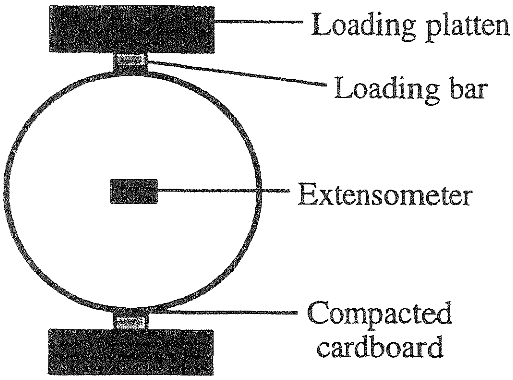

Fig. 1. Test configuration

diameter disc, two 25 mm wide bars were used, i.e. $w_b = d_c/6$, where w_b is the bar width (see Fig. 1). For other specimen sizes, the w_b/d_c ratio is kept constant to avoid loading width effects on the tensile strength (Rocco et al., 1997; Tang et al., 1992). Strips of wood or cardboard are used, as in the conventional test, to accommodate surface imperfections. The platten is free to rotate until matrix cracking occurs and fixed later to avoid asymmetric crack propagation.

As in other fracture tests, the most critical deformation of the specimen is the crack opening. By using this deformation as the control variable in a closed-loop feedback-controlled environment, stable post-cracking response can be obtained (Gettu et al., 1996). This also reduces rate effects due to the sudden failure that occurs under load and displacement control, especially in tests of plain concrete. The load and crack opening (COD) are monitored electronically so that a continuous record of the specimen behavior is obtained. Note that the extensometer for measuring crack opening is mounted across the loading/crack plane, preferably at the center. It should be ensured that the crack occurs within the gage length of the extensometer by making it longer than the fiber length and the maximum aggregate size. However, the smallest possible gage length is to be used in order to maximize the sensibility of the control.

3 Experimental details

The high-strength concrete (denoted as HSC) had the basic proportions of cement:gravel:sand:microsilica:water as 1:1.93:1.93:0.1:0.33, by weight.

Spanish I-45A cement (similar to CEM I 52.5R), crushed limestone gravel (5-12 mm), siliceous sand (0-5 mm) and densified silica fume were used. A dosage of 17.4 lt/m^3 of superplasticizer (naphthalene with a solid content of 33%) was employed to obtain a slump of 25 cm. The conventional compressive strength at 28 days was 61 MPa and the modulus of elasticity was 35.2 GPa. The fracture parameters according to the size effect method (Bažant and Kazemi, 1990) are fracture energy $G_f = 44.8$ N/m, and effective process zone length $c_f = 22$ mm; and according to the RILEM work-of-fracture method (RILEM, 1985) with the corrections proposed by Elices et al. (1992), the fracture energy is $G_F = 76.5$ N/m.

The fiber reinforced concretes (FRC) had the basic proportions of cement:sand:gravel:microsilica:water as 1:1.32:2.2:0.1:0.33, by weight. Spanish I-45A cement (similar to CEM I 52.5R), crushed limestone gravel (5-12 mm) and sand (0-5 mm), and a silica fume slurry were used. The fibers incorporated in the concrete were collated hooked steel fibers (with length = 30 mm, diameter = 0.5 mm, tensile strength = 2000 MPa and maximum elongation = 0.8-1.0%). The notation and other properties of the three concretes are given in Table 1, where V_f is the approximate fiber volume fraction. The compressive strengths were obtained from tests on 150 × 300 mm cylinders.

Table 1. FRC characteristics

Concrete	fiber content (kg/m^3)	V_f (%)	superplasticizer content (liter/m^3)	21-day compressive strength (MPa)
HPC-0.0	0	0.0	8	73 ± 4
HPC-0.5	40	0.5	15	66 ± 1
HPC-1.0	80	1.0	20	64 ± 2

For the HSC specimens, 60 mm wide discs were cut from standard cylinders (150 × 300 mm) using a diamond band saw. The ends of the cylinders were discarded to reduce boundary effects. Note that the specimen width is 5 times the maximum aggregate size. Also, in order to study the effect of specimen size, discs of the same width were cut from cylinders with diameters of 74, 100 and 290 mm and tested. The FRC specimens had a diameter of 150 mm and widths of 100 mm (more than 3 times the fiber length).

The test setup is shown in Fig. 1. Steel loading bars and compacted cardboard sheets (of width $w_b = d_c/6$) were used. The tests were conducted in a servo-hydraulic INSTRON 8505 system with a digital closed-loop controller. An INSTRON clip gage was mounted on one of the flat ends of the specimen along a diameter perpendicular to the loading plane. It was fixed between two knife edges glued about 65 mm apart. The measured deformation was used as the control variable and was increased at a constant rate chosen to obtain the peak load in about 1-3 minutes. The HSC tests were performed at the age of about 28 days and the FRC tests at the age of about 6 months, before which the specimens were kept in a fog room.

A majority of the specimens exhibited stable behavior in the pre- and post-cracking regimes. However, it was seen that the errors in positioning the specimen or loading bars produced instability and loss of control at the peak, indicating the high sensibility to errors in the test setup. Also, the control system has to be properly tuned in order to provide a stable transition from the uncracked (pre-peak) stage to the cracked (post-peak) stage.

4 Results of the tests on HSC specimens

The splitting-tensile strength for different sizes of HSC specimens are plotted in Fig. 2, where complementary results from tests with load control (normally used in conventional tests) are also shown. It can be observed that there is no clear size effect on the strength with respect to specimen diameter. The trend of the data for the largest specimens, for $d_c \geq 150$ mm, is similar to the predictions of Rocco et al. (1997). The values obtained in the tests with load control are higher than those under crack opening control probably due to rate effects produced by unstable failure in the former. More tests are needed to quantify the size effects adequately.

In all the tests, a single crack was observed, accompanied sometimes by the formation of a thin wedge below the loading strips. The load-COD curves obtained in the tests are given in Fig. 3. It can be seen that all the curves exhibit an initially linear response with some pre-peak nonlinearity, after which there is a smooth post-peak descent to a plateau.

In order to approximately evaluate the effect of the compression supported by the specimen after cracking, similar tests were performed on discs previously sawed into two halves, with the cut along the loading plane. These specimen pairs were prepared from the same cylinders as the whole discs. Typical curves obtained for a 150 mm diameter specimen, whole and as two half discs, are presented in Fig. 4. The halved specimen exhibits a plateau after a COD of about 100 μm, which practically coincides with that of the whole specimen, indicating that the plateau of the latter is primarily due to the compressive stresses generated in the split halves after cracking.

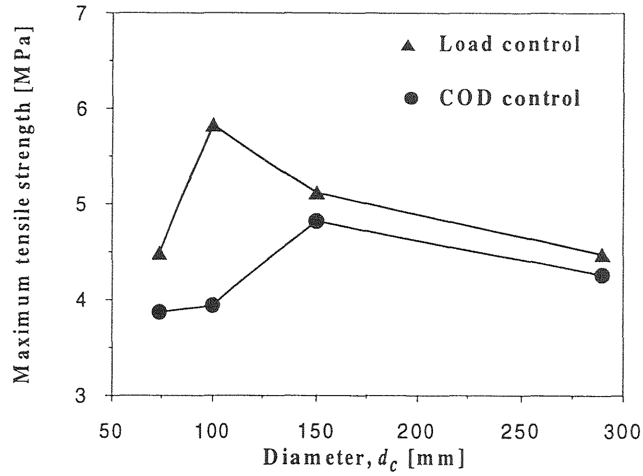

Fig. 2. Effect of size on the splitting-tensile strength

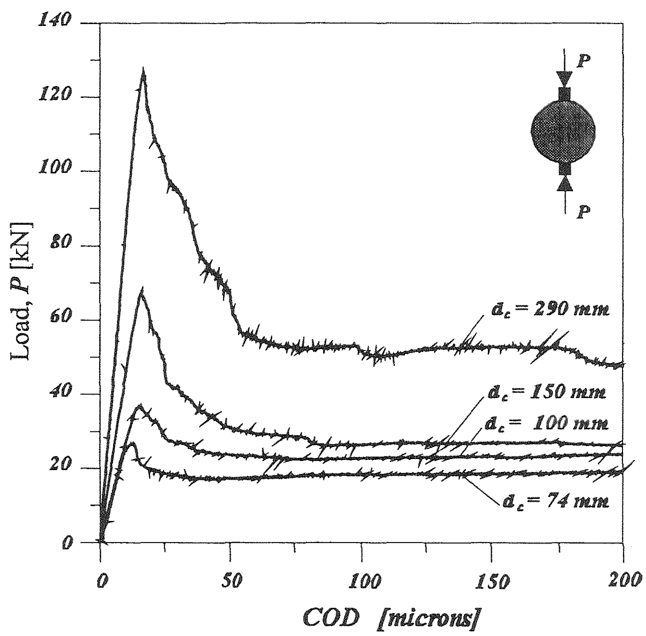

Fig. 3. Load versus crack opening curves for different sizes

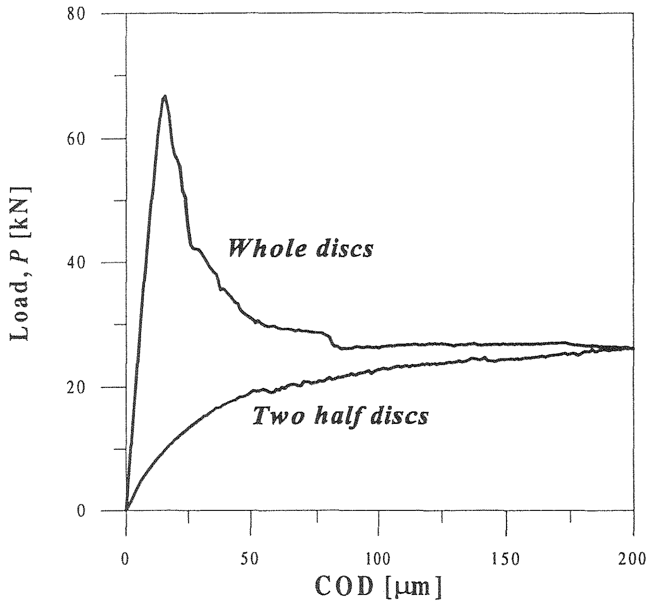

Fig. 4. Comparison of the responses of the whole and half discs

5 Tests on FRC specimens

Adequate toughness characterization is essential for the utilization of fiber reinforced concretes (FRC) since it quantifies the benefits of incorporating fibers on the post-cracking response and ductility. Conventionally, the toughness of FRC is taken to be an engineering measure (not related to the fracture toughness), obtained from the test of an unnotched beam (see Gopalaratnam and Gettu, 1995).

As an alternative, some researchers have used the split-cylinder test for determining the toughness of FRC. For example, Nanni (1991) conducted tests on FRC disks under displacement control. The diametrical deformation perpendicular to the crack plane was measured at the middle with two extensometers and the load-deformation curve was used to compute toughness indices. Also, Cho et al. (1992) performed splitting tests on 76×152 mm FRC cylinders, where the average diametrical deformation was used as the control variable. They concluded that stress state, especially in the vicinity of the loading, does not allow fiber-dominated post-cracking response. In the aforementioned tests, the load-deformation curves of FRCs exhibited elastic-plastic behavior without any softening. Moreover, it appears that the tests of plain concrete ended in sudden failure at the peak load.

In the present work, tests on the FRCs were performed using the method described earlier in order to determined the post-cracking response in a stable manner. The failure of the HPC-0.0 (plain concrete) specimens was similar to that of the HSC. In the FRCs, a band of cracks was formed along the crack plane whose width increased gradually at the edges. Typical load-COD curves obtained in the tests are given in Fig. 5. The pre-peak responses of the FRCs are similar to that of HPC-0.0 demonstrating that this regime is dominated by the matrix for low fiber volume-fractions. The enhancement of the post-peak response due to the addition of fibers is, however, quite evident. After a drop in load just after the peak, both FRCs exhibit hardening-type behavior. At a COD of about 400 microns, the load carrying capacity of HPC-0.0 is reduced to about 50% of the maximum while HPC-0.5 carries almost 100% and HPC-1.0 about 180% of the first-peak load. The FRCs reach a second peak at a COD of about 500 microns, more than 50 times their first-peak COD and the peak COD of the plain concrete. This clearly shows the advantage of incorporating steel fibers in high strength concretes. These curves can be used to define toughness indices that are comparable to those obtained from beam tests (as in Carmona et al., 1997).

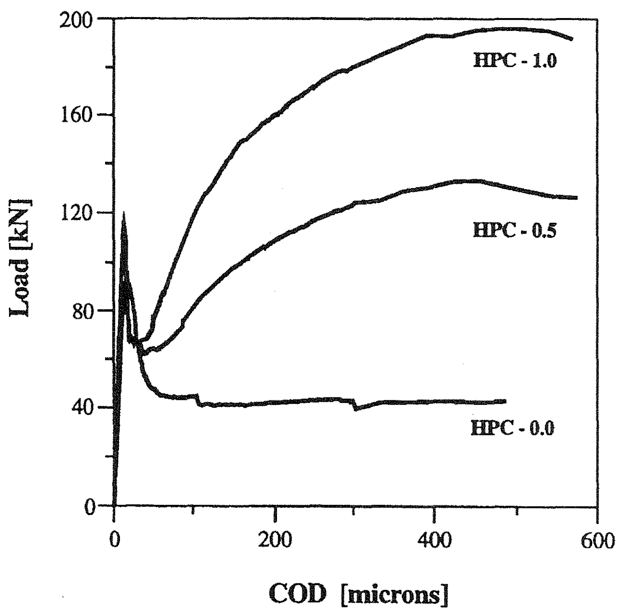

Fig. 5. Typical load-COD curves for plain and FRC specimens

6 Conclusions

The split-cylinder test can be controlled in a stable manner by slightly modifying the conventional experimental procedure and by using a closed-loop testing system. Stable tests have been conducted on plain and fiber reinforced concretes by restricting the loading areas and by controlling the deformation across the crack plane. Post-peak response of the plain concrete has been characterized over a scale of 1:4. In all the sizes a plateau is observed in the load-COD curves after some post-peak softening, which is similar to that seen in tests of previously cut half-discs. In the FRCs, the failure along a well-defined plane allows the determination of the post-peak load versus crack opening responses, which describe the toughening effect of fibers satisfactorily.

7 Acknowledgments

Partial funding from Spanish CICYT grants MAT96-0967 to the UPC, and from UTFSM, Valparaíso, Chile is gratefully appreciated. Materials used in this study were provided by Cementos Molins, Uniland Cementera, Grace and Bekaert.

8 References

ASTM (1992) Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimen, C 496-90, **ASTM Annual Book of Standards**, 04.02, ASTM, Philadelphia, USA, 269-272.

Bažant, Z.P., and Kazemi, M.T. (1990) Determination of Fracture Energy, Process Zone Length and Brittleness Number from Size Effect, With Application to Rock and Concrete, **Int. J. Fract.**, 44, 111-131.

Bažant, Z.P. and Planas J. (1998) **Fracture and Size Effect in Concrete and Other Quasibrittle Materials**, CRC Press, London.

Bažant, Z.P., Kazemi, M.T., Hasegawa, T., and Mazars, J. (1991) Size Effect in Brazilian Split-Cylinder Test: Measurement and Analysis, **ACI Mater. J.**, 88, 325-32.

Carmona, S., Gettu, R., and Aguado, A. (1997) Evaluation of the Fracture Behavior of High Performance Concrete, **Proc. of Int. Conference on Engineering Materials**, Advantage Inc., Ottawa, 2, 11-21.

Cho, B., El-Shakra, Z., and Gopalaratnam, V.S. (1992) Failure of FRC in Direct and Indirect Tensile Test Configuration, **Proc. Int. Symp. on Fatigue and Fracture Steel and Concrete Structures**, Oxford & IBH Publ., New Delhi, India, 587-601.

Elices, M., Guinea, G.V., and Planas, J. (1992) Measurement of the Fracture Energy Using Three-Point Bend Tests: Part 3 - Influence of Cutting the P-δ Tail", **Mater. Struct.**, 25, 327-334.

Gettu, R., Mobasher, B., Carmona, S., and Jansen, D.C. (1996) Testing of Concrete under Closed-Loop Control, **Advanced Cement Based Materials J.**, 3, 54-71.

Gopalaratnam, V.S., and Gettu, R. (1995) On the Characterization of Flexural Toughness in Fiber Reinforced Concretes, **Int. J. Cem. Concr. Composites**, 17, 239-54.

Nanni, A. (1991) Pseudoductility of Fiber Reinforced Concrete, **ASCE J. Struct. Engng.**, 117, 78-90.

RILEM (1985) Determination of the Fracture Energy of Mortar and Concrete by Means of the Three-Point Bend Tests on Notched Beams, TC 50-FMC Recommendation, **Mater. Struct.**, 18, 285-290.

RILEM (1994) Tension Splitting of Concrete Specimen, CPC6 1975, **Rilem Technical Recommendation for the Testing and Use of Construction Materials**, E & FN Spon, London, 21-22.

Rocco, C., Guinea, G.V., Planas, J., and Elices, M. (1997) Efecto del Tamaño de Probeta sobre la Resistencia a la Tracción Medida con el Ensayo Brasileño, **Hormigón y Acero** (Madrid, Spain), 2, 47-63.

Tang, T., Shah, S.P. and Ouyang, C. (1992) Fracture Mechanics and Size Effect of Concrete in Tension, **ASCE J. Struct. Engng**, 118, 3169-3185.