Fracture Mechanics of Concrete Structures,
Proceedings FRAMCOS-2, edited by Folker H. Wittmann,
AEDIFICATIO Publishers, D-79104 Freiburg (1995)

THE EFFECT OF THE BOUNDARY CONDITIONS ON THE CYLINDER SPLITTING STRENGTH

C. Rocco, G.V. Guinea, J. Planas and M.Elices
Departamento de Ciencia de Materiales
Universidad Politécnica de Madrid, Madrid, España.

Abstract
The tensile strength microconcrete (maximum aggregate size 5mm) was measured using the cylinder and cube splitting test, and the influence of two parameters – the width of the load bearing strips and the specimen size – were ascertained. It was found that the width of the strips greatly influences the splitting strength, a fact that is not reflected in available analitycal or numerical results. Specimen size (in the range of 50 to 300 mm) has a negligible influence on the splitting strength, which thus shows no size-effect.

1 Introduction

Tensile strength, f_t, is a basic property in characterizing quasi-brittle materials such as concrete, rocks and ceramics, and is directly related to crack nucleation and propagation, so a number of fracture models include this property as a parameter. However, its measurement is very elusive because of the difficulty in performing direct tensile tests, which are in theory the best suited for the purpose but their implementation has many disadvantages. The control of the boundary conditions is very difficult, the state in the fracture zone is far from uniform and usually two or more cracks propagate from the sides of the specimen. For these reasons alternative methods for measuring f_t have been developed, of which one of the most relevant is the cylinder splitting strength, also called the Brazilian test.

This test is based on the diametral compression of a cylinder. Its simplicity makes it one of the most universally employed and, for example, in the concrete field its use is normalized by a number of national standards such as the well known American ASTM-C496. The values obtained through this test compare well with those from flexural tests on three and four points, although the results are dependent on the size and shape of the specimen selected.

In recent years, questions arose about whether if the specimen size and the bearing strips have a prominent influence on the rupture mechanism and on the splitting strength or not.

This work analyzes the influence of the width of the bearing strips in combination with the specimen size. Results for a test series on a micro-concrete are presented. The plan of the paper is the following: In section 2 the fundamentals of the Brazilian test are introduced; section 3 shows the experimental work, and section 4 closes the paper with the analysis and conclusions.

2 The Brazilian test

2.1 Description of the test

This test was first introduced by Carneiro in 1943 during the 5th Conference of the Brazilian Association for Standardization, and since 1962 it is regulated for concrete by the ASTM C496 standard. The test arrangement is quite simple; a cylindrical specimen is placed with its axis horizontal between the platens of a testing machine and is loaded along two diametrically-opposed generators until failure by splitting along the vertical diameter (figure 1).

In order to reduce the effect of slight imperfections at the sides of the specimen and to avoid high compressive stresses immediately under the load two narrow strips are interposed between the cylinder and the platens. The ASTM standard prescribes strips of 3.2mm (1/8 in.) thick plywood, 25mm (1 in.) wide, for a standard specimen of 150mm (6 in.) diameter.

An alternative geometry is the prismatic specimen (see figure 1), that yields the same results as the splitting tests on cylinders, as reported by Nilsson (1961). This method is advantageous in all those countries where cubes are used in standard compression control tests and when samples are obtained by sawing a concrete plate.

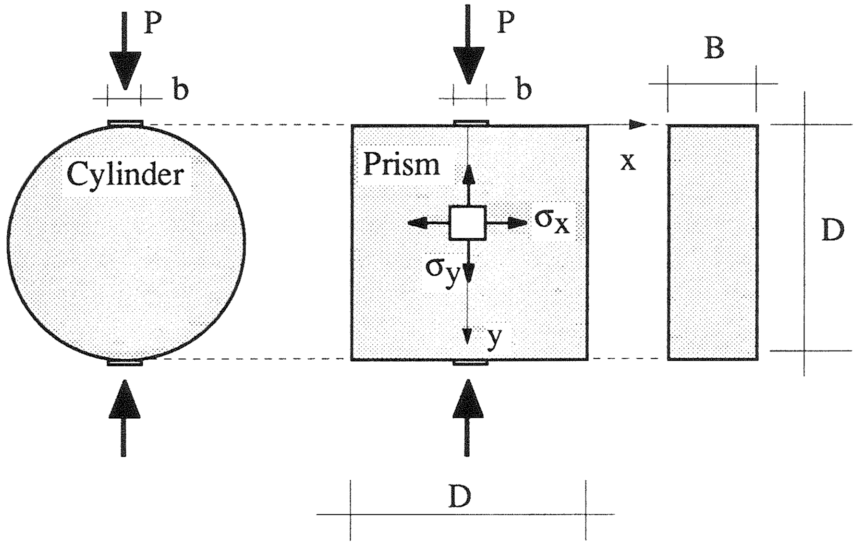

Fig.1. Geometries for the splitting test

2.2 The stress state

The elastic solution to the cylinder uniformly line-loaded along two generators may be obtained by a superposition scheme as in Timoshenko and Goodier text's (1951). With reference with the axes shown in figure 1, the stresses along the vertical diameter are:

$$\sigma_y\,(0,y) = -\,\sigma_N\left(\frac{D^2}{y(D-y)} - 1\right) \tag{1}$$

$$\sigma_x\,(0,y) = \sigma_N \tag{2}$$

where σ_N is the nominal stress, defined as:

$$\sigma_N = \frac{2P}{\pi BD} \tag{3}$$

being D the diameter, B the thickness and P the applied load.

As shown in equation 2, the horizontal tensile stress is uniform along the diameter.

The stress state in practice differs from equations 1 and 2 because the load is distributed over a narrow strip to avoid high compressions under the load, as recommended by the test standards. Assuming a uniform distribution, the horizontal stress σ_x is no longer constant along the vertical diameter and its maximum is at the center of the specimen. Its value, as a function of the width b where the load spreads, can be expressed as (Tang, 1994):

$$\sigma_x(0,D/2) = \frac{2P}{\pi BD}\,(1-(b/D)^2)^{3/2} \qquad (4)$$

When a prismatic specimen is considered the horizontal stresses σ_x are not uniform. Nevertheless, deviations from the value given in equation 2 are small (Goodier,1932; Davies et al., 1968), with D being now the prism depth. For an ideal line-load arrangement equation 2 still holds if taken as the average tensile stress along the vertical axis (Goodier,1932). For a uniformly distributed load over a width b the authors have computed by finite element analysis the elastic tensile stress at the center of the specimen, finding the following expression for $b/D < 0.2$:

$$\sigma_x\,(0,D/2) = \frac{2P}{\pi BD}\left\{(1-(b/D)^2)^{5/3} - 0.0115\right\} \qquad (5)$$

3 Experimental work

A tests series was carried out to find the influence of the width of the bearing strips b and the specimen size D on the splitting tensile strength. Cylinders and prisms made of microconcrete were obtained from the same batch, with the nominal dimensions displayed in Table 1. Three ratios b/D and four sizes D were investigated, ranging from 4 to 8 % and from 37 to 300 mm respectively.

The microconcrete used was designed according to ASTM C33 with a rapid hardening portland cement (ASTM Type III) and a natural rounded silica sand with maximum aggregate size of 5mm. The mix proportion of cement:sand:water was 1:3:0.5 (by weight) and the measured slump 120mm.

Cylinders were cast in steel moulds and prisms were sawn from a plate 50mm thick. All the specimens were stored under lime saturated water until testing time.

In addition to splitting tests, standard mechanical properties were determined at the same age according the ASTM standards –compressive strength and elastic modulus– and the RILEM-TC50 recommendation (RILEM, 1985) with some improvements (Guinea et al.,1992; Planas et al., 1992; Elices et al., 1992) –fracture energy–. Results of these tests are presented in Table 2, where values in brackets indicate standard deviations.

Table 1. Specimen geometry

Specimen	Type	Depth D(mm)	Thickness B(mm)	Bearing ratio b/D	number
STC75-16	Cylinder	75	50	0.16	6
STC75-8	Cylinder	75	50	0.08	3
STC75-4	Cylinder	75	50	0.04	3
STP75-16	Prism	75	50	0.16	8
STP75-8	Prism	75	50	0.08	8
STP75-4	Prism	75	50	0.04	8
STP300-8	Prism	300	50	0.08	4
STP150-8	Prism	150	50	0.08	6
STP75-8	Prism	75	50	0.08	8
STP37-8	Prism	37	50	0.08	8

Table 2. Mechanical properties

Property	Standard	Value
Compressive strength, f_c (MPa)	ASTM C39	38 (1)
Modulus of elasticity, E (GPa)	ASTM C469	31 (1)
Fracture energy, G_F (J/m^2)	RILEM-TC50	72 (2)

Splitting tests were carried out in a 1MN servohydraulic testing machine operated in displacement control mode. For the two larger sizes (300 and 150mm) loads were continuously measured by a 100kN load cell with 0.5 percent accuracy whereas for the smaller sizes (75 and 37mm) a load cell of 25kN and the same percent accuracy was selected. The applied load was distributed by means of two 3mm thick plywood strips interposed between the specimen and the machine platens, its width being variable. The loading rate was set within the range recommended by ASTM C496, equal to 0.7MPa/min.

4 Results and discussion

Table 3 summarizes the results obtained in the splitting tests. For each test group are given the mean value of the nominal stress at failure σ_{Nu}, the standard deviation S, and the coefficient of variation C_v, defined as the ratio S/σ_{Nu}.

Table 3. Results of the splitting tests

Specimen	Type	σ_{Nu}(MPa)	S(MPa)	Cv(%)
STC75-16	Cylinder	4.29	0.16	3.8
STC75-8	Cylinder	3.53	0.11	3.0
STC75-4	Cylinder	3.48	0.07	2.1
STP75-16	Prism	4.53	0.26	5.8
STP75-8	Prism	3.66	0.20	5.4
STP75-4	Prism	3.51	0.15	4.1
STP300-8	Prism	3.89	0.20	5.1
STP150-8	Prism	3.78	0.26	6.8
STP75-8	Prism	3.66	0.20	5.4
STP37-8	Prism	3.88	0.23	5.9

4.1 Influence of the width of the bearing strips

Figure 2 displays the variation of σ_{Nu} with the width b of the bearing strips for a medium specimen size of 75mm. It is shown in this figure that there is no practical difference between cylinders and prisms, as could be expected from the similar stress distribution in these two specimens. On the other hand, the width where the load spreads has a remarkable influence on the maximum load, which increases up to 25-30% when the bearing size grows from 4 to 16% of specimen depth.

For an explanation of this fact based on classical grounds we can make use of equations 4 and 5. If we admit that when peak load is reached the tensile stress at the center of the specimen is the same for two different distributions, b_1 and b_2, we can derive the following relationships:

$$\frac{\sigma_{Nu1}}{\sigma_{Nu2}} = \left(\frac{1-(b_2/D)^2}{1-(b_1/D)^2}\right)^{3/2} \qquad (6)$$

for cylinders and,

$$\frac{\sigma_{Nu1}}{\sigma_{Nu2}} = \frac{(1-(b_2/D)^2)^{5/3} - 0.0115}{(1-(b_1/D)^2)^{5/3} - 0.0115} \qquad (7)$$

for prisms.

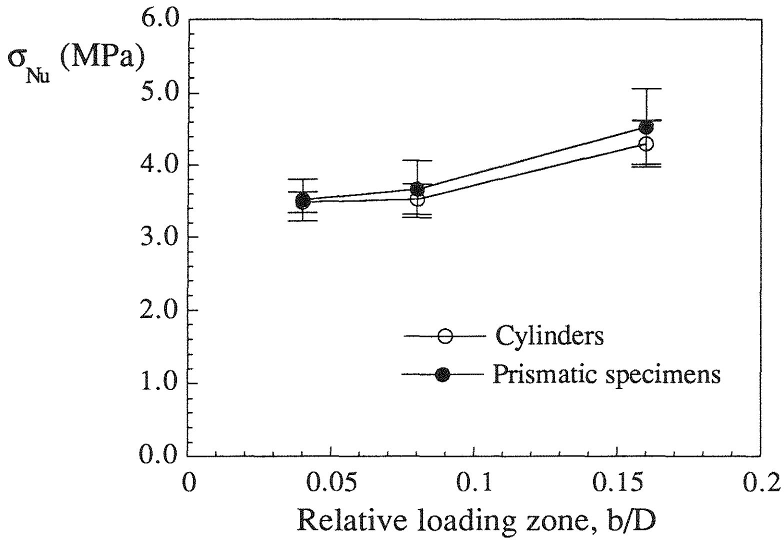

Fig.2. Results of nominal peak loads as a function of the width of the loading zone. (Specimen size, D=75mm)

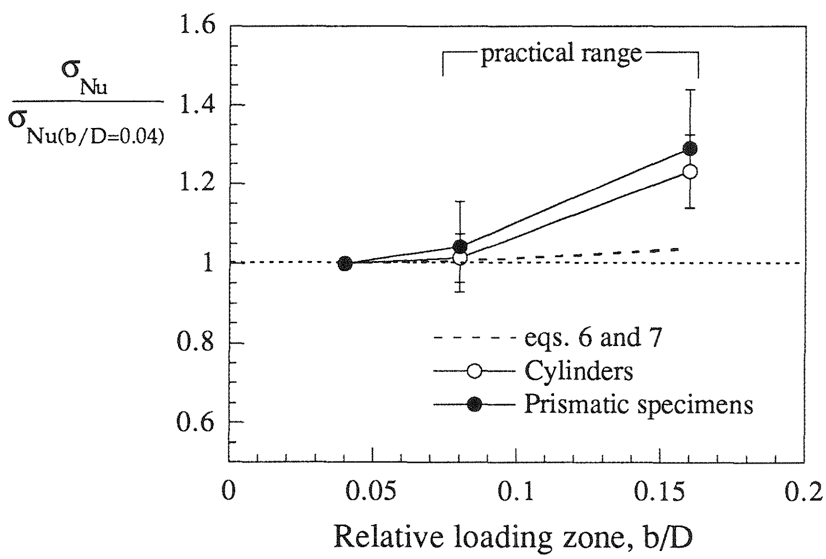

Fig.3. Relative peak loads as a function of the width of the loading zone

Equations (6) and (7) are represented in figure 3, where the nominal ultimate stresses have been referenced to the load distribution with b/D=0.04. The figure clearly shows that experimental results do not match the theoretical behavior. This could have far-reaching implications because the bearing width recommended by the standards and by most concrete handbooks falls between 8 and 16% of specimen depth, in a zone where the peak load has a great variation.

4.2 Influence of specimen size

The results for prismatic specimens with b/D=0.08 as a function of size are plotted in figure 4 togehter with results of split-cylinder tests by other authors (Sabnis and Mirza,1979; Chen and Yuan,1980; Bazant et al., 1991). In our tests, no appreciable size effect is present over a wide range of sizes, with D increasing eight-fold. It should be noted that even the smaller sizes are well over the maximum aggregate size (5mm). This behavior is in contrast with the other results reported in figure 4, where different trends of size dependence appear.

The only conclusion to be drawn from all this is that it is necessary to improve the analytical and numerical models to predict the observed behavior, taking into account the various failure mechanisms that can be operative. In addition, well-documented test results are needed, including measurements of fracture properties.

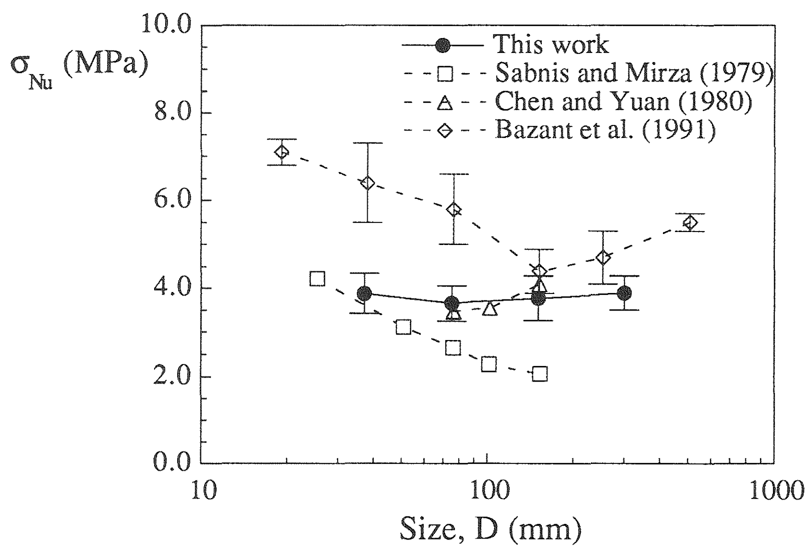

Fig. 4. Results of different splitting tests

5 Acknowledgments

The authors gratefully acknowledge financial support for this research provided by the Spanish Comision Interministerial de Ciencia y Tecnología (grant No. MAT94-0120-C03) and by the Dirección General de Investigación Científica y Técnica (grant No. PB93-0031).

6 References

Bazant, Z.P., Kazemi, M.T. Hasegawa,T and Mazars, J. (1991) Size effect in Brazilian Split-Cylinder Test: Measurements and fracture analysis. **ACI Materials Journal**,V38,3, 325-332.

Chen, W.F., and Yuan,R.L. (1980) Tensile strength of concrete:the double punch tests. **Journal of the Structural Division, ASCE**, 106, ST8, 1673-1693.

Davies, D. and Bose, D.K. (1968) Stress distribution in splitting tests. **ACI Journal**, August, 662-669

Elices,M., Guinea,G.V. and Planas,J. (1992) Measurement of the fracture energy using three-point bend tests: Part1-Influence of cutting the P-δ tail. **Materials and Structures**, 25, 327-334.

Goodier, J.N.(1932) **Transactions of the American Society of Mechanical Engineers**,53, 173-183.

Guinea,G.V., Planas,J. and Elices,M. (1992) Measurement of the fracture energy using three-point bend tests: Part1-Influence of experimental procedures. **Materials and Structures**, 25, 212-218.

Nilsson, S. (1961) The tensile strength of concrete determined by splitting tests on cubes. **RILEM Bulletin**, 11, 63-67.

Planas,J., Elices,M. and Guinea,G.V. (1992) Measurement of the fracture energy using three-point bend tests: Part2-Influence of bulk energy dissipation. **Materials and Structures**, 25, 305-312.

RILEM TC50-FMC (1985) Determination of the fracture energy of mortar and concrete by means of three-point bend tests on notched beams. **Materials and Structures**, 18, 285-290.

Sabnis,G.M., and Mirza, S.M.(1979) Size effects in model concretes ?", **Journal of the Structural Division**, ASCE, 105, ST6,1007-1020.

Timoshenko, S.P. and Goodier, J.N. (1951) **Theory of elasticity**. Mc.Graw-Hill, New York .

Tang,T. (1994) Effects of load distributed width on split tension of unnotched and notched cylindrical specimens. **Journal of Testing and Evaluation**, Vol 22, 5, 401-409.