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EXPERIMENTAL ANALYSIS OF FRACTURE PROCESSES IN CONCRETE

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Abstract. *This paper draws on the basic problems related to the determination of parameters to characterize the structural behavior of concrete using Fracture Mechanics concepts. Experimental procedures and results are discussed.*

Keywords: *Fracture Mechanics, Concrete, Crack, Fracture Toughness, Fracture Energy*

1. INTRODUCTION

Engineering materials are full of cracks. Although structures can be safely built with these materials, this fact is relevant for the design of a wide class of structures. Most of the design procedures currently in use are based on Strength of Materials concepts, i. e., stresses have yielding or rupture limits. However, stress concentrations around notches, , connections, etc. require that more sophisticated design procedures be used as safety factors are reduced due to increasing demands for materials and energy conservation.

The presence of cracks, apparently a sign that something is wrong with the component or structure, does not mean that the structure reached the limit of its useful life. With the development of Fracture Mechanics, the question now is not whether a crack exists or not, but whether the cracks are stable or not. In reinforced concrete structures, cracks have been tolerated since the earlier design procedures, in which concrete is responsible for compression while steel is responsible for tensile stresses required for equilibrium. Using Fracture Mechanics concepts, one would say that the reinforcement role is to arrest the cracks.

The state-of-the-art in Fracture Mechanics applied to concrete indicates a great variety of models requiring that parameters be obtained from concrete samples to characterize, basicaly, resistance to crack propagation. This paper draws on the determination of fracture parameters for concrete, describing experimental procedures and results.

2. THEORETICAL BACKGROUND

The basic theory of Fracture Mechanics, based on concepts of linear elasticity, developed from the studies of Inglis (1913), Griffith (1921), Westergaard (1939) and others.

Westergaard (1939) developed a linear elastic description for the stress field around the crack tip, using stress functions in the complex domain. The introduction of the concept of stress intensity factors became straightforward from Westergaard´s solution, which, associated to the concept of fracture toughness, establish the basis for the Linear Elastic Fracture Mechanics (LEFM). The earliest engineering applications emerged in the end of the fourties, with Irwin´s work (1948).

The fact that the elastic solution presents infinite stresses at the crack tip suggested that some sort of inelastic stress redistribution in the zone near the crack tip would take place. The size of this region, called *inelastic process zone*, is a parameter to evaluate the applicability of LEFM, when compared to crack and ligament sizes, and component thickness.

Dugdale (1960) and Barenblatt (1962), developed, independently and for different applications, solutions for the stress redistribution in a strip ahead of the crack tip, valid for ductile materials. Later, these basic concepts were used to model the cohesive crack model for quasi-brittle materials, applicable to concrete (Hillerborg, 1976; Bazant, 1983; Bittencourt, 1995). However, this solution, although suitable to model a single or a few cracks, is not sufficient to model a fracture process in concrete. Other models are necessary to simulate processes in which microvoids and microcracks propagate and coalesce to a group of macrocracks.

The development of sophisticated models for the concrete is meaningless if the appropriate parameters are not available for Engineering applications. In this paper, the development and application of experimental procedures for the determination of fracture parameters in concrete is described, using two different types of specimens.

3. EXPERIMENTAL METHODOLOGY

Fracture toughness tests were performed on short-rod and three-point-bend specimens of concrete, at room temperature and at ages 14, 28 and 56 days. Specimens were tested on a MTS Model 810 testing machine, under crack mouth opening displacement (CMOD) control. The load was applied at a rate between 2 and 3 N/s. During the test, plots of CMOD versus applied load were produced. Based on these plots, cycles of unloading to 10-20% of the maximum observed load, and subsequent reloading were performed, at least twice. These unloading-reloading cycles were meant to provide information for computation of a correction factor, to be applied to the fracture toughness computed directly by LEFM formulae, to account for the nonlinear behavior of the concrete.

3.1 Short-rod specimens

Short-rod specimens were built with loading bars, perpendicular to the chevron notch plane, as shown in Figure 1. Alternative systems for load application (Figure 2) were developed by others (Tschegg et al,1995; Hanson et al, 1999) and are currently being tested by USP/UNICAMP research group. CMOD was measured by a MTS Model 632.03C.20 clip on gage.

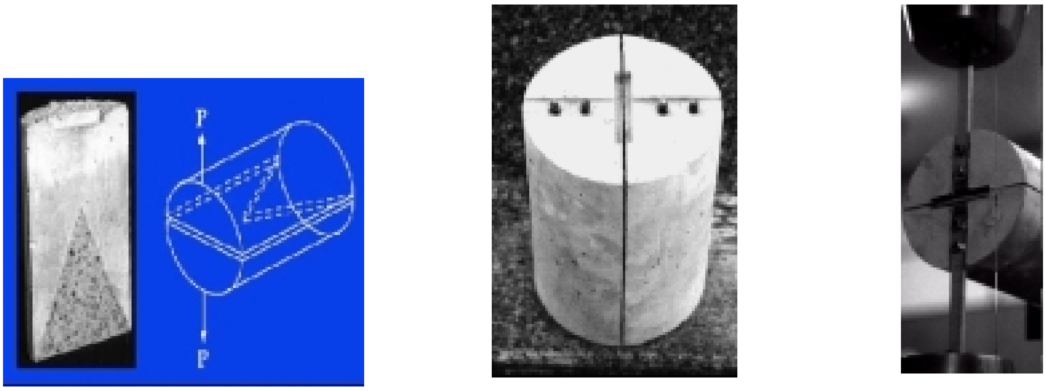
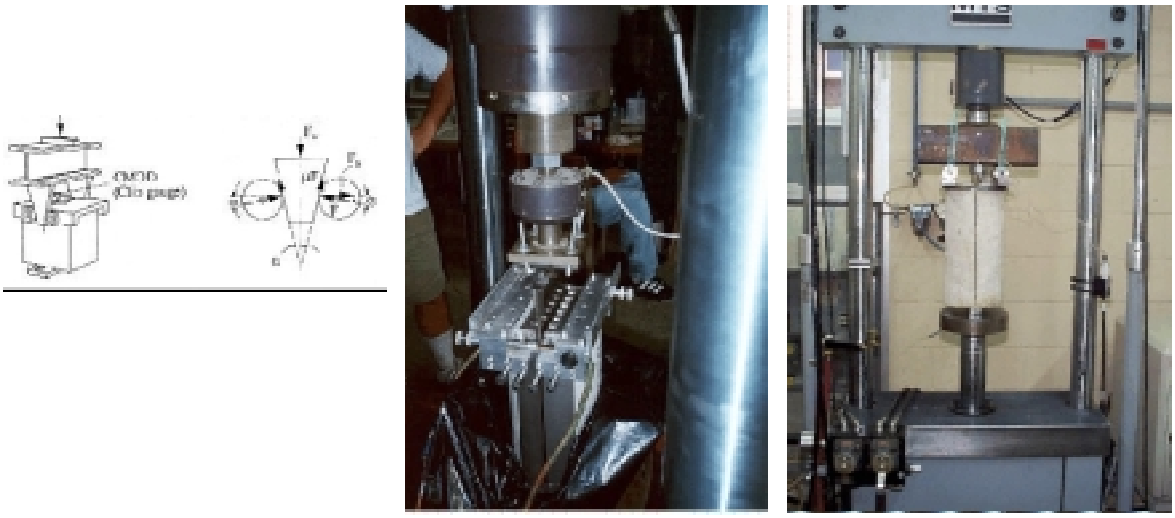


Figure 1 Short-rod specimen and load application system



(a) Wedge system applied to cubic specimens (Tschegg et al, 1995)

(b) Wedge system applied to Short Rods (Hanson & Ingraffea, 1999)

(c) Compressive system (Hanson & Ingraffea, 1999; Bittencourt *et al*, 1999)

Figure 2 Alternative systems for load application in short rod specimens

According to ISRM (1988), fracture toughness can be obtained by

$$K_{SR} = \sqrt{\frac{1+p}{1-p}} \cdot \frac{C_K \cdot 24 \cdot \overline{F}}{D^{1,5}} \tag{1}$$

where $p = \Delta x_0 / \Delta x$,

ΔX , ΔX_0 : according to Figure 3a;

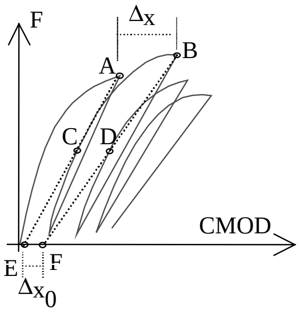
$\overline{F}$: average load (points A and B);

D: specimen diameter; e

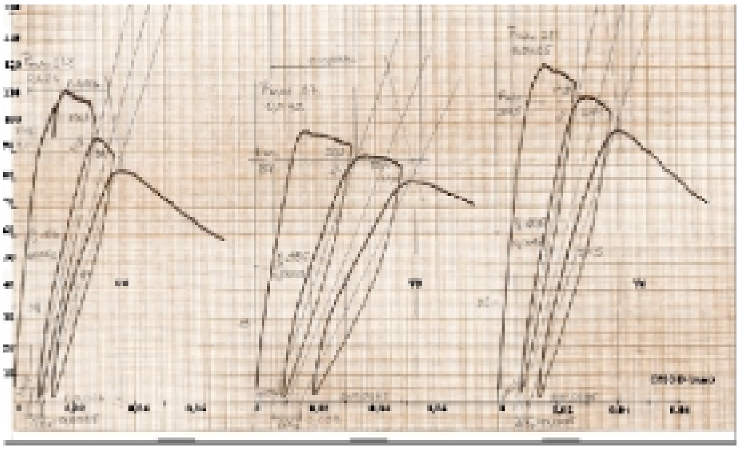
C_K : correction factor to account for the specimen size variation Eqn. (2):

$$C_K = (1 - \frac{0.60\Delta W}{D} + \frac{1.40\Delta a_0}{D} - 0.01\Delta\theta) \tag{2}$$

ΔW : variation in specimen height;
Δa_0 : initial position of notch apex;
$\Delta\theta$: chevron angle



(a) definitions for correction factor computations based on the load versus CMOD plot



(b) plots of load versus CMOD obtained from tests

Figure 3 Plots of load versus CMOD from a CMOD-controlled test for the determination of fracture toughness of concrete

3.2 Three-point-bend specimens

Size Effect on Fracture Energy and Fracture Toughness, K_{Ic}, was investigated for plain concrete, using three-point-bend tests on specimens with initial through notches (Figure 4). The investigation was conducted on similar beams, with height varying from 3 cm to 12 cm. Fracture Toughness was determined with the Two-Parameter Crack Model and the Effective Crack Model suggested by RILEM (International Union of Testing and Research Laboratories for Materials and Structures), and the linearization procedure proposed by ISRM (International Society of Rock Mechanics). Fracture Energy was determined using the Size Effect Model, also proposed by RILEM.

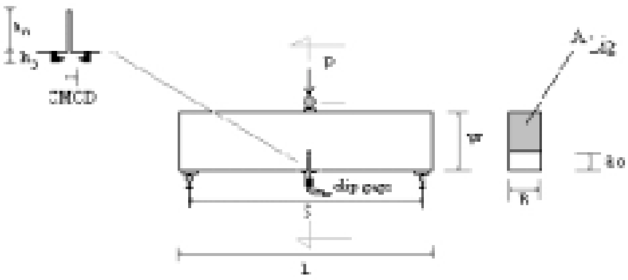


Figure 4 Three-Point-Bend Specimen

4. EXPERIMENTAL RESULTS

4.1 Short Rod specimens

Experimental tests were performed on short rod specimens. Results are presented in details by Santos et al (1998). Table 1 presents a summary of the results to illustrate the kind of results that could be obtained for 4 different mixes of concrete, varying strength and aggregate size, including the corresponding correction factor to take into account the non-LEFM behavior of the concrete at the specimen scale.

Table 1 : Experimental results for groups of short-rod specimens

	Compressive Strength (MPa)			Tensile Strength(MPa)			Correction factor $\sqrt{\frac{1+p}{1-p}}$			K_{Ic} (MPa $\sqrt{m}$)		
Age (Days)	14	28	56	14	28	56	14	28	56	14	28	56
Mix 1	22,3	24,9	31,0	2,1	2,6	2,6	0,88	0,86	1,04	1,34	1,19	1,36
Mix 2	19,0	22,2	27,0	2,0	2,2	2,5	0,79	0,90	1,01	1,21	1,33	1,47
Mix 3	40,6	47,2	54,5	3,6	4,4	3,5	0,14	1,50	1,65	2,04	1,98	2,03
Mix 4	47,0	46,9	51,2	4,2	4,3	3,9	0,15	1,66	1,58	2,09	2,49	2,35

The short rod specimen is very simple to test. The test setup developed lead to significant results, with only a few specimen lost during preparation and test. The rupture mode was uniform (mode I). Low values of standard deviation were observed in the experimental results, showing the reliability of the test procedures. Results indicated that fracture toughness is inversely influenced by the increase in the water/cement ratio and by the increase in the aggregate size. The ratio between the fracture toughness in level II and in level I ($\sqrt{\frac{1+p}{1-p}}$) increases as the aggregate size increases.

4.2 Three-point-bend specimens

Fracture Toughness values obtained from laboratory tests appear strongly influenced by Size Effect, within the range of sizes investigated. The phenomenon of relaxation, observed at peak load under a constant CMOD condition, was investigated and associated to a possible break down of the cohesive interface (Ferreira, 1998). Under these circumstances, the length of the cohesive interface at peak load was modeled. Fracture Toughness values originated from these lengths look almost constant, independently of specimen size (Ferreira, 1997).

5. CONCLUSIONS

A brief description of the first attempts performed by researchers towards the application Fracture Mechanics concepts to concrete and reinforced concrete was presented. Results obtained by two co-workers are briefly presented (Santos, 1998, and Ferreira, 1998). Although results are not exhaustive, an important area of research was initiated and is currently active in the research groups of USP and Unicamp, in collaboration with Ingraffea´s Cornell Fracture Group and other researchers.

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