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# An investigation on the "width and size effect" in the evaluation of the fracture energy of concrete

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**Abstract**

The parameters that describe the fracture behavior of concrete are crucial to investigate numerically the response of reinforced concrete (RC) structures. Among them, the fracture energy plays a key role in all those applications that aim to simulate the behavior of RC structures. The fracture energy is a characteristic property of a material but its experimental evaluation could be difficult for quasi-brittle materials such as concrete due to the "width effect" and "size effect" that can lead to some uncertainties in the definition of this parameter. This study presents the results of an experimental campaign conducted on notched specimens to evaluate the fracture energy of concrete. Concrete prisms with different sizes were tested using a three-point bending (TPB) set-up to evaluate the influence of the width and the size on the results. The setup has been designed to become potentially part of the ACI 446 report on fracture. Digital image correlation (DIC) was used to qualitatively and quantitatively study the strain field near the crack tip. Preliminary numerical simulations were performed to investigate the "width effect" in a discrete element framework.



*Keywords:* Fracture mechanics; concrete; fracture energy; width effect; size effect.

## 1. Introduction

The tensile strength and the fracture parameters of concrete are important properties of concrete when the anchorage of deformed bars, shear forces in slabs and beams, splitting under concentrated forces, unreinforced pipes, and bond of composite materials (Carloni, 2014) are investigated. Although the influence of these properties on the behavior of

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concrete elements is well known, they have been rarely used in design codes. For example, in many European codes the definition of the shear strength of concrete elements is based on empirical design formulas, neglecting any fracture parameters in these formulations. Fortunately, due to the increasing interest on the fracture mechanics of concrete in the last few decades and the pioneering work of some researchers (Bažant, 1997), some fracture parameters have been considered for design formulas. For example, the definition of the load-carrying capacity of composite strips bonded to concrete (Carloni, 2014) depends on the fracture properties of the interface.

The main fracture parameter of concrete is the fracture energy $G_F$, i.e. the energy required to create and fully break the elementary unit area of a cohesive crack. It is well known that the classical linear elastic fracture mechanics (LEFM) of sharp cracks is inadequate for concrete structures, as pointed out first by Kesler et al. (1972). This conclusion was confirmed by Walsh et al. (1976), who conducted an experimental campaign on geometrically similar notched beams of different sizes. Plotting the results in a double logarithmic diagram of nominal strength versus size they observed that the diagram deviates from a straight line of slope -1/2 predicted by LEFM. The inapplicability of LEFM to concrete is due to the development of a sizable nonlinear zone that develops at the fracture front. In concrete and other quasi-brittle materials, the nonlinear zone is almost entirely filled by the fracture process zone (FPZ) that is defined as the zone in which the material undergoes softening damage, while the plastic flow is next to nonexistent. In addition, the length of the FPZ, which is equal or proportional to the so-called characteristic length (Hillerborg, 1985), $l_{ch}$, may occupy a larger portion of the cross-section of the structural member or encompass the whole cross-section. Due to the high influence of the concrete element dimensions on the crack propagation and on fracture parameters, the "size and width effects" have gained a terrific interest in the evaluation of the fracture energy of concrete. Fracture mechanics of quasi brittle materials was studied also through numerical analysis. New approaches to the modelling of quasi-brittle fracture, as the lattice model, have been developed, proposing as an alternative to traditional nonlinear analysis as the cohesive crack model proposed by Hillerborg (1976) and by Petterson (1981) or the crack band model proposed by Bažant (1983).

This study presents the results of an experimental campaign conducted on notched specimens to evaluate the fracture energy of concrete. Concrete prisms with different sizes were tested using a three-point bending (TPB) set-up to evaluate the influence of the width and the size of the prisms on the results. The set-up has been designed to become potentially part of the ACI 446 report on fracture. Digital image correlation (DIC) was used to qualitatively and quantitatively study the strain field near the crack tip. Preliminary numerical simulations were performed to investigate the "width effect" and to confirm experimental results.

## 2. Experimental Program

### *2.1. Materials*

All concrete prisms were cast from the same batch of concrete. The concrete was normalweight with portland cement and a maximum aggregate size of 15 mm. Compressive and tensile strength of concrete were measured at different ages. Compressive strength was determined using 150 mm side cubes and 150 mm × 300 mm cylinders that were tested according to EN 12390-3 (2009). Tensile strength was determined using 150 mm × 300 mm cylinders that were tested according to EN 12390-6 (2009). The average values of three tests for each age are plotted in Figure 1.

Fracture mechanics tests were performed approximatively 300 days after prisms were cast. The behavior of the cubic compressive strength at different ages was fitted using the formula proposed in Eurocode 2 (2004):

$$R_{cm}(t) = \exp\left\{ s\left[1-\left(\frac{28}{t}\right)^{1/2}\right]\right\} R_{cm} \tag{1}$$

where $R_{cm}$ is the mean cubic compressive strength at 28 days obtained from experimental tests, while $s$ is a parameter defined through a non-linear regression. The coefficient $s$ was found to be equal to 0.31, which is slightly higher than prescriptions suggested in Eurocode 2 (2004). The same formula was used to fit the results of tensile tests, using the mean tensile strength at 28 days obtained from splitting tests, $f_{tm}$, instead of $R_{cm}$ (coefficient $s$ equal to 0.15). Since the