ABSTRACT. The initiation and propagation of a continuous crack in concrete occurs after the formation at the crack front of a fracture process zone the size of which is not negligible compared to structural dimensions. The results of experimental observations are reported and proposed techniques for the analysis of crack propagation in concrete through nonlinear constitutive relations are illustrated. The concept of R-curve is introduced as a method for the application of linear elastic fracture mechanics to concrete, and the parameters involved in the definition of the R-curve are determined on the basis of the size effect law.

1. INTRODUCTION

The formation of a crack in concrete is a complex phenomenon in which a finite region of material first undergoes severe microcracking and then unloads giving rise to a localization of strain until complete separation occurs. Ahead of the "true" crack there is, then, a process zone composed of a part in which a discontinuity in the displacement field is developing (although forces bridging the crack are still transmitted due to debonding and aggregate interlock), and a part in which microcracking is diffused in a region of finite width. Several experimental methods can be used for the observation of this phenomenon, but so far only techniques which measure the strain field on the surface of the specimen have been reported in detail and will be illustrated here. It will appear that the length of the process zone is not negligible compared to the structure size, and that the crack tip is not easily definable, so that linear fracture mechanics cannot be directly applied. A nonlinear analysis is then best suited for the prediction of crack propagation, and two strain-softening material models will be illustrated, based one on a discrete crack representation, the other on the smeared crack approach. Frequently, however, the fracture process zone does not alter the remote stress field with respect to that corresponding to a linear fracture mechanics solution for a certain equivalent
crack length. It is possible, then, to analyze fracture in concrete with approximate methods based on linear fracture mechanics introducing the concept of $R$-curve, i.e. the variation of fracture energy with crack extension. The "raw" experimental data do not allow a direct determination of the $R$-curve; they must first be "smoothed", and this can be accomplished by using the size effect law.

2. EXPERIMENTAL OBSERVATION OF THE FRACTURE PROCESS ZONE

Since the formation and coalescence of microcracks are responsible for the existence of the fracture process zone, this can be detected by optical microscopy, and a review of its application can be found in [1]. The impregnation of cracks with dyes allows, by sectioning the specimen after the tests, the recognition of the spread of cracking inside the specimen. The limit of optical microscopy is the effective resolution, which can be estimated to be [2] in the order of 20 $\mu$m; it can be augmented through the use of ultraviolet light and fluorescent dye [3]. Also X-rays [4] can be used to detect cracks inside thin slices of concrete, with a resolution similar to the one achieved with microscope and fluorescent dye. Techniques which use the Scanning Electron Microscope have proved [2] the existence on the surface of concrete specimen of tortuous cracks having width of fractions of $\mu$m, with branching and multiple fine cracking near the end of each branch. At this scale the phenomenon is essentially three-dimensional, and so complex that it is not possible to discriminate between the advancing true crack and the fracture zone ahead of it. All these techniques for the observation of microcracks are very useful for a phenomenological description of the fracture process, but do not give information expressed in macroscopical terms of strain.

Acoustic methods can also be used in order to give a measure of the extension and level of damage in the material. Methods based on the measure of acoustic emission due to microcracking and other dissipative phenomena are described in [5]. In [6] this technique has been applied to a double cantilever beam specimen, and the cumulative sum of acoustic energy has been correlated to other fracture mechanics parameters. The change in ultrasonic pulse transit time can alternatively be used, and in [7] it has been applied to a variable section beam, obtaining some indication on the extension of the fracture process zone.

A method recently developed is infrared thermography, by which the heat generated by exciting the material beyond its stable reversible limit can, under vibratory loading, show the coalescence of damage in a limited zone of the specimen [8].

The measure of the displacement (or strain) field in the surroundings of a notch can give a direct indication of the extension of the fracture process zone. Strain gages have been used in [9] and [10]; however the length of their basis is too large to capture the localization of strain, as it has been proved in [11] and, moreover, they do not allow a continuous measure of the strain field. For this purpose methods based on speckle metrology and holographic interferometry are