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Finite Element Analysis of Fracture in Concrete Structures: State-of-the-Art

Reported by ACI Committee 446

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Fracture is an important mode of deformation and damage in both plain and reinforced concrete structures. To accurately predict fracture behavior, it is often necessary to use finite element analysis. This report describes the state-of-the-art of finite element analysis of fracture in concrete. The two dominant techniques used in finite element modeling of fracture—the discrete and the smeared approaches—are described. Examples of finite element analysis of cracking and fracture of plain and reinforced concrete structures are summarized. While almost all concrete structures crack, some structures are fracture sensitive, while others are not. Therefore, in some instances it is necessary to use a consistent and accurate fracture model in the finite element analysis of a structure. For the most general and predictive finite element analyses, it is desirable to allow cracking to be represented using both the discrete and the smeared approaches.

Keywords: Concrete; crack; cracking; damage; discrete cracking; finite element analysis; fracture; fracture mechanics; reinforced concrete; structures; size effect; smeared cracking.

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CHAPTER 1—INTRODUCTION

In this report, the state-of-the-art in finite element modeling of concrete is viewed from a fracture mechanics perspective. Although finite element methods for modeling fracture are undergoing considerable change, the reader is presented with a snapshot of current thinking and selected literature on the topic.

1.1—Background

As early as the turn of the 19th century, engineers realized that certain aspects of concrete behavior could not be described or predicted based upon classical strength of materials techniques. As the discipline of fracture mechanics has developed over the course of this century (and indeed, is still developing), it has become clear that a correct analysis of many concrete structures must include the ideas of fracture mechanics.

The need to apply fracture mechanics results from the fact that classical mechanics of materials techniques are inadequate to handle cases in which severe discontinuities, such as cracks, exist in a material. For example, in a tension field, the stress at the tip of a crack tends to infinity if the material is assumed to be elastic. Since no material can sustain infinite stress, a region of inelastic behavior must therefore surround the crack tip. Classical techniques cannot, however, handle such complex phenomena. The discipline of fracture mechanics was developed to provide techniques for predicting crack propagation behavior.

Westergaard (1934) appears to have been the first to apply the concepts of fracture mechanics to concrete beams. With the advent of computers in the 1940s, and the subsequent rapid development of the finite element method (FEM) in the 1950s, it did not take long before engineers attempted to analyze concrete structures using the FEM (Clough 1962, Ngo and Scordelis 1967, Nilson 1968, Rashid 1968, Cervenka and Gerstle 1971, Cervenka and Gerstle 1972). However, even with the power of the FEM, engineers faced certain problems in trying to model concrete structures. It became apparent that concrete structures usually do not behave in a way consistent with the assumptions of classical continuum mechanics (Bazant 1976).

Fortunately, the FEM is sufficiently general that it can model continuum mechanical phenomena as well as discrete phenomena (such as cracks and interfaces). Engineers performing finite element analysis of reinforced concrete structures over the past thirty years have gradually begun to recognize the importance of discrete mechanical behavior of concrete. Fracture mechanics may be defined as that set of ideas or concepts that describe the transition from continuous to discrete behavior as separation of a material occurs. The two main approaches used in FEM analysis to represent cracking in concrete structures have been to 1) model cracks discretely (discrete crack approach); and 2) model cracks in a smeared fashion by applying an equivalent theory of continuum mechanics (smeared crack approach). A third approach involves modeling the heterogeneous constituents of concrete at the size scale of the aggregate (discrete particle approach) (Bazant et al. 1990).

Kaplan (1961) seems to have been the first to have performed physical experiments regarding the fracture mechanics of concrete structures. He applied the Griffith (1920) fracture theory (modified in the middle of this century to become the theory of linear elastic fracture mechanics, or LEFM) to evaluate experiments on concrete beams with crack-simulating notches. Kaplan concluded, with some reservations, that the Griffith concept (of a critical potential energy release rate or critical stress intensity factor being a condition for crack propagation) is applicable to concrete. His reservations seem to have been justified, since more recently it has been demonstrated that LEFM is not applicable to typical concrete structures. In 1976, Hillerborg, Modeer and Petersson studied the fracture process zone (FPZ) in front of a crack in a concrete structure, and found that it is long and narrow. This led to the development of the fictitious crack model (FCM) (Hillerborg et al. 1976), which is one of the simplest nonlinear discrete fracture mechanics models applicable to concrete structures.

Finite element analysis was first applied to the cracking of concrete structures by Clough (1962) and Scordelis and his coworkers Nilson and Ngo (Nilson 1967, Ngo and Scordelis 1967, Nilson 1968). Ngo and Scordelis (1967) modeled discrete cracks, as shown in Fig. 1.1, but did not address the problem of crack propagation. Nilson (1967) modeled progressive discrete cracking, not by using fracture mechanics techniques, but rather by using a strength-based criterion. The stress singularity that occurs at the crack tip was not modeled. Thus, since the maximum calculated stress near the tip of a crack depends upon element size, the results were mesh-dependent (nonobjective). Since then, much of the research and development in discrete numerical modeling of fracture of concrete structures has been carried out by Ingraffea and his coworkers (Ingraffea 1977, Ingraffea and Manu 1980, Saouma 1981, Gerstle 1982, Ingraffea 1983, Gerstle 1986, Wawrzynek and Ingraffea 1987, Swenson and Ingraffea 1988, Wawrzynek and Ingraffea 1989, Ingraffea 1990, Martha et al. 1991) and by Hillerborg and coworkers (Hillerborg et al. 1976, Petersson 1981, Gustafsson 1985).

Another important approach to modeling of fracture in concrete structures is called the smeared crack model (Rashid 1968). In the smeared crack model, cracks are modeled by changing the constitutive (stress-strain) relations of the solid continuum in the vicinity of the crack. This approach has been used by many investigators (Cervenka and Gerstle 1972, Darwin and Pecknold 1976, Bazant 1976, Meyer and Bathe 1982, Chen 1982, Balakrishnan and Murray 1988). Bazant (1976) seems to have been the first to realize that, because of its strain-softening nature, concrete cannot be modeled as a pure continuum. Zones of damage tend to localize to a size scale that is of the order of the size of the aggregate.