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Fracture Mechanics Applications in Concrete

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Preface

Fracture Mechanics Applications in Concrete

Over the last decade, new developments in fracture mechanics and the increase of computational capacity have improved the accuracy of modeling the quasi-brittle nature of concrete. This enhanced modeling capacity has facilitated the application of fracture mechanics to solving full-scale design problems and evaluating new concrete and cementitious materials. The papers presented in this special publication focus on the implementation of fracture mechanics techniques in fiber-reinforced concrete, fiber-reinforced polymers, bonding, large structures, beam shear, pavements, and concrete deterioration. Where applicable, the papers compare modeling results with experimental tests. The objective of this publication is to present these recent developments in a manner that facilitates both further research by faculty and students and implementation by civil engineering practitioners. This special publication of the ACI Committee 446 contains ten papers on applications of fracture mechanics in concrete. Many of these papers were originally collected and presented at the Spring Convention in 2012 in Phoenix, AZ. In the first paper, Saouma presents an overview of his 35 years of experience in applying fracture mechanics to concrete structures, providing several fracture mechanics examples in many civil engineering applications as well as a list of future desires for implementation of fracture mechanics by the concrete industry. Next, Mu, Vandenbossche, and Janssen address the use of fracture mechanics to model the bond between Portland cement concrete pavement overlays and existing asphalt pavements. Tompkins, Khazanovich, Bolander, and Stolarski suggest the implementation of fracture information into a lattice finite element model to describe the interface of two composite pavement layers and their likelihood of debonding, while Kim and Bordelon highlight the use of total fracture energy to analyze the fiber component contribution in the fracture behavior of fiber-reinforced concrete. Mobasher, Bonakdar, and Bakhshi propose a back-calculation procedure to determine fracture properties of fiber-reinforced concrete from cyclical flexural fracture tests. Le and Bazant review the problems of accounting for probability in the mechanics-based modeling of strength of concrete, demonstrating the importance of size effect in the reliability analysis of large concrete structures through an example analysis of the Malpasset Dam. Wendner, Strauss, and Novak present an overview of the role of fracture mechanics in the reliability analysis of structures, and Yu and Bazant present a review of recent work on shear failure tests and size effect related to shear for reinforced concrete beams. Rao and Sundaresan use a strut-and-tie model to perform a size-dependent prediction of the ultimate shear strength of reinforced concrete deep beams. Finally, Riveros and Gopalaratnam further analyze the shear response of reinforced concrete deep beams and validate the fracture-mechanics-based numerical model with experiments. We would like to thank the authors who contributed to this special issue as well as the reviewers for their valuable feedback.

Cristián Gaedicke, PhD, PE
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Editors, ACI 446 SP

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Paper 01:

Applications of Fracture Mechanics to Cementitious Materials

A Personal Perspective

Victor E. Saouma

Synopsis

It has been well over thirty years since Hillerborg and Bažant presented their landmark papers (cohesive crack and size effect models respectively), and thirty years since the author submitted his Ph.D. dissertation on the application of fracture mechanics to concrete, (Saouma, 1980). Yet, since then, the practical applications of fracture mechanics to concrete structures have been few and far in between.

In this paper, the author shares his experience in trying to apply fracture mechanics not only to concrete structures, but also to other "neighboring" materials such as polymers and ceramics, and he argues for improved collaboration with adjacent disciplines. The underpinnings (experimental, computational) of reported applications will be briefly highlighted.

Finally, the paper concludes with a personal assessment of the current of state in the application of fracture mechanics to concrete structures and venture in some recommendations.

Victor Saouma is a Professor at the University of Colorado in Boulder, and president of the International Association for Fracture Mechanics of Concrete and Concrete Structures (IA-FraMCoS). He received his PhD from Cornell (under the supervision of Anthony Ingraffea). He has multiple areas of research interests: fracture mechanics, deterioration of concrete (he is currently completing a book on *Numerical Modeling of AAR*), numerical modeling of concrete dams and nuclear reactors, real time hybrid simulation, innovative testing procedures.

His research is characterized by an attempt to start from either laboratory work or first principles, followed by model developments, implementation in finite element codes, validation and then application.

His research has been primarily funded by industry, the Electric Power Research Institute (EPRI), and then the Tokyo Electric Power Company (TEPCO) through which he developed over more than 20 years a finite element code Merlin. He has taught (and had research collaboration) with France, Switzerland, Spain, Italy, and Japan.

He has been a consultant on the nonlinear dynamic analysis of very high arch dams in seismic zones, on the fracture mechanics analysis of the delamination of a nuclear power plant, on the prognosis for a massive reinforced concrete structures suffering from AAR, and most recently on the development of Performance based Earthquake Engineering for concrete dams abroad.

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1 INTRODUCTION

It has been over thirty years since Hillerborg et al. (1976) and Bažant, Z.P. (1976) (simultaneously) published their landmark papers on the cohesive crack model and the size effect respectively, and thirty years since the author submitted his Ph.D. dissertation on the application of fracture mechanics to concrete, (Saouma, 1980). Since then, there has been countless publications, as well as eight FraMCoS conferences focusing on the fracture of concrete.

Discarding case studies where one performs a numerical simulation of a laboratory test, it is blatantly clear that there are few, very few, reported cases of practical applications of fracture mechanics. From a computational side, this issue was addressed by Emery et al. (2007).

This is indeed a matter of concern, as our infrastructure is aging, and most failure result in micro (under compression), (Hsu et al., 1963) or macro cracks. Whether cracks are the cause failure or are the consequence of (another) failure (mechanism), is another fundamental issues often neglected. Hence, one has to remain hopeful that ultimately fracture mechanics will play a more prominent role in the safety assessment of existing structures, or in forensic studies (which often require a nonlinear analysis) than for the design of new ones[1].

Whereas academic papers emphasize theoretical/experimental aspects and terminate with some sort of an application, this one will start with applications, and conclude with an overview of the theoretical/experimental underpinnings which made these applications possible and credible.

2 Applications

Trying to put things into perspective, the author's PhD thesis, (Saouma, 1980) was probably one of the first doctoral dissertations focusing on the fracture mechanics of concrete structures. Largely inspired by the earlier work of his mentor, (Ingraffea, 1977), it developed a computer program (Finite Element Fracture Analysis Program) with adaptive remeshing for discrete crack propagation. Fig. 1 is an illustrative example of the analysis of the "mythical" reinforced concrete beam widely known as OA-1 tested by Bresler and Scordelis (1961) who were investigating the shear strength of reinforced concrete beams.

Fig. 1(a) is a snap-shot of the mesh after 13 crack propagation increments. The (crude) automatic remeshing is evident, yet such an early analysis (where the only nonlinearity was caused by the nucleation/propagation of a discrete crack governed by linear elastic fracture mechanics) yielded already a nonlinear load-displacement curve, Fig. 1(c). Finally, a realistic crack profile, consistent with ACI-318 prediction was obtained, Fig. 1(b).

Though this program was used for a couple of subsequent years, when the opportunity came (through the financial support of EPRI), an entirely new program (Merlin) was developed (Saouma et al., 2010) and all results presented in this paper are based on it. In the following

[1] Though ironically, design is now based on "limit state", while the analysis remains linear elastic

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