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FRACTURE TOUGHNESS AND FRACTURE ENERGY OF CONCRETE

Edited by

FOLKER H. WITTMANN

FRACTURE TOUGHNESS AND FRACTURE ENERGY OF CONCRETE

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PREFACE

To mark the end of the activities of a RILEM Technical Committee on Fracture Mechanics of Concrete (50-FMC), an International Conference was organized at the Swiss Federal Institute of Technology, Lausanne, October 1-3, 1985. The subsequent work of this group lead to the publication of a RILEM recommendation on the determination of the fracture energy of concrete (see Materials and Structures, 18, 285-290, 1985). Several series of comparative tests were carried out, with the participation of more than ten laboratories worldwide. Experience gathered in this way was taken into consideration in the final version of the recommendation. The theoretical basis and experimental data leading to the recommendation were presented during the conference and are documented in this volume.

The first aim of the RILEM Technical Committee 50-FMC was achieved with the publication of a comprehensive state-of-the-art report on the fracture mechanics of concrete in 1983 (Fracture Mechanics of Concrete, edited by F.H. Wittmann, Elsevier, 1983). An annotated bibliography is included in that volume. At that time, research activities were concentrated essentially on the application of classical concepts of fracture mechanics to concrete.

Nevertheless, it has often been questioned whether fracture mechanics can be applied to describe failure of concrete. The elements of the composite structure are usually not small in comparison with the dimensions of a beam, a slab, or a column. In addition, it is known that, even in tension, concrete does not fail in a brittle manner. Therefore it is not surprising that linear elastic fracture mechanics can only be considered to be a rough approximation of the real material behaviour.

Because of these difficulties, Arne Hillerborg at Lund Institute of Technology developed a new approach which is particularly suitable for finite element analysis. In this concept, fracture toughness is replaced by fracture energy, and thus the descending branch of the stress-strain diagram can be taken into consideration. As can be seen from the annotated bibliography covering the years 1982 to 1985, compiled by Sidney Mindess and included in this volume, so far many papers are still based on classical linear elastic fracture mechanics while others have adopted the concept of fracture energy. It can be stated that this volume is published in the middle of a transition period. Most recent results of both concepts are presented here.

Several contributions describe advanced numerical methods to simulate and analyse the behaviour of composite structures such as concrete (numerical concrete). It has become obvious that today numerical methods efficiently complement experimental and theoretical studies.

It is hoped that this publication will stimulate further development in this area.

Lausanne, September 1986 F.H. WITTMANN

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FRACTURE PROCESS
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Elsevier Science Publishers B.V., Amsterdam, 1986 – Printed in The Netherlands

INTERACTION OF A CRACK WITH SOME MICROCRACK SYSTEMS

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ABSTRACT

Interaction of a crack with microcracks (modelling "damage") can significantly alter the stress concentration at the crack tip. Some important features of interaction ("shielding" and "amplification" effects, influence of microcrack orientations, etc.) are demonstrated on several simple microcrack systems.

1. INTRODUCTION

Microcracking in a process zone near microcrack tips has been observed in many brittle materials (ref. 1, 2). Interaction of the microcrack array with the main crack can significantly alter the stress concentration at the main crack tip. Depending on the geometry of the microcrack array, its presence can either increase the effective stress intensity factor, SIF (stress "amplification") or decrease it (stress "shielding"). Several simple microcrack configurations analyzed below demonstrate important features of the crack-microcrack interactions (relative strength of the amplification and shielding effects, influence of the microcrack orientations, etc.).

Consideration is based on the method of analysis proposed recently (ref. 3, 4) for the general case of elastic solids with many cracks. This method can be considered as a further development of the earlier work (ref. 5-7) based on polynomial approximations of tractions on microcracks. The method is much simpler and yields approximate analytical solutions which are quite accurate up to very small distances between cracks.

2. GENERAL FORMULATION

The configuration considered consists of a semi-infinite crack and a microcrack. First, we assume the mode I remote loading conditions and that the microcrack array is symmetric with respect to the main crack (so that the mode I conditions on the main crack are not violated). Then the stress field can be represented as a superposition

$$\underset{\sim}{\sigma}(\underset{\sim}{x}) = K_I\, \underset{\sim}{\sigma}_I(\underset{\sim}{x}) + \sum_{i=1}^{N} \underset{\sim}{\sigma}_i(\underset{\sim}{x}) \qquad (2.1)$$

(N is the number of microcracks) where $\underset{\sim}{\sigma}_I = \underset{\sim}{f}_I(\theta)/\sqrt{2\pi r}$ denotes the mode I asymptotic crack tip field and $\boldsymbol{\sigma}_i$ is the i-th microcrack-generated field (the stress field that would have been generated by an isolated i-th crack loaded by the tractions $\boldsymbol{t}_i = \boldsymbol{t}_i(\xi_i)$ induced along its line $-\ell_i<\xi_i<\ell_i$ by the other cracks and by the K_I-dominated field).

In accordance with the key idea of the method (ref. 3,4), for the general crack array, tractions $\boldsymbol{t}_i$ on the i-th crack ℓ_i are taken as induced on ℓ_i by the remote loading $\boldsymbol{\sigma}^\infty$ and the other cracks loaded by uniform <u>average</u> tractions on them; influence of traction non-uniformities on the other cracks having zero average on the traction on a given crack is thus neglected. The average tractions are then found by interrelating the traction averages on individual cracks through "transmission factors" (characterizing attenuation of the average tractions in transmission of stress from one crack onto another crack's line).

Applying this method to the configuration "crack-microcrack array", we represent the traction $\boldsymbol{t}_i$ on the i-th microcrack ℓ_i in the form (K_I-field plays the role of $\boldsymbol{\sigma}^\infty$)

$$\boldsymbol{t}_i(\xi_i) = \boldsymbol{n}_i \cdot \Big\{ K_I \boldsymbol{\sigma}_I(\xi_i) + \sum_{k=1,\, k\neq i}^{N} [\langle t_k^n \rangle \boldsymbol{\sigma}_k^n(\xi_i) + \langle t_k^\tau \rangle \boldsymbol{\sigma}_k^\tau(\xi_i)] \Big\} \tag{2.2}$$

where $\boldsymbol{n}_i$ is a unit normal to ℓ_i and $\langle t_k^n \rangle, \langle t_k^\tau \rangle$ are the normal and shear traction averages on the k-th microcrack. $\boldsymbol{\sigma}_k^n$, $\boldsymbol{\sigma}_k^\tau$ are the "standard" stress fields, generated by the k-th microcrack loaded by uniform tractions of unit intensity, normal and shear, correspondingly (they are expressed in elementary functions, see, for example, (ref. 9)). Taking average of (2.2) over the i-th crack line yields

$$\langle \boldsymbol{t}_i \rangle = \boldsymbol{\psi}_i K_I^{eff} + \sum_{k=1,\, k\neq i}^{N} \boldsymbol{\Lambda}_{ik} \cdot \langle \boldsymbol{t}_k \rangle \tag{2.3}$$

where the second rank tensor $\boldsymbol{\Lambda}_{ik}$ is a <u>transmission factor</u> characterizing interaction of the i-th and k-th crack in terms of the average tractions on them; namely, $\boldsymbol{\Lambda}_{ik} \cdot \langle \boldsymbol{t}_k \rangle$ (no summation over k) is the vector of average traction induced along ℓ_i by the k-th crack loaded by a uniform traction $\langle \boldsymbol{t}_k \rangle$. Calculation of $\boldsymbol{\Lambda}_{ik}$ involves averaging of the "standard" stress fields $\boldsymbol{\sigma}_i^n$, $\boldsymbol{\sigma}_i^\tau$ generated by the i-th crack over ℓ_k. The vector $\boldsymbol{\psi}_i = \boldsymbol{n}_i \cdot \langle \boldsymbol{\sigma}_I \rangle_{\ell_i}$ (the average traction induced by $\boldsymbol{\sigma}_I$ along ℓ_i) characterizes the impact of the main crack tip on the i-th microcrack.

N vectorial linear algebraic equations (2.3) contain N vectorial unknowns $\langle \boldsymbol{t}_k \rangle$ and an unknown scalar K_I. The additional scalar equation expresses the microcracks' impact on the main crack:

$$K_I = K_I^0 + \sqrt{\frac{2}{\pi}} \int_0^\infty \frac{1}{\sqrt{\xi}} \boldsymbol{n} \cdot \sum_{i=1}^{N} \boldsymbol{\sigma}_i(\xi) \cdot \boldsymbol{n} \, d\xi \tag{2.4}$$

where K_I^0 denotes the SIF on the main crack in the absence of microcracks, $\boldsymbol{n}$ is a unit normal to the main crack and $\boldsymbol{\sigma}_i$ is taken as the i-th microcrack response