

DEVELOPMENTS IN CIVIL ENGINEERING, 18

FRACTURE TOUGHNESS
AND FRACTURE ENERGY
OF CONCRETE

Edited by

FOLKER H. WITTMANN

TU 37

FRACTURE TOUGHNESS AND FRACTURE ENERGY OF CONCRETE

Proceedings of the International Conference on Fracture Mechanics of
Concrete, Lausanne, Switzerland, October 1-3, 1985

Edited by

FOLKER H. WITTMANN

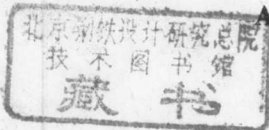
Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland



ELSEVIER

Amsterdam - Oxford - New York - Tokyo

1986



892287

BR 28/302

ELSEVIER SCIENCE PUBLISHERS B.V.
Sara Burgerhartstraat 25
P.O. Box 211, 1000 AE Amsterdam, The Netherlands

Distributors for the United States and Canada:

ELSEVIER SCIENCE PUBLISHING COMPANY INC.
52, Vanderbilt Avenue
New York, NY 10017, U.S.A.

Cover design: Computer generated graphic resembling the fracture process zone in concrete, by
Tilman Reinhardt, The Hague, The Netherlands

ISBN 0-444-42733-3 (Vol. 18)
ISBN 0-444-41715-X (Series)

© Elsevier Science Publishers B.V., 1986

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior written permission of the publisher, Elsevier Science Publishers B.V./ Science & Technology Division, P.O. Box 330, 1000 AH Amsterdam, The Netherlands.

Special regulations for readers in the USA - This publication has been registered with the Copyright Clearance Center Inc. (CCC), Salem, Massachusetts. Information can be obtained from the CCC about conditions under which photocopies of parts of this publication may be made in the USA. All other copyright questions, including photocopying outside of the USA, should be referred to the publisher.

Copyright of pages 101-116, 163-175, 197-200, 215-218, 241-268, 281-290, 535-544, 615-618 has not been transferred

Printed in The Netherlands

P R E F A C E

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 led 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

Developments in Civil Engineering

- Vol. 1 The Dynamics of Explosion and its Use (Henrych)
- Vol. 2 The Dynamics of Arches and Frames (Henrych)
- Vol. 3 Concrete Strength and Strains (Avram et al.)
- Vol. 4 Structural Safety and Reliability (Moan and Shinozuka, Editors)
- Vol. 5 Plastics in Material and Structural Engineering (Bares, Editor)
- Vol. 6 Autoclaved Aerated Concrete, Moisture and Properties (Wittmann, Editor)
- Vol. 7 Fracture Mechanics of Concrete (Wittmann, Editor)
- Vol. 8 Manual of Surface Drainage Engineering, Volume II (Kinori and Mevorach)
- Vol. 9 Space Structures (Avram and Anastasescu)
- Vol. 10 Analysis and Design of Space Frames by the Continuum Method (Kollár and Hegedűs)
- Vol. 11 Structural Dynamics (Vértes)
- Vol. 12 The Selection of Load-Bearing Structures for Buildings (Horváth)
- Vol. 13 Dynamic Behaviour of Concrete Structures (Tilly, Editor)
- Vol. 14 Shells, Membranes and Space Frames (Heki, Editor)
- Vol. 15 The Time Factor in Transportation Processes (Tarski)
- Vol. 16 Analysis of Dynamic Effects on Engineering Structures (Bata and Plachý)
- Vol. 17 Post-Buckling of Elastic Structures (Szabó, Gáspár and Tarnai, Editors)
- Vol. 18 Fracture Toughness and Fracture Energy of Concrete (Wittmann, Editor)

TABLE OF CONTENTS

	<u>Page</u>
PREFACE	v
1. FRACTURE PROCESS AND MECHANICS OF CRACK GROWTH	1
Interaction of a Crack with some Microcrack Systems	3
<i>by M. Kachanov</i>	
Mechanisms of Subcritical Crack Growth in Portland Cement Paste	11
<i>by J.J. Beaudoin</i>	
A Fracture Mechanics Evaluation of Static and Fatigue Crack Growth in Cement Mortar	21
<i>by R.B. Tait, and G.G. Garrett</i>	
The Influence of Mechanical Stresses on the Corrosion of Cementitious Materials	31
<i>by U. Schneider, and E. Nägele</i>	
The Fracture Process of Concrete at High Temperatures and Compressive Stresses	41
<i>by C. Ehm, and U. Schneider</i>	
On the Effects of Strain Gradients on the Limit State of Cracking of Concrete and the Stable Development of Microcracking	51
<i>by A. Bascoul, and J.C. Maso</i>	
Experimental Investigation of Slow Crack Growth in Concrete	55
<i>by K.L. Kovler</i>	
2. DAMAGE THEORY	59
A Model for a Unilateral Elastic Damageable Material and its Application to Concrete	61
<i>by J. Mazars</i>	

VIII

	<u>Page</u>
A Microcrack Model of Concrete's Behaviour under Applied Loads <i>by L. Nobile</i>	73
Fatigue of Concrete Via a Damage Theory <i>by Chien H. Wu</i>	81
3. COMPUTER SIMULATION AND NUMERICAL STUDIES	89
Computer Simulation Models of Fracture in Concrete <i>by X.Z. Hu, B. Cotterell, and Y.W. Mai</i>	91
Simulation of Behaviour of Light-Weight Concretes under Load and its Experimental Trial <i>by Y.V. Zaitsev, V.I. Kondrashenko, and A.A. Arshabov</i>	101
Fracture Process in Numerical Concrete <i>by P.E. Roelfstra, and H. Sadouki</i>	105
Influence of Material Parameters and Geometry on Cohesive Crack Propagation <i>by A. Carpinteri, A. Di Tommaso, and M. Fanelli</i>	117
Strain-Softening Analysis of Concrete Fracture Specimens <i>by J.G. Rots</i>	137
Composite Fracture Model for Strain Softening Computations of Concrete <i>by K. Willam, N. Bicanic, E. Pramono, and S. Sture</i>	149
Numerical Method to Link Strain Softening with Failure of Concrete <i>by P.E. Roelfstra, and F.H. Wittmann</i>	163
Numerical Simulation of Composite Materials as Concrete <i>by H. Schorn</i>	177
Accuracy of the Numerical Description of Cohesive Crack Propagation <i>by A. Carpinteri, G. Colombo, and G. Giuseppetti</i>	189
Computer Simulation of Concrete Fracture Process <i>by Li Chi-Ling, and Wu Keru</i>	197

	<u>Page</u>
Simulation of Plain Concrete Behaviour and its Experimental Examination	201
<i>by Y.V. Zaitsev, M.B. Kazatskij, and T.O. Saralidze</i>	
J-Integral Analysis of Stress Intensity Factor of Concrete	205
<i>by K. Kishitani, T. Hirai, and K. Murakami</i>	
The Finite Element Analysis of Specimens Giving a Mode II Type of Failure	209
<i>by J. Davies, T.G. Morgan, and A.W. Yim</i>	
4. INFLUENCES ON STRENGTH	213
Influence of Surface Tension of Several Kinds of Impregnated Liquids on the Strength and Young's Modulus of Cement Mortar	215
<i>by S. Ohgishi, H. Ono, and I. Tanahashi</i>	
Influence of Water Content on Concrete Strength under Direct and Diametral Tension	219
<i>by L.J. Lima, D. Violini, and R. Zerbino</i>	
The Analysis and Experimental Research on Fracture Strength and Volumetric Effect of Concrete	223
<i>by Xu Jishan, and He Xixi</i>	
5. FRACTURE PROCESS ZONE	227
Analysis of Micro-Cracked Zone in Concrete	229
<i>by F. Ansari</i>	
Techniques to Observe the Fracture Zone in Mortar and Concrete	241
<i>by L.I. Knab, H. Jennings, H.N. Walker, J.R. Clifton, and J.W. Grimes</i>	
Infrared Vibrothermography of Plain Concrete	249
<i>by M.P. Luong</i>	
Acoustic Emission Technique to Evaluate Fracture Mechanics Parameters of Concrete	259
<i>by M. Izumi, H. Mihashi, and N. Nomura</i>	

	<u>Page</u>
6. FRACTURE TOUGHNESS	269
Influence of Slow Crack Growth on the Fracture Toughness of Plain Concrete	271
<i>by P. Mallathambi, and B.L. Karihaloo</i>	
Influence of Test Conditions on Fracture Toughness of Cement Paste and Mortar	281
<i>by S. Ohgishi, H. Ono, M. Takatsu, and I. Tanahashi</i>	
Effect of the Composition of Mortars and Testing Procedures on Fracture Toughness	291
<i>by Ch.H. Détriché, and S.A. Ramoda</i>	
Fracture Toughness of Concrete	299
<i>by Tian Ming-Lun, Huang Song-Mei, Liu En-Xi, Wu Li-Yan, Long Kai-Qi, and Yang Zhi-Shan</i>	
Further Study of the Compact Compression Test Specimen Geometry	307
<i>by B.I.G. Barr, I.M. Shaker, and B.B. Sabir</i>	
Practical Fracture Toughness Test Specimens for Concrete	319
<i>by B.I.G. Barr, and E.B.D. Hasso</i>	
The Use of Small and Large Beams for Evaluating Concrete Fracture Characteristics	323
<i>by M.G. Alexander, and G.E. Blight</i>	
Size Effect in Plain Concrete under Fatigue Conditions	333
<i>by P.C. Perdikaris, A. Calomino, and A. Chudnovsky</i>	
A Study on the Probability Distribution and the Size Effect of the Fracture Toughness of Concrete	337
<i>by Xu Shilang, and Zhao Guofan</i>	
Notch Sensitivity of Concrete and Size Effect	343
<i>by Y.V. Zaitsev, and K.L. Kovler</i>	
Fracture Toughness of Concrete for Mode II	347
<i>by M. Izumi, H. Mihashi, and N. Nomura</i>	
Non-Linear Analysis of Concrete Cracking Under Short-Term Loading	355
<i>by Lin Jian-Hua, and Qian Ji-Cheng</i>	

	<u>Page</u>
Fracture Toughness Testing of Concrete at Kansas State University : is LEFM Acceptable ? <i>by S.E. Swartz</i>	359
Development of Fracture Mechanics of Concrete in China <i>by Xu Shilang, Chen Shiming, and Zhao Guofan</i>	363
Dynamic Fracture Parameter Research of Polymer Concrete by Means of Photoelastic Coatings <i>by G.L. Khesin, V.N. Sakharov, and N.A. Gorlanova</i>	375
7. FRACTURE ENERGY	379
Towards a Measure of G_f : an Analysis of Experimental Results <i>by J. Planas, and M. Elices</i>	381
The Influence of the Maximum Aggregate Size and the Size of Specimen on Fracture Mechanics Parameters <i>by H.D. Kleinschrodt, and H. Winkler</i>	391
Automatical Measuring System of Load-Displacement Curves Including Post-Failure Region of Concrete Specimens <i>K. Rokugo, S. Ohno, and W. Koyanagi</i>	403
Dimensionless Presentation and Sensitivity Analysis in Fracture Mechanics <i>by A. Hillerborg</i>	413
Experimental Evaluation of Concrete Fracture Energy through a New Identification Method <i>by A. Carpinteri, A. Di Tommaso, G. Ferrara, and G. Melchiorri</i>	423
Specimen Size Effects on Non-Linear Fracture Parameters in Concrete <i>by M. Wecharatana</i>	437
8. STRAIN RATE EFFECTS	441
The Impact Behaviour of Concrete in Bending <i>by S. Mindess, N. Banthia, and A. Bentur</i>	443

	<u>Page</u>
Strain Rate Effects on Mode I Crack Propagation in Concrete	453
<i>by S.P. Shah, and R. John</i>	
The Rate Theory and the Impact Tensile Behaviour of Plain Concrete	467
<i>by H.A. Körmeling</i>	
Concrete under Biaxial Compressive-Impact Tensile Loading	479
<i>by A.J. Zieliński</i>	
The Experimental Research of Dynamic Fracture Properties of Concrete	491
<i>by Zhang Yumei, Cao Jianguo, and Guo Guilan</i>	
9. FIBRE REINFORCED CONCRETE	497
Application of two Parameter Fracture Model to Concrete and Fibre Reinforced Concrete	499
<i>by Y.S. Jenq, and S.P. Shah</i>	
Fracture Mechanical Interpretation of the Fibre/Matrix Debonding Process in Cementitious Composites	513
<i>by H. Stang, and S.P. Shah</i>	
Comparison between Plain Concrete Toughness and Steel Fibre Reinforced Concrete Toughness	525
<i>by P. Rossi, O. Coussy, C. Boulay, P. Acker, and Y. Malier</i>	
Analytical Modelling of Crack Growth Resistance Curves in Double Cantilever Beam Fibre Reinforced Cement Specimens	535
<i>by R.M.L. Foote, B. Cotterell, and Y.-W. Mai</i>	
The Prognosis of Non-Linear Deformation of Fiber Reinforced Concrete Due to Secondary Macrocracking on the Basis of Mechanics of Fracture.	545
<i>by V.B. Aronchik, and V.B. Grapp</i>	

	<u>Page</u>
Mechanical Anchoring and Hydrogen Bonding between Fibres and Cement	549
<i>by A. Cheikh Larbi, F. Puccini, M. Andreani and D. François</i>	
10. APPLICATIONS AND REINFORCED CONCRETE	559
Fundamental Study on the Abrasive Behaviour of Concrete	561
<i>by Zhang Xin-Hua, and Huang Yiun-Yuan</i>	
Experiments and Theory for the Application of Fracture Mechanics to Normal and Lightweight Concrete	565
<i>by H.A.W. Cornelissen, D.A. Hordijk, and H.W. Reinhardt</i>	
Fracture Mechanics in Design of Concrete and Concrete Structures	577
<i>by H.H. Bache</i>	
Application of Fracture Energy of Concrete in Compression to Section Design of Reinforced Concrete Members	587
<i>by K. Rokugo, H. Iwase, and W. Koyanagi</i>	
Stability Analysis of Vertical Cracks on Upstream Face of Diamond Head Buttressed Dam at Zhexi Hydropower Station	597
<i>by Yu Yaozhong, and Zhang Yanqiu</i>	
Fracture Analysis in Reinforced Concrete and Fracture Toughness K_{IC}	607
<i>by Chen De-Pei, Xu Dao-Yuan, and Xiang Zhen-Xian</i>	
Reinforced Concrete Member Analysis in the Terms of the Structural Failure Mechanics	615
<i>by E.N. Peresyphkin, V.P. Kramskoy, and V.P. Pochinock</i>	
Experimental Study on Dynamic Restoring Force Characteristics of RC Members Subjected to Seismic Loading	619
<i>by M. Saisho</i>	
Application of Failure Mechanics to Research on Concrete and Reinforced Concrete Performance	623
<i>by V.A. Rakhmanov, E.A. Kogan, E.L. Rozovsky, and M.M. Kholmyansky</i>	

	<u>Page</u>
11. THE CRACKING AND FRACTURE OF CONCRETE	627
An Annotated Bibliography, 1982-1985	629
Author Index	695
<i>by S. Mindess</i>	

CHAPTER ONE

FRACTURE PROCESS
AND
MECHANICS OF CRACK GROWTH

INTERACTION OF A CRACK WITH SOME MICROCRACK SYSTEMS

Mark KACHANOV

Department of Mechanical Engineering, Tufts University, Medford, MA 02155, USA

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

$$\sigma(x) = K_I \sigma_I(x) + \sum_{i=1}^N \sigma_i(x) \quad (2.1)$$

(N is the number of microcracks) where $\sigma_I = f_I(\theta)/\sqrt{2\pi r}$ denotes the mode I

asymptotic crack tip field and \underline{g}_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 $\underline{t}_i = \underline{t}_i(\xi_i)$ induced along its line $-\xi_i < \xi_i < \xi_i$ 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 \underline{t}_i on the i -th crack ℓ_i are taken as induced on ℓ_i by the remote loading $\underline{\sigma}^\infty$ and the other cracks loaded by uniform average 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 \underline{t}_i on the i -th microcrack ℓ_i in the form (K_I -field plays the role of $\underline{\sigma}^\infty$)

$$\underline{t}_i(\xi_i) = \underline{n}_i \cdot \left\{ K_I \underline{g}_I(\xi_i) + \sum_{k=1, k \neq i}^N [\langle t_k^n \rangle \underline{g}_k^n(\xi_i) + \langle t_k^t \rangle \underline{g}_k^t(\xi_i)] \right\} \quad (2.2)$$

where \underline{n}_i is a unit normal to ℓ_i and $\langle t_k^n \rangle, \langle t_k^t \rangle$ are the normal and shear traction averages on the k -th microcrack. $\underline{g}_k^n, \underline{g}_k^t$ 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

$$\langle \underline{t}_i \rangle = \underline{\psi}_i K_I^{\text{eff}} + \sum_{k=1, k \neq i}^N \underline{\Delta}_{ik} \cdot \langle \underline{t}_k \rangle \quad (2.3)$$

where the second rank tensor $\underline{\Delta}_{ik}$ is a transmission factor characterizing interaction of the i -th and k -th crack in terms of the average tractions on them; namely, $\underline{\Delta}_{ik} \cdot \langle \underline{t}_k \rangle$ (no summation over k) is the vector of average traction induced along ℓ_i by the k -th crack loaded by a uniform traction $\langle \underline{t}_k \rangle$. Calculation of $\underline{\Delta}_{ik}$ involves averaging of the "standard" stress fields $\underline{g}_i^n, \underline{g}_i^t$ generated by the i -th crack over ℓ_k . The vector $\underline{\psi}_i = \underline{n}_i \cdot \langle \underline{g}_I \rangle_{\ell_i}$ (the average traction induced by $\underline{\sigma}_I$ 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 $\langle \underline{t}_k \rangle$ and an unknown scalar K_I . The additional scalar equation expresses the microcracks' impact on the main crack:

$$K_I = K_I^0 + \sqrt{\frac{2}{\pi}} \int_0^\infty \frac{1}{\sqrt{\xi}} \underline{n} \cdot \sum_{i=1}^N \underline{g}_i(\xi) \cdot \underline{n} d\xi \quad (2.4)$$

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