Constraint Effects in Fracture

Theory and Applications: Second Volume

Mark Kirk and
Ad Bakker, editors

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Foreword

This publication, *Constraint Effects in Fracture: Theory and Applications*, contains papers presented at the symposium of the same name, held in Dallas/Forth Worth, TX on 17–18 Nov. 1993. The symposium was sponsored by ASTM Committee E-8 on Fatigue and Fracture along with the European Structural Integrity Society. Mark Kirk of Edison Welding Institute in Columbus, OH and Ad Bakker of Delft University of Technology Laboratory for Materials Science in the Netherlands presided as symposium chairs and are the editors of the resulting publications.

Terry Ingham

The conference chairmen and ASTM Committee E08 on Fatigue and Fracture note with great sorrow and regret the death of our colleague Terry Ingham. Terry passed away on January 18, 1994, a short two months after we all enjoyed his presence and discussions at the symposium on which this STP is based. He will be remembered not only for the quality of his work, but also for his energy and commitment even in the later stages of his illness.

Terry graduated from the University of Leeds (United Kingdom) with a degree in Metallurgy in 1965. Subsequently, he joined the United Kingdom Atomic Energy Authority (UKAEA). His work included the development of experimental fracture toughness test methods and their relationship to structural behavior, irradiation damage in pressure vessel steels, the effect of specimen size on the fracture toughness transition regime in ferritic steels, and acoustic emission. All of these topics resulted in noteworthy contributions to the literature, particularly his contributions to an international study of irradiation damage in steel, and to the pressure vessel materials section of the UK Light Water Reactor Study Group Report.

Within the European Structural Integrity Society (ESIS) he was a member of the Working Party on Fracture Mechanics Testing Standards, for which he contributed substantially to the R-curve test procedure, P1-87D.

In 1985, he joined the UK Nuclear Installations Inspectorate (NII) as a Principal Inspector, where he was involved in the licensing of gas cooled reactors and nuclear fueled processing plants. Although this endeavor entailed a departure from his experimental work, his interest in fracture mechanics continued at both national and international levels. His work at the NII was recognized in 1994 by the award of the Order of the British Empire (OBE), an honor for which he was justifiably proud.

Our sympathy is extended to his wife and two daughters; we will all miss him.

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Overview

The Conference

On 17–18 November, 1993, the American Society for Testing and Materials (ASTM) and the European Structural Integrity Society (ESIS) co-sponsored the Second Symposium on Constraint Effects in Fracture. This symposium was held in Ft. Worth, TX; it followed on the success of the first symposium held in May 1991 in Indianapolis, IN (ASTM STP 1171). A total of 24 papers were presented. Of these, 13 were submitted from North America and 11 were submitted from Europe.

Motivation

The application of conventional fracture mechanics techniques to assess the integrity of a cracked structure relies on the notion that a single parameter uniquely characterizes the resistance of a material to fracture. Material resistance to catastrophic brittle fracture is characterized by a critical value of the stress intensity factor K_{Ic}, while resistance to the onset of ductile, or upper-shelf, fracture is characterized by a critical value of the J-integral J_{Ic}.

Testing standards that govern the measurement of K_{Ic} and J_{Ic}, ASTM E 399 and ASTM E 813 respectively, require sufficient specimen thickness to produce predominantly plane strain conditions at the crack tip and sufficient crack depth to position the crack tip in a highly constrained bending field. These restrictions are designed to insure the existence of severe conditions for fracture as described by the Hutchinson Rice Rosengren (HRR) asymptotic fields. The requirements of the testing standards thereby guarantee that K_{Ic} and J_{Ic} are lower bound, geometry insensitive measures of fracture toughness. However, cracks in civil, nuclear, and marine structures are seldom this highly constrained, which makes predictions of structural fracture resistance based on laboratory fracture toughness values overly pessimistic. Excessive pessimism in structural assessment can lead to the unwarranted repair or decommissioning of engineering structures to protect the public safety at a great, often unwarranted, cost and inconvenience.

Many researchers have long advocated a more pragmatic, engineering approach to assess the fracture integrity of cracked structures. This approach requires that constraint in the fracture toughness test specimen approximate that of the structure to provide an "appropriate" toughness for use in an assessment of structural integrity. The appropriate constraint is achieved by matching thickness and crack depth between specimen and structure. Experimental studies demonstrate the validity of this approach. These studies show that use of geometry dependent fracture toughness values allows more accurate prediction of the fracture performance of structures than is possible using conventional fracture mechanics. However, the task of characterizing fracture toughness becomes more complex than is presently the case using ASTM standard test methods. Testing of nonstandard specimens is required, and different fracture toughness data are needed for each geometry of interest. Further, this approach cannot be applied economically to thick section structures (e.g., nuclear pressure vessels). This limitation has motivated the development of theories that extend significantly the range of deformation over which fracture mechanics can be applied accurately to predict the performance of structures. Many of the research efforts discussed at the Second Constraint Symposium were undertaken to this end.

Overview of the Papers Presented

Considerable advancement in both the understanding and characterization of constraint effects occurred during the two and a half years between the first and second symposia. Evidence of advancement is available by contrasting the topics of papers presented at the two meetings. During the First Symposium, considerable emphasis was placed on the development of appropriate strategies for characterizing constraint effects on initiation fracture toughness, whether by purely brittle (lower shelf) or by purely ductile (upper shelf) mechanisms. Both theoretical analysis and experimental investigations focused on the study of fracture in simple laboratory test specimen geometries. At the Second Symposium, considerable emphasis was placed on the study of factors whose resolution will ultimately increase the engineering utility of constraint theories. In specific, the following topics were addressed.

- The competition between cleavage and ductile fracture in the transition temperature regime
- Finite element modelling and theoretical parameterization of crack growth processes
- The effects of bi-axial loading

Additionally, a number of papers reflected cooperative efforts between different engineering specialties. Several studies combined aspects of both solid mechanics and metallurgy, or addressed both experimentation and numerical analysis. These investigations, particularly the former, signal a fundamental shift of focus in the understanding and characterization of fracture processes in metals. There was a general recognition among attendees at the symposium that it is necessary, in certain instances, to incorporate variables that characterize a material at a sub-continuum scale into fracture theories that are used to assess the safety and suitability of structures for continued service. This is a major philosophical shift from the tenants of single parameter fracture mechanics (SPFM) that have been widely viewed as the most rational approach for the last 40 years.

This STP is divided topically into the following five categories:

- 2-Parameter Fracture Mechanics (2PFM) theories, 3 papers
- Crack Growth Modelling, 4 papers
- Micromechanical Modelling, 4 papers
- Experimental Validation of Constraint Models, 6 papers
- Application of Constraint Models, 7 papers

This distribution of papers indicates that the understanding of constraint effects on fracture is approaching a critical juncture. There is nearly an even division between efforts aimed at development of an appropriate and physically defensible characterization of constraint effects (papers in the first three categories) and efforts aimed at applications or codification (papers in the latter two categories).

Summary of Major Findings

All of the various constraint models presented at the symposium share a common goal: to extend significantly the validity range of SPFM and thereby facilitate more accurate prediction and assessment of the conditions that cause fracture in structures. Available constraint models include the mechanics-based approaches of two-parameter fracture mechanics (2PFM) (that is, J-T, J-Q, J-A_2, J-α_g), statistical techniques based on the Weibull model, and micro-mechanical approaches that address fracture by both cleavage and ductile mechanisms. At this stage, the following general statements can be made:

1. In the lower transition regime where cleavage fracture occurs before or just after the onset of ductile tearing, all of the 2PFM constraint models can be applied to parameterize the variation of

critical fracture toughness with constraint. Of the various models available, the *J-Q* approach of O'Dowd and Shih applies rigorously to the highest deformation levels and to the broadest range of materials. Experimental evidence is available, which shows the validity of this approach. All of the 2PFM approaches, however, suffer from the disadvantage that they complicate considerably the task of characterizing material toughness because the toughness at a given temperature becomes a function of constraint rather than a single value.

2. In the lower transition regime it is also possible to predict, without resort to empirical argument, this variation of toughness with constraint using the results of standard fracture toughness tests coupled with the micro-mechanics approach of Dodds and Anderson. At this conference the applicability of this model was extended into the upper transition regime where significant stable tearing may precede the onset of cleavage. Again, experimental evidence is available which shows the validity of this approach. Certain issues remain with respect to the proper treatment of 3D effects; these are currently under investigation.

3. A "master curve" approach to the analysis of fracture toughness data in the transition regime has been proposed in a draft ASTM standard on this topic (ASTM Task Group E08.08.03 on Elastic-Plastic Fracture Mechanics Technology in the Ductile-to-Brittle Transition Regime). Combination of this approach with a statistical correction for thickness effects based on the Weibull model appears to provide a powerful tool for the predicting toughness of geometrically similar specimens from one another (e.g. thick C(T)s predicted from thin C(T)s) across a wide range of thicknesses.

4. 2PFM models can be applied on the upper shelf to parameterize constraint effects on *R*-curve behavior. However, these approaches lack a rigorous theoretical basis in this application as a reference infinite body field solution that is self-similar to the solutions for growing cracks in finite bodies is not available. As a consequence, it can be expected that "size effects" on fracture toughness will likely reveal themselves in such an application. On the upper shelf the way forward appears to be through application of some form of local approach wherein sub-continuum material variables are incorporated into the models to provide a capability to predict accurately structural behavior from smaller scale fracture toughness test results.

Acknowledgments

The chairmen would like to acknowledge Dorothy Savini of ASTM for her professionalism in guiding us through the planning and smooth execution of the symposium. Further, Therese Pravitz and Shannon Wainwright of ASTM are to be commended for their assistance during the peer review process. We are indebted to our colleagues who assisted us with the abstract review process and with the conduct of the symposium. These individuals included Ted Anderson of Texas A&M University, Wolfgang Brocks of the Fraunhofer-Institut für Werkstoffmechanik, Bob Dodds of the University of Illinois, Steve Garwood of TWI, Phillipe Gilles of Framatome, Ed Hackett of the Nuclear Regulatory Commission, Lee James of Westinghouse, Dietmar Klingbell of BAM, Ronald Koers of Shell Research, Randy Nanstad of the Oak Ridge National Laboratory, MarjorieAnn E. Natishan of the University of Maryland, and C. Fong Shih of Brown University.

Others to be thanked include the authors who submitted the papers that comprise this publication. Discussions by the authors and attendees energized symposium atmosphere. Finally thanks go to the peer reviewers for their critiques and comments, which helped ensure the quality of this STP.

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