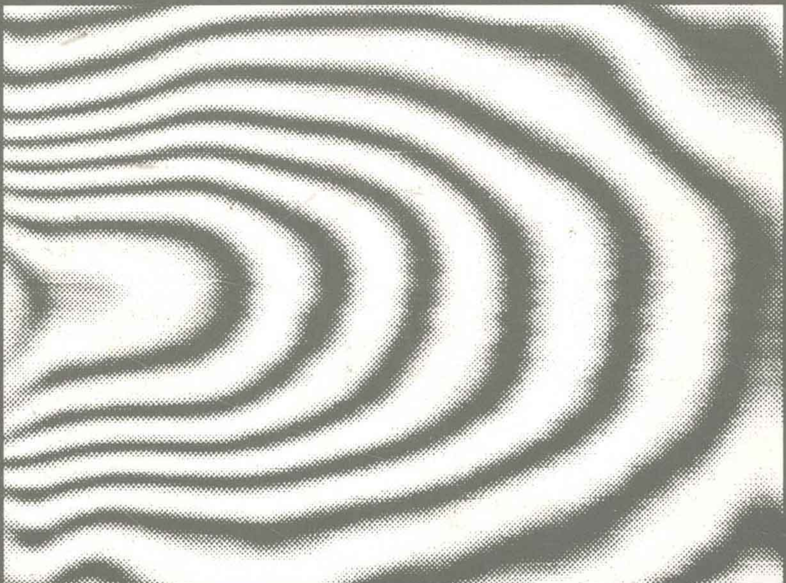
Fracture Mechanics

Twenty-Third Symposium



Ravinder Chona, editor

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Fracture Mechanics: Twenty-Third Symposium

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Peer Review Policy

Each paper published in this volume was evaluated by three peer reviewers. The authors addressed all of the reviewers' comments to the satisfaction of both the technical editor(s) and the ASTM Committee on Publications.

The quality of the papers in this publication reflects not only the obvious efforts of the authors and the technical editor(s), but also the work of these peer reviewers. The ASTM Committee on Publications acknowledges with appreciation their dedication and contribution to time and effort on behalf of ASTM.

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Foreword

The Twenty-Third National Symposium on Fracture Mechanics was held on 18–20 June 1991 in College Station, Texas. ASTM Committee E24 on Fracture Testing was the sponsor. Ravinder Chona, Texas A&M University, presided as symposium chairman and is the editor of this publication.

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Linear-Elastic Fracture Mechanics—Applications

Overview

The National Symposium on Fracture Mechanics has evolved, since its beginnings in 1965, into an annual forum for the exchange of ideas related to the fracture of engineering materials. The Twenty-Third National Symposium carried on this tradition and was held in College Station, Texas, on 18–20 June 1991. The symposium was sponsored by ASTM Committee E24 on Fracture Testing, with the cooperation and support of the Department of Mechanical Engineering at Texas A&M University.

The diversity of interests and the wide range of problem areas in which fracture mechanics can play a role in ensuring structural integrity was reflected in the topic areas that were addressed in the 63 papers that were presented at the symposium. The symposium drew 110 attendees from 18 countries around the world, highlighting the strong international flavor that the National Symposium and ASTM's fracture-related activities have acquired over the years.

The efforts of the authors of the manuscripts submitted for publication and the diligence of the persons entrusted with the task of peer-reviewing these submittals have resulted in the compilation of papers that appear in this volume. These papers represent a broad overview of the current state of the art in fracture mechanics research and should serve as a timely recording of advances in basic understanding, as a compilation of the latest test procedures and results, as the basis of new insights and approaches that would be of value to designers and practitioners, and as a stimulus to future research.

The volume opens with the paper by Dr. John M. Barsom, who delivered the Second Annual Jerry L. Swedlow Memorial Lecture at this symposium. Barsom's presentation addressed the need for a better understanding of the basic issues involved in several different structural applications of fracture mechanics technology. As such, it serves as a road map for future directions and is a highly appropriate tribute to the memory of the individual who played a very important role in shaping the National Symposium into the forum that it is today.

Following the Swedlow Lecture are forty-five papers that have been broadly grouped into seven topical areas, based on the main theme of each paper. These groupings are, however, only intended as an aid to the reader, since no classification can ever be absolute. Topics of interest to a particular reader will therefore be found throughout this volume, and the reader is encouraged to consult the Index for the location of topics of specific interest.

The groupings that have been adopted are detailed next and are similar to the broad categories that were used to divide the presentations into coherent topical sessions at the symposium itself. The first group of nine papers addresses analytical and constraint-related issues in elastic-plastic fracture mechanics, with much of the emphasis being on topics related to transition range behavior. The next section of seven papers also deals with elastic-plastic fracture, but emphasizes applications. Following this are two sections that both address linear-elastic fracture mechanics, with a group of three papers emphasizing analytical aspects, and a group of four papers that are more applications oriented. Subcritical crack growth and nondestructive evaluation methods are the joint themes of the next group of eight papers. Following this are eleven papers addressing the fracture of composites and nonmetals, a topic area that is receiving increasing attention from the fracture community and which had significant representation at a National Symposium for the first time. Finally, a grouping of three papers dealing with probabilistic and dynamic issues closes out this volume.

In addition to the technical program, a highlight of the symposium was the presentation by Dr. George R. Irwin of the 1991 medal named in his honor to Dr. Hugo A. Ernst of the Georgia Institute of Technology, and the presentation by Dr. C. Michael Hudson, Chairman of Committee E24, of the 1991 Award of Merit and designation of Fellow of ASTM to Dr. Richard P. Gangloff of the University of Virginia.

The Symposium Organizing Committee consisting of Prof. T. L. Anderson, Prof. R. Chona, Dr. J. P. Gudas, Dr. W. S. Johnson, Jr., Prof. V. K. Kinra, Prof. J. D. Landes, Mr. J. G. Merkle, Prof. R. J. Sanford, and Mr. E. T. Wessel are pleased to have been a part of this very significant technical activity. The committee and the symposium chairman in particular would like to express their appreciation of the support received from the authors of the various papers presented at the symposium; of the thoroughness of the peer-reviewers who have played a major role in ensuring the technical quality and archival nature of the contents of this publication; of the efforts by various ASTM staff to help make the symposium and this volume a success, particularly Mr. P. J. Barr, Ms. L. Hanson, Ms. H. M. Hoersch, Ms. M. T. Pravitz, Ms. D. Savini, and Ms. N. Sharkey; and of the support, encouragement, and assistance extended by Prof. W. L. Bradley, Head of the Department of Mechanical Engineering at Texas A&M University. Finally, the symposium chairman would like to especially thank Ms. Katherine A. Bedford, Staff Assistant at Texas A&M University, for all her contributions during the planning of the symposium and the preparation of this volume.

Ravinder Chona

Department of Mechanical Engineering, Texas A&M University, College Station, Texas; symposium chairman and editor.

Jerry L. Swedlow Memorial Lecture

John M. Barsom[1]

Structural Problems in Search of Fracture Mechanics Solutions*

REFERENCE: Barsom, J. M., **"Structural Problems in Search of Fracture Mechanics Solutions,"** *Fracture Mechanics: Twenty-Third Symposium, ASTM STP 1189*, Ravinder Chona, Ed., American Society for Testing and Materials, Philadelphia, 1993, pp. 5–34.

ABSTRACT: This second Jerry L. Swedlow Memorial Lecture presents a few significant developments in fracture mechanics that occurred over the past 25 years and some unresolved problems relating to materials and design and to technology transfer and education. Examples of some accomplishments and problems needing solutions are presented in areas of fracture toughness, including elastic, elastic-plastic and short cracks, and of environmental effects.

Professor Jerry L. Swedlow was an educator and a researcher who devoted his career to the transfer of technology to his students and to scientists and engineers. Thus, the lecture appropriately concludes with a few observations, needs, and recommendations concerning technology transfer.

KEY WORDS: fracture mechanics, fatigue (materials)

It is an honor and a privilege to present the second Swedlow Memorial Lecture. Jerry was a colleague with whom I worked closely on several projects. He was a neighbor whose childre and mine spent several years playing and growing up together. Above all, Jerry was a frien whom I think of frequently and I miss terribly. I thank the National Symposium Committe for inviting me to make this presentation.

Although Jerry Swedlow's publications were concentrated in the analytical aspect of frac ture mechanics, his interests spanned all facets of the technology. He was very interested i applying fracture mechanics to practical problems and toiled hard as a professor and as chair man of the National Symposium on Fracture Mechanics to transfer the available knowledg to others. Jerry and others' contributions to the analytical aspects of fracture and some of th unresolved analytical problems have been presented by M. L. Williams [*1*] in the first Jerry L Swedlow Memorial Lecture. This second lecture presents a few significant fracture mechanic developments that occurred over the past 25 years and some unresolved problems relating t materials and design and to technology transfer and education.

Materials and Design Considerations

The application of national and international specifications results in safe and reliable engi neering structures. These specifications are continually being updated and should reflect th most current knowledge in a given field. Incorrect use and violation of the requirements of th specifications may result in failure of a component or an entire structure. Also, because spec ifications present minimum requirements, the need for additional requirements must b

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* Second Annual Jerry L. Swedlow Memorial Lecture.

investigated for new and improved designs, for use of new materials, for use of common materials in new and unique applications, and for any other nontraditional situation. Such an investigation should occur early in the design process, at which time the responsible engineer should obtain and incorporate the needed additional requirements.

Technical developments during the past 20 years resulted in significantly improved characterization of the behavior and performance of steel structures. These developments include understanding and prediction of the effects of temperature and rate of loading on fracture toughness, the fatigue crack initiation and propagation behavior of fabricated components under constant and variable amplitude loading, and corrosion fatigue crack initiation and propagation behavior of constructional steels in aqueous environments [*2*]. Some of these developments have been incorporated in specifications for bridges [*2,3*].

Although significant progress has occurred during the past 25 years, further technical accomplishments are needed to improve the safety, reliability, and economy of steel structures. Predictive models are needed to identify fatigue-crack initiation sites and unstable crack extension in weldments where large variations in mechanical properties and microstructure occur in neighboring small regions. Analytical and experimental procedures are needed to characterize the fatigue and fracture behavior of short cracks where traditional fracture mechanics analyses for deep cracks are not valid. Plant-life extension methodologies should be developed to predict the remaining life of plant components. Other problems exist for which solutions are needed and where fracture mechanics technology can contribute significantly. The following sections present some accomplishments and problems needing solutions in the areas of fracture toughness, including elastic, elastic-plastic, and short cracks and of environmental effects.

Linear Elastic Fracture-Toughness Characterization

Most constructional steels can fracture either in a ductile or in a brittle manner. The mode of fracture is governed by the temperature at fracture, the rate at which the load is applied, and the magnitude of the constraints that prevent plastic deformation. The effects of these parameters on the mode of fracture are reflected in the fracture-toughness behavior of the material. In general, the fracture toughness increases with increasing temperature, decreasing load rate and decreasing constraint. Furthermore there is no single unique fracture-toughness value for a given steel even at a fixed temperature and loading rate.

The increase of fracture toughness with temperature is shown in Fig. 1 for Charpy V-notch (CVN) specimens and in Fig. 2 for plane-strain critical stress intensity factor, K_{Ic}, specimens [*2,4*]. The data in Fig. 2 also show the shift of the fracture-toughness transition curve to higher temperature as the rate of loading increases.

From a failure analysis point of view, the fracture-toughness value for the material may be used to calculate the critical crack size at fracture under a given applied stress, or the magnitude of the stress at fracture for a given critical crack size. However, it is essential that the fracture-toughness value be determined at the fracture temperature and at the appropriate loading rate for the structural component of interest. A low dynamic fracture toughness [7 J for example, (5 ft·lbf)] at the fracture temperature does not necessarily mean that the steel did not possess adequate fracture toughness under slow loading conditions. Similarly, cleavage features at a short distance from the initiation site do not necessarily mean that the steel was brittle under slow loading conditions. Unfortunately, misunderstanding these simple and basic observations has resulted in erroneous analyses of fractures.

The Charpy V-notch impact specimen continues to be the most widely used specimen for characterizing the fracture-toughness behavior of steels. These specimens are routinely tested for many failures regardless of the relevance of the test results to the particular investigation.

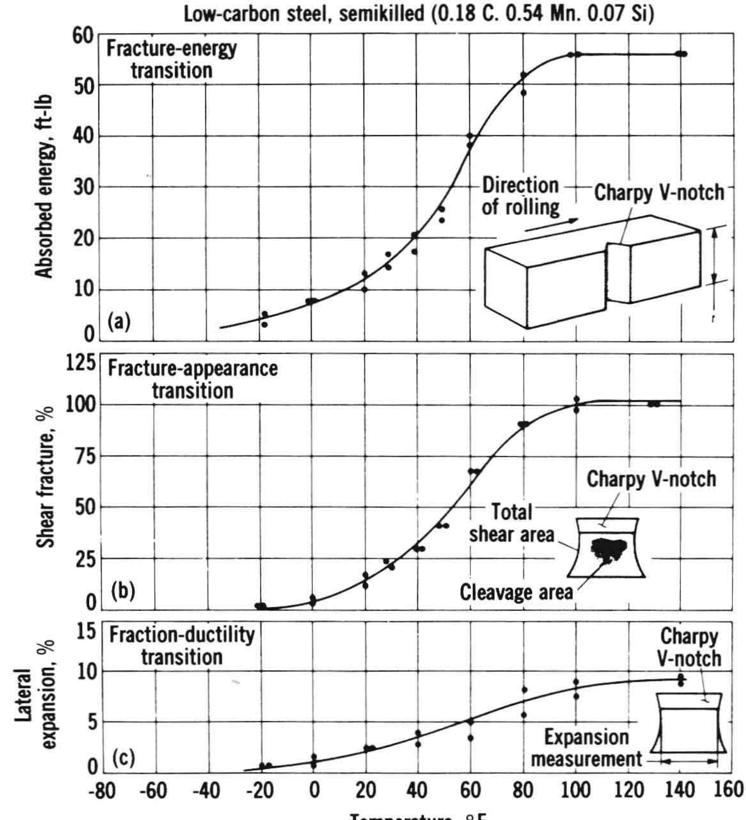

FIG. 1—*Charpy V-notch test results for a low-carbon steel.*

Furthermore, the steel is usually characterized as brittle and not having sufficient fracture toughness for its intended application if it exhibits Charpy V-notch values below about 20 J (15 ft·lbf) at the fracture temperature. The characterization is made without regard for the difference in loading rate between the test and the structure.

The static and dynamic (impact) fracture-toughness behavior for constructional steels can be understood by considering the fracture toughness transition curves, Fig. 3 [*2,4,5*]. The shift (that is, distance along the temperature axis) between the static and impact fracture-toughness transition curves depends on the yield strength of the steel, Fig. 4 [*2,4,5*]. Thus, the static and impact fracture-toughness transition curves are represented by a single curve for steels having yield strengths higher than about 897 MPa (130 ksi). On the other hand, the shift between these curves is about 71°C (160°F) for a 248 MPa (36 ksi) yield strength steel.

The fracture-toughness curve for either static or dynamic loading can be divided into three regions as shown in Fig. 3. In Regions I_s and I_d for the static and dynamic curves, respectively, the steel exhibits a low fracture-toughness value.

In Regions II_s and II_d, the fracture toughness to initiate unstable crack propagation under static and dynamic loading, respectively, increases with increasing temperature. In Regions III_s and III_d, the static and dynamic fracture toughness, respectively, reach a constant upper-shelf value.

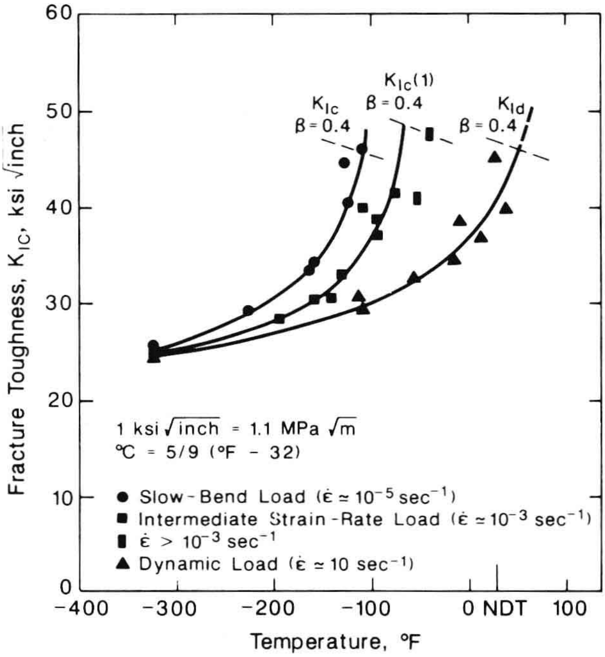

FIG. 2—*Effect of temperature and loading rate on plane-strain fracture toughness of an A36 steel plate.*

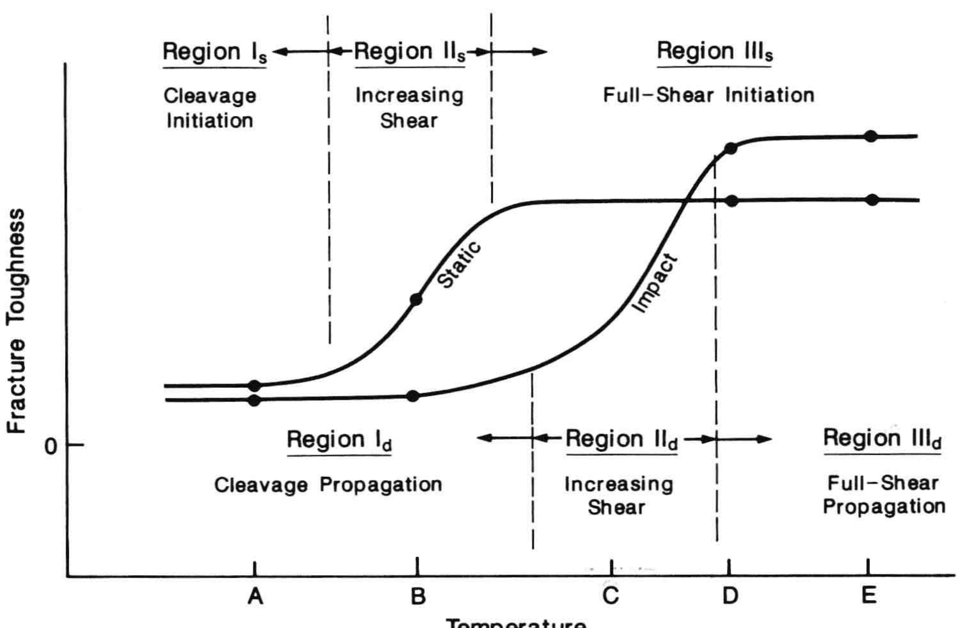

FIG. 3—*Fracture-toughness transition behavior of steels under static and impact loading.*

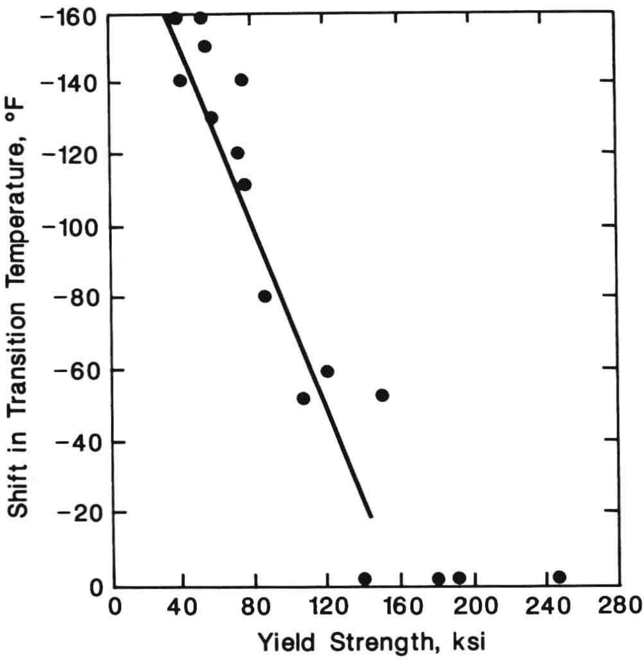

FIG. 4—*Effect of yield strength on shift in transition temperature between impact and static plane-strain fracture-toughness curves.*

In Region I_s, the static and the dynamic fracture-toughness values are essentially identical. Thus, the same low fracture-toughness values would be expected regardless of the loading rate used to fracture the specimens. In Regions II_s, the static fracture toughness increases to an upper-shelf value while the dynamic fracture toughness remains low. Therefore, the specimen may exhibit a high fracture-toughness value under static loading but a low fracture-toughness value under impact loading. Depending on the yield strength of the steel and the corresponding shift between the static and impact curve, this behavior may extend well into Region III_s. Within this temperature zone, the steel may have a high fracture-toughness value under static and intermediate loading rates yet exhibit a 7 J (5 ft·lbf) impact Charpy V-notch fracture-toughness value. Many constructional steels in actual engineering structures operate within this temperature zone. Consequently, a 7 J (5 ft·lbf) Charpy V-notch value at the fracture temperature does not necessarily mean that the steel did not possess sufficient fracture toughness for its use in a slowly loaded structure. This mistake has been made often in failure analyses despite the various documents that have been published on this subject.

In Region III_d, the static and dynamic fracture toughnesses are on the upper shelf. In this region, the mode of fracture is shear deformation that is governed by the yield strength and strain-hardening characteristics of the material. Because the dynamic yield strength for steels is about 172 MPa (25 ksi) higher than the static yield strength [*2*], the dynamic fracture toughness in Region III_d is higher than the static fracture toughness.

Fracture Surface Characteristics

Another error frequently made in failure analyses of steel components is caused by misinterpretation of the visual and fractographic observations on the fracture surface. Fractures of