Advances in Fatigue Crack Closure Measurement and Analysis

Second Volume

R. C. McClung
J. C. Newman
EDITORS

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Advances in Fatigue Crack Closure Measurement and Analysis: Second Volume

R. C. McClung and J. C. Newman, Jr., Editors

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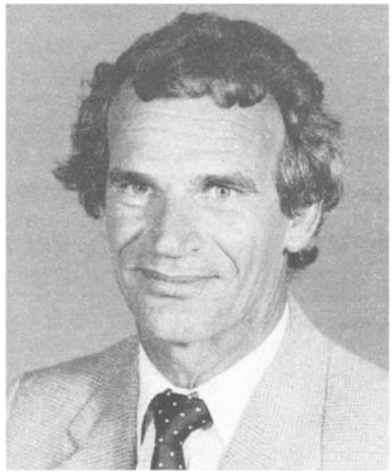

Dedication
of
ASTM STP 1343
to
Dr. Wolf Elber

Wolf Elber was born on 2 July, 1941, in Quellendorf, Germany. He earned both Bachelor of Science and Doctorate degrees in Civil Engineering from the University of New South Wales, Australia. While working on his doctorate, he discovered the phenomenon of plasticity-induced fatigue crack closure, which has revolutionized fatigue crack growth analyses. The publication of this pioneering work has become the most cited paper in the discipline.

Elber accepted a research position in 1969 at the Deutsche Forschungs-und Versuchsanstalt für Luft-und Raumfahrt, the German equivalent of NASA; and in 1970, accepted a National Research Council Postdoctoral Fellowship to continue his work on crack closure at the NASA Langley Research Center. He became a permanent NASA employee in 1972 and has served in several positions including the head of the Fatigue and Fracture Branch. Elber has served as the Director of the U.S. Army Research Laboratory Vehicle Technology Center (formally the Vehicle Structures Directorate) since October of 1992. He previously served as Director of the Aerostructures Directorate for the Army Aviation Command. His awards include the NASA Exceptional Scientific Achievement Award as well as numerous Special Achievement Awards.

The symposium marked the 30th anniversary of his discovery of fatigue crack closure. Wolf was presented with an ASTM Award of Appreciation at the symposium, "In recognition of his pioneering work on fatigue crack closure, for many significant contributions that the concept has made to fatigue crack growth research and applications, and the development of ASTM test method to measure crack closure."

FOREWORD

The Second Symposium on Advances in Fatigue Crack Closure Measurement and Analysis was held 12–13 November 1997 in San Diego, CA. The symposium was sponsored by ASTM Committee E8 on Fatigue and Fracture and was held in conjunction with the 10–12 November standards development meetings of that committee.

The symposium was chaired by R. Craig McClung, with Southwest Research Institute, San Antonio, TX and James C. Newman, Jr., at the NASA Langley Research Center in Hampton, VA. These men also served as editors of this resulting publication.

CONTENTS

OVERVIEW

The discovery of the phenomenon of plasticity-induced fatigue crack closure by Elber was truly a landmark event in the study of fatigue crack growth (FCG) and the development of practical engineering methods for fatigue life management. Subsequent research identified other contributing mechanisms for crack closure, including crack surface roughness and oxide debris. Fatigue crack closure is now understood to be an intrinsic feature of crack growth behavior that must be considered to understand or treat many FCG problems, although closure may not be an issue in all problems and does not always provide a complete explanation of crack growth behavior.

The first ASTM International Symposium on Fatigue Crack Closure was held in Charleston, South Carolina in May 1986, nearly twenty years after the Elber discovery. The large symposium audience and the thirty-nine papers in the resulting Special Technical Publication (*Mechanics of Fatigue Crack Closure, ASTM STP 982*) served effectively to document both the perspectives of that day and the high level of research interest in the topic.

As the thirtieth anniversary of the Elber discovery approached, the strong, continuing international interest in crack closure prompted the organization of another ASTM symposium. The Second Symposium on Advances in Fatigue Crack Closure Measurement and Analysis, sponsored by ASTM Committee E8 on Fatigue and Fracture, was held in San Diego, California on 12–13 November 1997. An international audience numbering over sixty-five persons heard thirty papers contributed by authors from twelve different countries, with more than half of the papers originating from outside the United States. This STP volume contains peer-reviewed manuscripts for twenty-seven of those presentations, plus one peer-reviewed paper that could not be presented at the symposium.

Closure researchers represented on the symposium program and in this volume employed a number of tools to conduct their investigations, including a variety of both experimental and analytical/numerical techniques. However, this STP volume is not segregated by research tool or technique, as is often the case. Instead, the STP is organized according to the particular class of closure problems or questions being addressed. Experiment and analysis are both shown to provide valuable, often complementary, perspectives on common issues. The experimentalist reader will be well-served by a careful study of the analysis papers, and the analyst reader should likewise pay close attention to the evidence published by the experimentalists.

Fundamental Studies

The first two papers address fundamental questions about the very existence of plasticity-induced crack closure and the adequacy of closure concepts to explain a wide range of growth behaviors. Since the first symposium on crack closure (*ASTM STP 982*), the question of plasticity-induced crack closure under pure "plane strain" conditions has been actively discussed, analyzed, and disputed. Continuum mechanics models and analyses under plane strain conditions exhibit closure but some recent dislocation models do not show closure. Riemelmoser and Pippan develop a discrete dislocation model that shows crack face contact in plane strain due to these dislocations.

Elber's effective stress intensity factor range was a simple modification of Paris's stress intensity factor range by replacing the minimum stress intensity factor with the crack opening stress intensity factor. But a number of attempts have been made to relate crack tip damage to a more fundamental parameter, such as the cyclic hysteresis energy. Ranganathan analyzed crack growth rate data on an aluminum alloy using the traditional crack closure concept and an energy-based method. Most of the crack growth effects attributed to closure could be explained using the energy concept.

Experimental Characterization of Closure

Among the most active current topics in closure studies are the optimum experimental method to measure crack opening levels and the correct way to incorporate this closure information in the effective value of the stress intensity factor range. Several researchers have observed previously that conventional remote measurement techniques indicate very high levels of closure near threshold, and the resulting conventionally calculated values of the effective stress intensity factor range appear to be inconsistent with near-threshold growth rate behavior. As a result, some have suggested that alternative experimental methods should be employed, or that some portion of the stress range below the crack opening level should be included in the effective stress range. Several authors in this volume have addressed this question by experimentally measuring closure and growth rates or by analyzing the mechanics of the fatigue crack and simulating experimental techniques.

Pippan, Riemelmoser, and Bichler employ simple models and experiments to evaluate the measurability of closure from asperity and wedge-like contact and the influence of closure on crack-tip shielding. Bray and Donald investigate the use of the new adjusted compliance ratio (ACR) technique to define an effective stress intensity factor range that is larger than the conventional value based on K_{open}, adding an additional K_{max} term to correlate FCG rate data. Donald and Phillips use the ACR method to analyze data from a previous ASTM round-robin on closure measurement methods and compare the results with the conventional closure analysis approaches. Graham, Tregoning, and Zhang also compare the ACR and current ASTM methods of characterizing closure from their tests on Ti-6Al-4V. McClung and Davidson use finite element closure analysis and high-resolution experiments to study crack-tip deformation above and below the crack-tip opening stress and to quantify the relationship between remote closure measurements and near-tip deformation, evaluating both the ACR and ASTM methods. Newman employs his modified Dugdale closure model to perform a similar study of crack-tip deformation and experimental methods, evaluating the contributions of stresses below the opening level to crack-tip damage and simulating various experimental measurement techniques. Sutton et al. describe a new high-resolution closure measurement system using computer vision and a far-field microscope to interrogate the near-tip region. In a companion paper, Riddell et al. use the new system to investigate closure in the near-threshold regime, in conjunction with three-dimensional finite element simulations that suggest an appropriate application of the experimental measurements to correlate FCG rates. Finally, Schindler introduces a new experimental technique to determine crack closure from residual stresses measured by the cut compliance technique.

Load History Effects

Perhaps the most useful application of the crack closure concept has been to develop life prediction methods accounting for retardation and acceleration effects under variable-amplitude and spectrum loading. These methods are in current use by aerospace and nuclear industries around the world. But as the research community conducts tests and analyses beyond the usual crack growth rate regimes, such as at very high stress ratios or under extreme environments, or by observing the crack-tip deformations with advanced techniques or methods, the current concepts are found to be lacking and numerous questions arise.

Bichler and Pippan make some direct observations of the residual plastic deformations caused by a single tensile overload in the mid-thickness of a specimen using scanning electron micrography and stereophotogrammetric reconstruction of the fracture surfaces. Lang attributes the changes in measured crack growth rates after single and multiple overload sequences to the compressive residual stresses in front of the crack tip. Stephens et al. study fatigue crack growth and closure at three different temperatures in a high-strength titanium alloy (Ti-62222) proposed for use in a future supersonic transport. Tests are conducted under constant-amplitude load-reduction procedures near threshold conditions and under single-spike overloads. McMaster and Smith study the effects of simple load excursions on fatigue crack growth and closure measurements in 2024-T351 aluminum alloy at two thicknesses, using both remote and local displacement gages. Jono, Sugeta, and Uematsu conduct an investigation on crack growth and closure on side-grooved specimens of a Ti-6Al-4V titanium alloy under constant-amplitude and repeated two-step loading.

Hsu, Chan, and Yu study crack growth and closure under simulated aircraft spectrum loading with a significant number of compression cycles. They use a local strain gage method to measure crack opening loads and apply an analytical crack closure model to predict the behavior under the spectrum loading. Varvani-Farahani and Topper conduct tests on SAE 1045 steel under load histories containing periodic compressive loads. They develop a model of plastic deformation of fracture surface asperities and compare the measured and calculated fatigue lives of solid cylindrical and tubular specimens. Romeiro, Domingos, and de Freitas extend crack growth and closure studies to very low stress ratios ($0.7 \geq R \geq -3$) on a carbon steel.

Since the discovery of crack closure, the finite element method has been widely used to study crack growth and closure. Park and Song use a two-dimensional finite element method to investigate various types of variable-amplitude loading.

Surface Roughness Effects

In the literature, the development of fatigue crack growth thresholds has been attributed to an increase in crack surface roughness due to the development of Stage I or Stage-I-like (alternating shear, zigzag) crack growth, as the threshold is approached. But how roughness interacts with plasticity-induced closure to affect crack growth rates is a fundamental question for life prediction methods, and researchers are actively pursuing this issue. Modeling of roughness-induced crack closure, in combination with plasticity-induced closure, has been very limited. Several authors in this volume have addressed this issue by developing models that include both effects.

Chen and Lawrence combine the strip-yield model of Newman (plasticity-induced crack closure) with the zigzag (Stage I) fatigue crack growth (roughness-induced crack closure) to develop a model to predict the total fatigue life of notched components using a fracture mechanics approach. Sehitoglu and Garcia develop a model that is characterized by the distribution of asperity heights, asperity densities, and asperity radii. Comparisons are made with plasticity-induced closure results to assess when one mechanism dominates the other. As Schijve pointed out in the first symposium on crack closure (*ASTM STP 982*), crack front incompatibility (flat or slant crack growth) can influence crack growth rates. Zuidema, van Soest, and Janssen study the effect of surface roughness induced by shear lips and conventional plasticity-induced closure on crack growth in aluminum alloys.

Closure Effects on Crack Behavior

Fatigue crack closure, as an intrinsic feature of growing fatigue cracks, can have an influence on many different aspects of crack growth. Daniewicz investigates the influence of closure variations around the perimeter of a surface crack on the evolution of the flaw shape itself, based on a modified strip-yield model employing the slice synthesis method. Dankert, Greuling, and Seeger demonstrate the role of crack closure in the growth behavior of short cracks growing from notch roots, developing a unified model that accounts not only for crack closure but also for notch root deformation and employs elastic-plastic fracture mechanics. Pawlik and Saff present a numerical method for predicting closure and its effects on thermomechanical fatigue crack growth, including the influence of constraint, temperature, and variable-amplitude loads. Toribio and Kharin suggest from their finite element studies that closure-induced residual stresses in the crack wake can have a significant influence on stress-assisted hydrogen diffusion towards rupture sites in the crack tip zone, and hence that crack closure has an indirect influence on hydrogen-assisted cracking. de Koning, ten Hoeve, and Henriksen use a strip-yield closure analysis to define the strain rate at the crack tip, expanding an existing FCG model to address the effects of environment and frequency on the crack growth rate.

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