Fatigue and Fracture Mechanics

30th Volume

Kenneth L. Jerina and Paul C. Paris, editors

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Dedication

This volume of proceedings of the 30th National Symposium is dedicated to Edward T. Wessel for his long-standing support of the Symposium series and for his leadership associated with ASTM committee activities.

Mr. Wessel began his activities with the E-8 Committee through its predecessor E-24 when it was an ASTM special committee investigating fracture problems associated with the Polaris rocket motor cases in the late 1950s. During that time and to the present, he and the group he led at Westinghouse Research Laboratories made many monumental contributions to fracture mechanics. Scores of outstanding research papers from individuals in his research group have been published in the National Symposium volumes. The hallmark of his leadership was a spirited team effort to understand and advance many aspects of fracture mechanics. Therefore, this dedication is a well-deserved "thank you" to Edward T. Wessel and is enthusiastically endorsed by all associated with the National Symposium series.

Edward Wessel (left) with E-8 Chairman Stephen W. Hopkins at the 30th National Symposium banquet.

Foreword

The 30th National Symposium on Fatigue and Fracture Mechanics was held at Washington University in St. Louis 23–25 June 1998. The technical session presentations were in the "Moot Court Room" of the Anheuser-Busch Hall, and the conference banquet was held in Holmes Lounge, a recently renovated room in Ridgley Hall that dates back to the 1904 World's Fair. Professors Kenneth L. Jerina and Paul C. Paris hosted and co-chaired the festivities (Fig. 1).

It is of special interest to note that Dr. George R. Irwin, a founder of this symposium series and 91-years-old attended these sessions. His arrival at the technical sessions was greeted with a standing ovation. Whereupon he proceeded to a front row seat and participated in discussions of the technical presentations. Sadly, a few months later, in October 1998, Dr. Irwin passed away. Figure 2 shows him at the banquet surrounded by many friends.

The banquet for the 30th National Symposium took on a "belle epoch" theme from the 1904 World's Fair Holmes Lounge venue, the classic cuisine provided by Cafe de France and the entertainment provided by the Ragtimers, a ragtime musical group associated with Washington University. In addition, the banquet provided an elegant forum for Stephen W. Hopkins, Chairman of the ASTM E-8 sponsoring committee, to present several awards and honors. The first was to announce and congratulate Edward T. Wessel for being chosen for a special award of ASTM for his many years of leadership within E-8. Next, Professor John D. Landes was honored with a plaque acknowledging his presentation of The Swedlow Memorial Lecture at this symposium, as depicted in Fig. 3.

Mr. Hopkins also surprised Professor Paris by presenting him with the ASTM Dudley Medal for co-founding the symposium series and his contributions to these symposia. Professor Paris was also

FIG. 1—*Co-chairmen Professors Jerina (left) and Paris.*

FIG. 2—*Dr. George R. Irwin (center) and friends.*

designated as the National Symposium subcommittee "honorary chairman" and keeper of the "symposium bell" by E-8 Chairman Hopkins. Figure 4 shows this presentation.

Another award associated with this symposium was that for the best presentation of a paper. This award was presented to Professor Richard W. Hertzberg at the November 1998 meeting of ASTM Committee E-8 by Chairman Hopkins. This presentation is shown in Fig. 5.

FIG. 3—*Professor John D. Landes (left) receiving his award from E-8 Chairman Hopkins.*

FIG. 4—*Professor Paris receiving the ASTM Dudley Medal.*

FIG. 5—*Professor Hertzberg receiving the best presentation award.*

FIG. 6—*Ms. S. TerMaath cited for the best student presentation by Mr. J. Schiele.*

Special emphasis was placed on receiving student papers for this symposium, of which nine were presented. Each of the student presenters was acknowledged at the banquet with a certificate for their meritorious efforts. Plaques were awarded for the two best papers. Figure 6 shows Ms. Stephanie Ter-Maath of Cornell University receiving a cash award for the best student presentation from Mr. James Schiele, CEO of St. Louis Screw and Bolt Company, who donated the award.

Kenneth L. Jerina
Materials Research Laboratory
Washington University,
St. Louis, MO

Paul C. Paris
Mechanical Engineering
Washington University
St. Louis, MO

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Jerry L. Swedlow Memorial Lecture

John D. Landes[1]

Elastic-Plastic Fracture Mechanics: Where Has It Been? Where Is It Going?

REFERENCE: Landes, J. D., **"Elastic-Plastic Fracture Mechanics: Where Has It Been? Where Is It Going?"** *Fatigue and Fracture Mechanics: 30th Volume, ASTM STP 1360,* P. C. Paris and K. L. Jerina, Eds., American Society for Testing and Materials, West Conshohocken, PA, 2000, pp. 3–18.

ABSTRACT: Elastic-plastic fracture mechanics (EPFM) is the name given to a body of fracture technology that includes parameters, test methods, and analysis techniques. EPFM began in the 1960s, soon after it was recognized that the linear elastic approach to fracture mechanics was too limited to cover many engineering applications. It began in response to real engineering problems and continues to develop in the same application-driven mode. The development of EPFM spans more than three decades. It involved many people and a multitude of good ideas. Some of the people have gone on to other pursuits, and many of the ideas have been set aside or discarded in the never-ending debate about which is the best approach. The development of EPFM is not complete, nor is the controversy ended. It is important to look back at the factors that influenced such a vast development of technology before trying to forge ahead.

This paper takes a look at the area of fracture mechanics called EPFM. It considers the development of a technology that involved people, places, and a seemingly inexhaustible supply of technical ideas. It considers what happened in the past, what is going on in the present, and speculates about what will happen for the future. Its purpose is to stop for a moment and consider for EPFM: Where has it been? Where is it going?

KEYWORDS: elastic-plastic, fracture mechanics, history, people, events, technology, future

It is an honor to be chosen as the 9th Jerry Swedlow Memorial lecturer. Jerry Swedlow was a friend and colleague in the field of fracture mechanics research. He was a long-time national chair of this Symposium series. He was also a contributor to the subject whose history will be recounted in this lecture. His life and contributions to the field of fracture mechanics are still remembered by many of us.

Introduction

The history of the development of fracture mechanics involves more than the body of technical literature that evolved. That alone is voluminous; much of it is lost or forgotten. A thorough recounting of all of the literature could provide one type of history, one that is technically complete and factual but hopelessly boring. Rather, the more interesting part of this development involves events, places, and mainly people. This part of the history exists in peoples' memories; it will soon be forgotten and lost forever unless it is documented in writing. The lecture that forms the basis of this paper is scheduled for 35 minutes, not for the entire three days of the symposium; even that would not be enough. Therefore, the scope of this history has to be limited. The subject that I want to address is a little of the history of the development of the part of fracture mechanics called elastic-plastic fracture mechanics (EPFM). This will not be a comprehensive and definitive treatise on the subject. Neither will the claim be made that it is the whole truth or nothing but the truth. Rather it is limited to the facts,

[1] University of Tennessee, 310 Perkins Hall, Knoxville, TN 37996-2030.

tempered by time, that remain in my memory, what I saw and what appeared to me to make an impact on this subject. The part of the history that I present would not be the same one that another person might write. Therefore, events, places, and people that were undoubtedly important to another person might be missing, not because they do not belong, but because they do not form the part of my memory that I am recording here.

Beginnings at Lehigh

The beginning of the fracture mechanics story for me was at Lehigh University. I went there in 1960 as a prospective freshman, complete with brown and white dink (some kind of freshman hat) and loads of anxiety. The first person I met in what was to become my decade at Lehigh was my dormitory counselor, a Lehigh junior named James Rice; he was a member of the upperclassmen counselors group called Gryphons. Of course, there was no way to know at the time that I was meeting someone who was to become a legend in the fracture mechanics field as well as the entire field of applied mechanics, the very person who would start me on the path to a career in fracture mechanics. He was just a friendly face, someone who tried to help new freshmen recover from homesickness. Jim Rice in those days soon gained a reputation for his ability to help with those conceptual problems with physics and mathematics that all new university students have. "What does it mean in the limit as Δx goes to zero; why not let it be zero to start with and avoid this confusion." Every evening when study time began, a line would form at his door; these were freshmen with seemingly unsolvable technical problems that Jim could solve or explain in a minute or so. First the lineup was small, containing students from our section of about 25 students, those who had Jim as their counselor, but soon the lineup became bigger and bigger, as the entire freshmen class found that here was someone who knew the answers to all of the technical problems ever posed to freshmen. I still did not understand his special ability; I thought that all upperclassmen could do that. Upon meeting another upperclassmen counselor, I asked, "Why don't you help your students like Jim Rice does for us; then they wouldn't have to bother him every night." "You don't understand," he replied, "Jim has an understanding that is levels above ours; we can't do what he does." The world of fracture mechanics would soon learn this.

As a relief from the nightly lineup, Jim that year got involved in student politics. Along with that were the meetings and sessions of liquid refreshment that followed. Often he would not return to his room until after midnight. The line was always there waiting. He always took the time to help, no matter how he felt. In spite of his many talents, what he could not do for himself was wake up in the morning. The various members of his section had wake up duty, assigned on a rotating basis. That required going into his room at the appointed time (his door was never locked), pulling him out of his bed, and standing him up to make sure he was awake. For the person who did not take his assignment seriously enough, this process was completely reversible.

Jim Rice told all of the freshmen who were engineering students about a new department and major, Engineering Mechanics, led by Ferd Beer, later famous for his undergraduate engineering textbooks. This new major was Jim's choice and his recommendation for everyone not set on a specific engineering discipline. On hearing about the basic and theoretical nature of the curriculum, I asked, "What advantage does this have over basic curricula like physics and mathematics." "In those," Jim said, "you need a Ph.D. before you are seriously considered as a contributor to new technology. In mechanics, you can become a contributor at a much earlier stage in your career." Jim was an early contributor. He also mentioned a previous undergraduate, named John Hutchinson, who had completed this program and then gone on to Harvard to become a superstar. Jim finished a B.S. degree in 1962. He stayed at Lehigh for graduate work, finishing an M.S. degree in 1963 and a Ph.D. in 1964. He could take five graduate classes per semester for credit while teaching undergraduate classes and work on his dissertation at the same time. Then, in his spare time, he worked on topics that were not part of his dissertation research and wrote papers that have become all-time classics in the field of fracture mechanics. On a recommendation form for a fellowship, one professor had to answer the question, "Is this person creative?" He answered, "Jim Rice is the most creative person on campus; that includes all students and faculty."

Anyway, about one third of Jim's section, including me, signed up for that new major, Engineering Mechanics. That was a critical decision that began my career in fracture mechanics. During my third year as an undergraduate, a new honors program was introduced to us. Thanks to the efforts of Jim Rice, our class was the biggest in the history of that major and ready for an honors program. In that program, I was introduced to two young professors, Paul Paris and George Sih. They told us about their research area called fracture mechanics, a new research field started only a few years before by George Irwin. The objective of the honors program was to begin a summer project that would carry to the fourth and senior year. I chose to work with Paul Paris on a fatigue crack growth project, for no good reason other than Professor Paris told a good story about his work. About six students were involved. All of the others chose different professors. The projects involved simple mechanics concepts that undergraduates could understand. They required intuitive reasoning and a simple experimental setup. When it came to simplifying a problem and designing experimental setups, only Paul Paris seemed to have the intuitive skills and experimental know how to make the projects work. By mid-summer, Paul Paris was advising all of the honors students, not only me.

The young professor, Paul Paris, was committed to helping students developing rudimentary skills in fracture mechanics. Also, he was extremely busy, traveling nearly every week. Paul was difficult to find when you wanted a conference, but when you finally did find him, he would give you the rest of the day if needed. He never once said, "Come back some other time, I am too busy right now." Knowing what I do now about being a professor, he was probably always too busy; he simply chose to let the students' needs come first.

My first formal instruction in fracture mechanics came from a course that Paris and Sih were offering, what I believe was the first fracture mechanics course on a university campus. I took this course in the spring of 1964. At that time it was already a seasoned course, although the bulk of what we know as fracture mechanics technology had yet to be discovered. In that course I sometimes pondered the problems of fracture mechanics with a graduate student named Dick Hertzberg, now known among other accomplishments for his textbook on deformation and fracture. That course, as well as the interaction with Paul Paris in the honors program, guided me into the discipline known as fracture mechanics; I decided to stay at Lehigh for graduate work; it was the biggest university center for fracture mechanics work at that time, I would guess perhaps of all time.

A theoretical M.S. thesis in fracture advised by Fazil Erdogan convinced me that I would prefer the experimental approach. The help with the experimental approach came from an expert in experimental fracture mechanics work named Bob Wei, who joined the faculty in 1966. He was my Ph.D. advisor. A year later George Irwin joined the Lehigh faculty. During my Ph.D. years at Lehigh, Paul Paris felt that fracture mechanics was ready for its own symposium. With help from George Irwin, the National Symposium on Fracture Mechanics was initiated and held at Lehigh in 1967. Still being part of the group that was headed by Paul Paris, I was asked to be one of the projectionists. So my first offering to this Symposium series that has now reached its thirtieth meeting was as a projectionist. This role continued for the second and third Symposia, 1968 and 1969. I got to meet all of the speakers; I had to load their slides. One of the speakers that I met in 1967 was Ed Wessel. He as well as the others were enthusiastic about this new field called fracture mechanics. After my Ph.D. experience at Lehigh, my desire to pursue a career in fracture mechanics was certain.

Early Westinghouse Years

My decision to go to work at Westinghouse after finishing a decade at Lehigh was not just an accident. My professors at Lehigh said that a group headed by Ed Wessel at Westinghouse was doing the best work in the field of experimental fracture mechanics, my main interest at the time. I was fortunate enough to be hired. I moved to Pittsburgh in January of 1970. Two of the first things that Ed did after I began working was to describe the major task that he wanted to address and to introduce me to Jim Begley. I already knew Jim from Lehigh, but I was a mechanics student and he was a metallurgy student. At Lehigh our paths crossed only occasionally; at Westinghouse we were to become a team formed to attack a new and important problem.

Jim Begley in those years was extremely creative; he always seemed to be working on a new idea. His head was so full of research plans that he sometimes forgot the smaller details of life like where did he park his car, or when is that meeting scheduled, likely yesterday. I can remember times when there was a project review upcoming, something often feared by many researchers and sometimes requiring at least a week of preparation and worry. Jim had a different approach. Several times on the morning of such a review, when asked, "Jim are you ready for the project review today," he would answer, "Is that thing today? I forgot all about it." Then with only a piece of chalk and a blackboard he could lay out the project goals, progress, and reasons why this project was better than most in previous history, in such a way that the sponsor was completely sold on the work we were doing. Although Jim and I only worked together about five years, that work had a marked influence on our careers.

Ed Wessel during the decade of the 1970s went on to develop perhaps the most recognized group ever assembled to do fracture mechanics research. He had a definite philosophy for attacking problems, which he would express with sayings like; "I pick good people and let them alone to do the work; I take care of all the administrative horse potatoes so that the workers do not get bogged down with that." Also, "when we work, we work hard; when we play, we play hard." He led the way in both categories. Perhaps the thing that best illustrates his success as a manager is the final demise of the group. Westinghouse thought that the group was doing so well that anyone could manage it. In the early 1980s they decided to replace Ed with another manager. The group soon dispersed and the researchers left for other organizations, going to universities, national laboratories, and other companies.

The task that Ed Wessel described to Jim Begley and me seemed difficult. "After more than ten years of fracture mechanics, we can still handle only predominantly linear-elastic behavior. The materials that we use in the structures that Westinghouse builds do not experience fracture under linear-elastic loading. We have to extend the current approach of fracture mechanics to cover the cases of interest to Westinghouse." Then he showed us what is now called the million dollar fracture toughness curve, a series of K_{Ic} test results from an A533B steel plate on specimen sizes going from 1T (1 inch thick) to 12T (twelve inches thick). Even with 12 inches thick there was no valid K_{Ic} past a very limited temperature value, far below operating temperature of the nuclear reactor pressure vessels that used this material. "The design of the nuclear reactor pressure vessel is so critical that we have to develop a way to measure fracture toughness, all the way to operating temperature," Ed said. Jim Begley and I were assigned to begin to work on this problem.

It is interesting to me to note that at the time we began this work there was adequate funding to do the job. Also, nobody asked for a detailed write-up of what we planned to find with this funding and exactly when we planned to find it. We did not have a lot of milestones, monthly deliverables, strategic plans. We had a problem to solve, funding to go ahead, but none of the modern controls that impede technical progress in the guise of fiscal responsibility or safeguarding the taxpayers' money. I sometimes wonder whether starting 20 years later, in this modern funding climate, the elastic-plastic fracture mechanics work that was conducted at Westinghouse in the 1970s could have been accomplished today.

The work that Jim Begley and I began at Westinghouse led to the proposal of the J integral [*1*] as a parameter to characterize fracture toughness when linear-elastic conditions no longer prevail. The decision to try J was not so straightforward as I now like to present. "Since K is the single parameter that gives the magnitude of the dominant term of the crack tip stresses under linear-elastic conditions, etc., and a crack tip stress equation can be written for nonlinear elastic conditions with J, etc., then J is the logical extension of K for elastic-plastic conditions." It was not that straightforward in the be-