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Advanced Fracture Mechanics

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Advanced Fracture Mechanics

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PREFACE

Prospective authors of a technical book are faced with a dilemma. If their subject is well established—the theory of elasticity, for example—then it is likely that they have been preceded by someone who has taken far more pains to produce a book than they possibly could. On the other hand, if they have not been so pre-empted, it may well be because their subject is still evolving. Their “snapshot” of a subject in its infancy might then rapidly become out of date.

Fracture mechanics is a subject that has not yet fully matured. Yet, it has existed long enough, and its practical applications are important enough, that a great deal of information is already available. Nevertheless, we wrote this book believing that fracture mechanics is currently at a unique stage. Enough research has been performed to provide a solid foundation upon which future progress will build. At the same time, societal dictates for optimum uses of energy and materials are increasingly forcing structural integrity assessments to be made in the more realistic way afforded by a fracture mechanics approach. Accordingly, a book offering its readers a unifying treatment of the subject for a wide variety of structural materials and application areas is one that should be of value, even though much work remains to be done.

While a number of excellent books on fracture mechanics have already been written—many by our friends and colleagues—we do not feel these offer the particular perspective we have sought in this book. We have addressed the subject from the point of view of applied mechanics. At the same time we feel that some fundamental aspects have not been made as clear in the existing books as they perhaps should be for the newcomer to this field. We hope that we can also improve on this aspect for our readers.

To those not well acquainted with it, the subject of fracture mechanics may appear to be rather exotic and mysterious. But it should not. Any reader who understands the basic concepts of stress and strain, as might be acquired in an undergraduate course on the strength of materials, should find little conceptual difficulty with it. In essence, fracture mechanics circumvents the difficulty arising from the presence of a sharp crack in a stress analysis problem (where there would be an infinite stress, and fracture, under any load) by providing a parameter that characterizes the propensity of the crack to extend. This parameter, which can be generally referred to as the crack extension force, can be calculated knowing the stress-strain behavior of the material, the crack/structure geometry, and the boundary conditions. A critical value of the crack extension force is generally taken as a property of the material. This property, which can

be inferred from simple tests, constitutes the only additional information needed.

Fracture mechanics, be it for elastic-brittle, ductile, time-dependent, or heterogeneous materials, is simply based on equating the calculated crack extension force for a cracked structure to the fracture property for the structural material. The result is an explicit relation for crack extension for prescribed applied load, crack size, component dimensions, and material. Applying this method in any particular circumstance may not be obvious. This book would not be necessary if it were. But the basic approach is both simple and widely applicable.

We now state more definitely what we mean by the term “fracture mechanics.” In common with most researchers in the field, we define the term in the following way: Fracture mechanics is an engineering discipline that quantifies the conditions under which a load-bearing body can fail due to the enlargement of a dominant crack contained in that body. This definition is obviously quite general. Accordingly, what it does not include is perhaps equal in importance to what it does.

First, this definition does not restrict the size, shape, or location of the crack. Nor does it limit the direction or the rate at which it enlarges. Hence, relatively slow crack growth rates as in stress corrosion and fatigue are included along with dynamic processes such as rapid “brittle” crack propagation. Second, no constraint is placed on the constitutive relation obeyed by the cracked body. It follows that elastodynamic, elastic-plastic, and viscoplastic continuum material behavior, along with heterogeneous and atomistically viewed materials, are equally admissible with the conventional (and most widely used) linear elastic continuum view. Third, the causation of crack extension is not specified in our definition. Mechanical and thermal stresses that vary arbitrarily in time along with environmental agents, separately or in combination, can be considered. As a final point the definition leaves the nature of failure itself unspecified. Thus, any condition from the mere appearance of a detectable crack to catastrophic fracture can be considered within the domain of fracture mechanics.

What should follow from the definition just given is the vacuousness of statements that imply that fracture mechanics does not work in some given area. As an example, not too many years ago many people concerned with the use of fiber composites for aircraft structures undoubtedly would have subscribed to the sentiment expressed by one of them: “Fracture mechanics will work only for a composite structure that someone has attacked with a hatchet.” The interpretation of such a remark is this: linear elastic fracture mechanics techniques developed for high strength metals are not directly applicable to a composite unless a through-wall crack exists that is large in comparison to the scale of the micromechanical failure events that precede fracture. Linear elastic fracture mechanics, to be sure, is by far the most highly developed and widely applied version of fracture mechanics. But, it is just that—a specializa-

tion of the general subject that must not be considered as synonymous with the subject as a whole. Thus, when “fracture mechanics doesn’t work,” it is very likely because the methodology has been applied at too simple a level.

A key feature of any fracture mechanics definition is the explicit requirement of a dominant crack. This is the essential difference between fracture mechanics and other kinds of structural analysis. That cracks can and do appear in every type of structure is, of course, the *raison d’être* of fracture mechanics. But, the requirement that at least one identifiable crack exist can be troublesome. For example, fracture mechanics cannot predict failure in a simple tensile test. No engineering structure can be assessed via fracture mechanics unless at least one crack is either observed (or postulated) to exist in that structure.

Another drawback to fracture mechanics is a subtle one that even many people with long experience in the field do not always recognize. Fracture property values cannot be directly measured. Such values can only be inferred—via the interposition of some assumed analysis model—from quantities that can be experimentally determined. The reason is that there is no instrument that can be made to provide fracture property values for all materials in all testing conditions to the extent that a strain gage measures a change in a length or a thermocouple measures a change in temperature. To “measure” a material fracture property, the theoretical crack driving force is calculated for the crack length and load level at the observed point of crack extension. The fracture property is just the critical value of this crack driving force. While this is true even under linear elastic conditions, there is little difficulty in that regime. But, in nonlinear and dynamic fracture mechanics, serious consequences can result from not recognizing that the fracture “property” can be strongly affected by the analysis method used with the measurement process.

The foregoing requirements suggest a constraint on the definition of fracture mechanics. To qualify as a true fracture mechanics approach, the measured fracture properties must be broadly applicable and not restricted only to the special conditions in which the characterizing experiments are performed. Approaches in which a specific structural component is closely simulated are therefore not in this spirit. Even though such tests are performed on cracked materials, if a basic fracture parameter is not correctly involved, the results are limited to an interpolative function; that is, reliable predictions can only be made for conditions that correspond to those in which the experiments were performed.

The hallmark of a true fracture mechanics approach is that it has an extrapolative function. It should be possible to obtain reliable predictions even for conditions that differ significantly from those in which crack growth measurements were made. In accord with this constraint, fracture mechanics makes possible the use of small-scale laboratory tests (e.g., compact tension specimens) to provide material crack growth and fracture property data for integrity assessments of large-scale structures. Of

course, a properly founded analysis approach provides the critical link needed to make such a transition possible.

Our basic definition of fracture mechanics may also help readers of this book to appreciate just how broad the subject of fracture mechanics is. Far from being a specialized subject, it underlies all structural analysis and materials science. No structural material is exempt from a defect condition, and, if it could not fail because of such defects, it would be pointless to analyze it in any other way. Consequently, each and every structural component is, or could be, a candidate for treatment by fracture mechanics. While all applications obviously do not now receive such scrutiny, it is clear from present trends that the years to come will see fracture mechanics assessments become more and more commonplace.

We have sought to satisfy two general groups of readers. In the first group are those who may have had little or no association with fracture mechanics, but possess a background in stress analysis and/or materials science equivalent to that acquired in an undergraduate engineering program. The second group contains those who have worked, perhaps extensively, in a particular aspect of fracture, but who have not been exposed to the variety of application areas covered. Our presentation can be likened to a paraphrase of a remark on the nature of science attributed to the French mathematician Poincaré: a technical book is built of facts the way a house is built of bricks, but an accumulation of facts is no more a book than a pile of bricks is a house. That is, we have sought to provide more than just a haphazard collection of analysis approaches and results. We want instead to show the essential unity of fracture mechanics and the basic commonality of its many specializations. Simply put, our goal is to demonstrate principles rather than recount details. Thus, we want our book to be judged on whether it enables its readers to understand fracture mechanics, not on its worth as a source of up-to-the-minute data and problem-solving techniques.

This book is partly based on lecture notes for a two-quarter course on fracture mechanics taught in the Department of Engineering Mechanics at the Ohio State University. The introductory course for advanced undergraduate and beginning graduate students is confined primarily to linear elastic or small-scale yielding fracture mechanics. It draws upon material from Chapters 1 through 3, supplemented with selected topics from Chapter 5. The more advanced topics in Chapters 2 and 4 through 7 form the subject matter for the second course. Since experience has demonstrated that the book contains more material than can conceivably be covered in a two-quarter course, the book should also be suitable for use in a two-semester course. Chapter 1 evolved from notes developed for short courses designed to introduce fracture mechanics to practicing engineers interested in structural integrity and nondestructive evaluation.

In common with most engineering-oriented subjects, fracture mechanics practitioners have had to face the problems arising from the use of different sets of units. We are convinced that the SI system will eventually

become universally accepted and, accordingly, have tried to use it to the extent possible in this book. However, a great amount of data has been collected and reported in English units. We do not feel obliged to convert these data, and, in fact, because the English system is still far from obsolete, feel that we would not be providing a service in so doing. Dual systems are tedious and tend to become much more of a hindrance than a help to understanding. We have provided a conversion chart at the front of the book to assist the reader with a need to have particular results in a system other than the one in which we have reported it.

In writing this book we have been able to draw upon a vast amount of published material. This is of course not an unmixed blessing. There are simply too many worthwhile reports of research activities in fracture mechanics for us to report on but a fraction of them. For example, the two primary journals exclusively devoted to the subject—*The International Journal of Fracture* and *Engineering Fracture Mechanics*—contained some 3100 pages between them in 1983. Added to this are perhaps two dozen other technical journals that regularly contain papers on some aspect of fracture mechanics together with countless volumes of conference proceedings and other compilations. Accordingly, we make no pretense of completeness in covering the subject. We believe that the approximately 800 references we have cited will provide ready access to the remaining literature in any particular specialized area. Furthermore, we have selected references to reflect the main contributors to the subject, thereby identifying the people from whom important work in each area of interest to our readers can be expected in the future. In so doing, we have provided citations that are readily obtainable in English and would be available in most technical libraries. Our apologies to those whose major contributions we have unintentionally (and inevitably) overlooked, and to those whose claims of historical priority—particularly in non-English-language papers—we have thereby violated.

We have found it possible to embark upon the preparation of this book because of the wide diversity of the research we have been involved in. For this, both of us must primarily credit our associations with the Battelle Memorial Institute. Each of us could also compile a long list of colleagues and co-workers who have in some way contributed to extending our knowledge of fracture mechanics. That we have not named them individually does not, we hope, suggest that our debt to these associations is a small one. It is not. There are, however, four individuals whose influence on the first author have been such that he would be extremely remiss not to acknowledge them specifically. These are Mr. Eugene Eschbach, who guided his first professional work while both were employed by the General Electric Company in Richland, Washington; the late Professor Norman Goodier, his teacher, advisor and friend at Stanford University; Dr. George Hahn, his co-worker for many years at Battelle's Columbus Laboratories; and the one foremost in his affections, his wife, Jean. The second author would like to acknowledge his friend and mentor, the late

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ADVANCED FRACTURE MECHANICS

CONVERSION FACTORS FOR STRESS

	MPa	ksi	kg mm ⁻²
1 MPa (N mm ⁻²) =	1	0.1450	0.1019
1 ksi =	6.895	1	0.7031
1 kg mm ⁻² =	9.807	1.4223	1

CONVERSION FACTORS FOR THE STRESS INTENSITY FACTOR

	MPa m ^{1/2}	ksi in ^{1/2}	N mm ^{-3/2}	kg mm ^{-3/2}
1 MPa m ^{1/2} =	1	0.910	31.62	3.224
1 ksi in ^{1/2} =	1.099	1	34.75	3.542
1 N mm ^{-3/2} =	0.03162	0.02878	1	0.1019
1 kg mm ^{-3/2} =	0.3102	0.2823	9.807	1

INTRODUCTION AND OVERVIEW

The existence of crack-like flaws cannot be precluded in any engineering structure. At the same time, increasing demands for energy and material conservation are dictating that structures be designed with smaller safety margins. Consequently, accurate quantitative estimates of the flaw tolerance of structures is increasingly becoming of direct concern for the prevention of fracture in load-bearing components of all kinds. This has not always been so. Prudent design procedures that avoided large stress concentrations—together with immediate repair or retirement from service of components that exhibited cracks—have been reasonably effective in preventing catastrophic failures. However, two important factors have now emerged to negate this traditional strategy.

First, improved nondestructive evaluation (NDE) procedures have enabled defects to be found that would have gone unnoticed earlier. Second, the presence of a crack-like defect does not necessarily mean that a structural component is at (or even near) the end of its useful service life. The cost of the repair or replacement of a flawed component can therefore be balanced against the possibility that continued service could lead to a failure. The new engineering concept known as *damage tolerance* has been developed to provide quantitative guidance for this purpose. It, in turn, is largely based upon the technology of *fracture mechanics*. While not the only ingredient of structural integrity assessments, as this book will make clear, it plays a central role.

Concern for fracture has surely existed back to antiquity. While much of this concern is unrecorded, some evidence of scholarly study that substantially predates our times does exist; see for examples Gordon's books (1.1). As described in Timoshenko's history of the strength of materials (1.2)—see also Irwin's review paper (1.3)—da Vinci performed experiments to determine the strength of iron wires in the fifteenth century. He found an inverse relationship between the wire length and the breaking load for constant diameter wires. Because this result would otherwise imply that strength is dependent upon the wire length, it can be surmised that the presence of cracks dictated the fracture stress; that is, the larger the volume of material tested, the more likely it is that a large crack exists. Considering the wire quality available at that time, this is highly plausible. Nevertheless, little of a quantitative nature could be done with this possibility. Fracture theories based on crack extension require the mathematical concepts of stress and strain that were not forthcoming until given by Cauchy and the other great French mathematician/engineers of the nineteenth century (1.4).