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978-0-521-19489-1 — Fracture Mechanics
Robert P. Wei
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1 Introduction

Fracture mechanics, or the mechanics of fracture, is a branch of engineering science that addresses the problem of the integrity and durability of materials or structural members containing cracks or cracklike defects. The presence of cracks may be real, having been introduced through the manufacturing processes or during service. On the other hand, their presence may have to be assumed because limitations in the sensitivity of nondestructive inspection procedures preclude full assurance of their absence. A perspective view of fracture mechanics can be gained from the following questions:

- How much load will it carry, with and without cracks? (a question of *structural safety and integrity*).
- How long will it last, with and without cracks? Alternatively, how much longer will it last? (a concern for *durability*).
- Are you sure? (the important issue of *reliability*).
- How sure? (*confidence* level).

The corollary questions are as follows, and will not be addressed here:

- How much will it cost? To buy? (capital or acquisition cost); to run? (operational cost); to get rid of? (disposal/recycling cost)
- Optimize capital (acquisition) costs?
- Optimize overall (life cycle) cost?

These questions appear to be simple, but are in fact profound and difficult to answer. Fracture mechanics attempts to address (or provides the framework for addressing) these questions, where the presence of a crack or cracklike defects is presumed.

The first of the questions deals with the stability of a crack under load. Namely, would it remain stable or grow catastrophically? The second question deals with the issue: “if a crack can grow stably under load, how long would it take before it reaches a length to become unstable, or become unsafe?” The third question, encompassing the first two, has to do with certainty; and the last deals with the confidence in the answers. These questions lead immediately to other questions.

Can the properties that govern crack stability and growth be computed on the basis of first principles, or must they be determined experimentally? How are these properties to be defined, and how well can they be determined? What are the variations in these properties? If the failure load or crack growth life of a material can be measured, what degree of certainty can be attached to the prediction of safe operating load or serviceable life of a structural component made from that material?

1.1 Contextual Framework

In-service incidents provide lasting reminders of the "aging" of, or cracking in, engineered systems. Figure 1.1 shows the consequence of an in-flight rupture of an eighteen-foot section of the fuselage of an Aloha Airlines 737 aircraft over the Hawaiian Islands in 1988. The rupture was attributed to the "link up" of extensive fatigue cracking along a riveted longitudinal joint. Fortunately, the pilots were

Figure 1.1. In-flight separation of an upper section of the fuselage of a B737-200 aircraft in 1988 attributed to corrosion and fatigue.

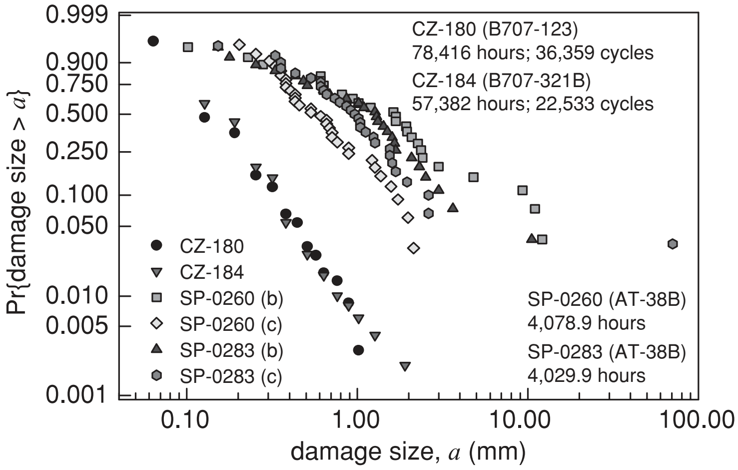

Figure 1.2. Damage distribution in aged B707 (CZ-180 and CZ184) after more than twenty years of service, and AT-38B aircraft after more than 4,000 hours of service [3].

able to land the aircraft safely, with the loss of only one flight attendant who was serving in the cabin. Tear-down inspection data on retired commercial transport and military aircraft [1, 2] (Fig. 1.2), provide some sense of the damage that can accrue in engineered structures, and of the need for robust design, inspection, and maintenance.

On the other end of the spectrum, so to speak, the author encountered a fatigue failure in the "Agraph" of a chamber grand piano (Figs. 1.3 and 1.4). An Agraph is typically a bronze piece that supports the keyboard end of piano strings (wires). It

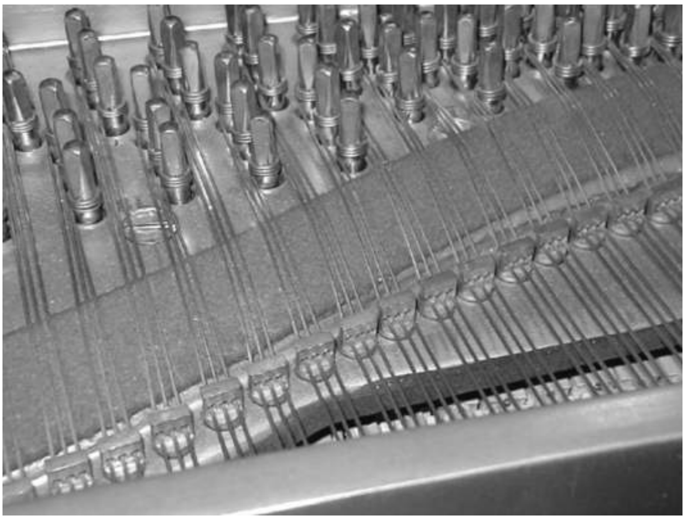

Figure 1.3. Interior of a chamber grand piano showing a row of Agraphs aligned just in front of the red velvet cushion.

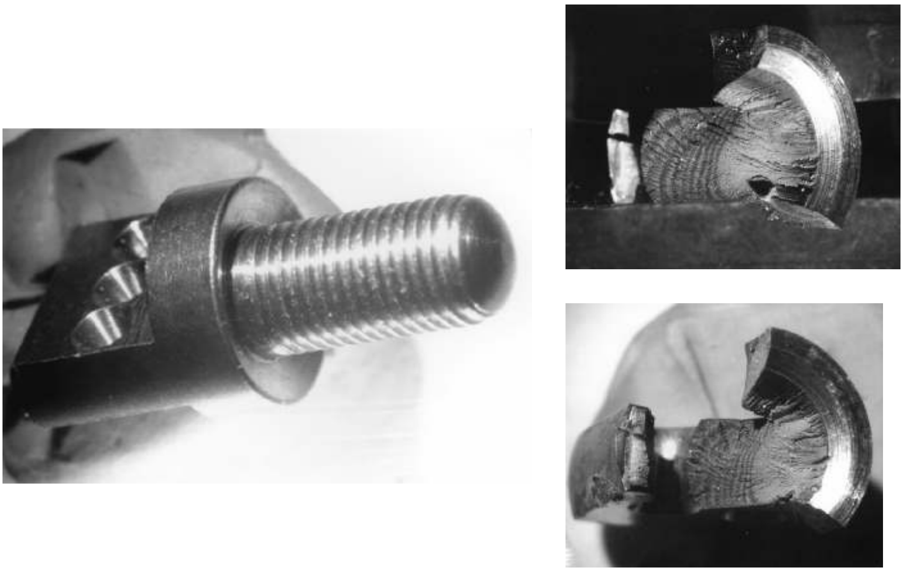

Figure 1.4. (left) Photograph of a new Agraph from a chamber grand piano, and (right) scanning electron micrographs of the mating halves of a fractured Agraph showing fatigue markings and final fracture.

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sets the effective length of the strings and carries the effect of tension in the strings that ensures proper tuning. As such, it carries substantial static (from tuning tension) and vibratory loads (when the string is struck) and undergoes fatigue.

1.2 Lessons Learned and Contextual Framework

Key lessons learned from aging aircraft and other research over the past four decades showed that:

- Empirically based, discipline-specific methodologies for design and management of engineered systems are not adequate.
- Design and management methodologies need to be science-based, much more holistic, and better integrated.

Tear-down inspections of B-707 and AT-38B aircraft [1, 2] showed:

- The significance of localized corrosion on the evolution and distribution of fatigue damage was not fully appreciated.
- Its impact could not have been predicted by the then existing and current technologies.

As such, transformation in thinking and approach is needed.

Fracture mechanics need to be considered in the context of a modern design paradigm. Such a contextual framework and simplified flow chart is given in Fig. 1.5. The paradigm needs to address the following:

- Optimization of life-cycle cost (*i.e.*, cost of ownership)
- System/structural integrity, performance, safety, durability, reliability, etc.
- Enterprise planning
- Societal issues (*e.g.*, environmental impact)

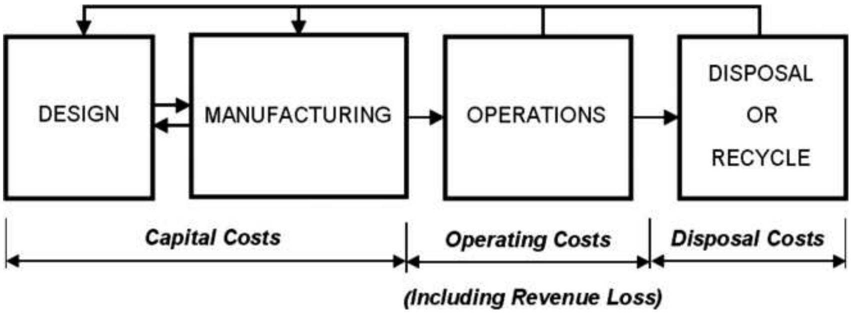

Figure 1.5. Contextual framework and simplified flow diagram for the design and management of engineered systems.

A schematic flow diagram that underlies the processes of reliability and safety assessments is depicted in Fig. 1.6. The results should be used at different levels to aid in operational and strategic planning.

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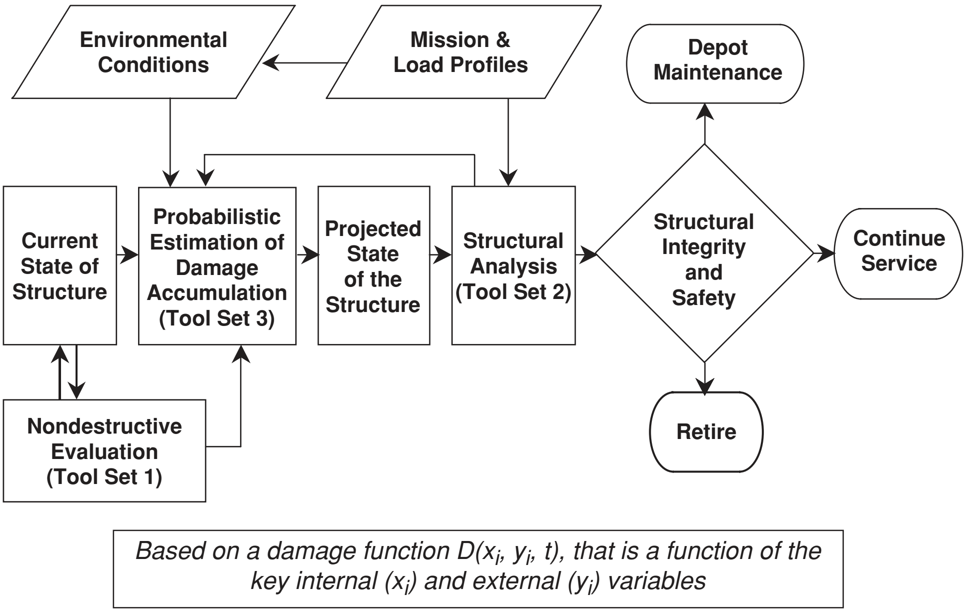

Figure 1.6. Simplified flow diagram for life prediction, reliability assessment, and management of engineered systems.

Fracture mechanics, therefore, must deal with the following two classes of problems:

- Crack tolerance or residual strength
- Crack growth resistance

A brief consideration of each is given here to identify the nature of the problems, and to assist in defining the scope of the book.

1.3 Crack Tolerance and Residual Strength

The concept of crack tolerance and residual strength can be understood by considering the fracture behavior of a plate, containing a central crack of length $2a$, loaded in remote tension under uniform stress σ (see Fig. 1.7). The fracture behavior is illustrated schematically also in Fig. 1.7 as a plot of failure stress versus half-crack length (a). The line drawn through the data points represents the failure locus, and the stress levels corresponding to the uniaxial yield and tensile strengths are also indicated. The position of the failure locus is a measure of the material's crack tolerance, with greater tolerance represented by a translation of the failure locus to longer crack lengths (or to the right).

The stress level corresponding to a given crack length on the failure locus is the residual strength of the material at that crack length. The residual strength typically would be less than the uniaxial yield strength. The crack length corresponding to a given stress level on the failure locus is defined as the critical crack size. A crack that is smaller (shorter) than the critical size, at the corresponding stress level, is defined

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as a subcritical crack. The region below the failure locus is deemed to be safe from the perspective of unstable fracture.

The fracture behavior may be subdivided into three regions: A, B, and C (see Fig. 1.7). In region A, failure occurs by general yielding, with extensive plastic deformation and minor amounts of crack extension. In region C, failure occurs by rapid (unstable) crack propagation, with very localized plastic deformation near the crack tip, and may be preceded by limited stable growth that accompanies increases in applied load. Region B consists of a mixture of yielding and crack propagation. Hence, fracture mechanics methodology must deal with each of these regions either separately or as a whole.

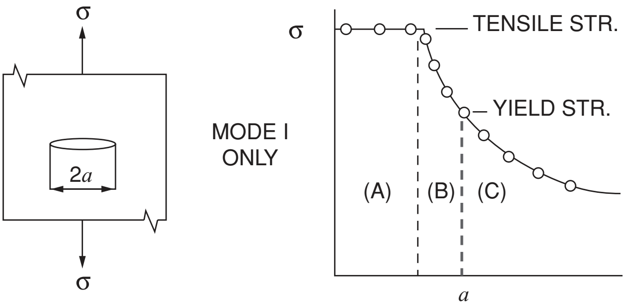

Figure 1.7. Schematic illustration of the fracture behavior of a centrally cracked plate loaded in uniform remote tension.

In presenting Fig. 1.7, potential changes in properties with time and loading rate and other time-dependent behavior were not considered. In effect, the failure locus should be represented as a surface in the stress, crack size, and time (or strain rate, or crack velocity) space (see Fig. 1.8). The crack tolerance can be degraded because of the strain rate sensitivity of the material, and time-dependent changes in microstructure (*e.g.*, from strain aging and radiation damage), with concomitant increases in strength. As a result, even without crack extension and increases in applied load (or stress), conditions for catastrophic failure may be attained with time or an increase in applied load (or stress), or an increase in loading rate (see path 3 in Fig. 1.8b).

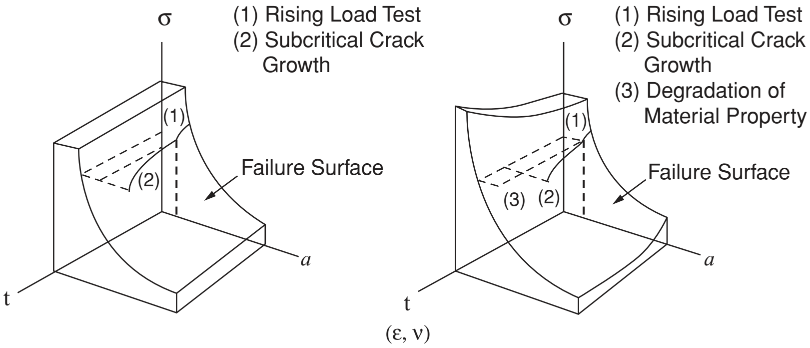

Figure 1.8. Schematic illustration of the influence of time (or strain rate, or crack velocity) on the fracture behavior of a centrally cracked plate loaded in uniform remote tension.

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1.4 Crack Growth Resistance and Subcritical Crack Growth

Under certain loading (such as fatigue) and environmental (both internal and external to the material) conditions, cracks can and do grow and lead to catastrophic failure. The path for such an occurrence is illustrated by path 2 in Fig. 1.8. Because the crack size remains below the critical size during its growth, the processes are broadly termed subcritical crack growth. The rate of growth is determined by some appropriate driving force and growth resistance, which both must be defined by fracture mechanics.

The phenomenon of subcritical crack growth may be subdivided into four categories according to the type of loading and the nature of the external environment as shown in Table 1.1.

Table 1.1. *Categories of subcritical crack growth*

Loading condition	Inert environment	Deleterious environment
Static or sustained	Creep crack growth (or internal embrittlement)	Stress corrosion cracking
Cyclic or fatigue	Mechanical fatigue	Corrosion fatigue

Under statically applied loads, or sustained loading, in an inert environment, crack growth is expected to result from localized deformation near the crack tip. This phenomenon is of particular importance at elevated temperatures. Under cyclically varying loads, or in fatigue, crack growth can readily occur by localized, but reversed deformation in the crack-tip region. When the processes are assisted by the presence of an external, deleterious environment, crack growth is enhanced and is termed environmentally assisted crack growth.

Environmentally enhanced crack growth is typically separated into stress corrosion cracking (for sustained loading) and corrosion fatigue (for cyclic loading), and involves complex interactions among the environment, microstructure, and applied loading. Crack growth can occur also because of embrittlement by dissolved species (such as hydrogen) in the microstructure. This latter problem may be viewed in combination with deformation-controlled growth, or as a part of environmentally assisted crack growth.

1.5 Objective and Scope of Book

The objective of this book is to demonstrate the need for, and the efficacy of, a mechanistically based probability approach for addressing the structural integrity, durability, and reliability of engineered systems and structures. The basic elements of engineering fracture mechanics, materials science, surface and electrochemistry, and probability and statistics that are needed for the understanding of materials behavior and for the application of fracture mechanics-based methodology in design and research are summarized. Through examples used in this book, the need for and efficacy of an integrated, multidisciplinary approach is demonstrated.

The book is topically divided into four sections. In Chapters 2 and 3, the physical basis of fracture mechanics and the stress analysis of cracks, based on linear elasticity, are summarized. In Chapters 4 and 5, the experimental determination of fracture toughness and the use of this property in design are highlighted (How much load can be carried?). Chapters 6 to 9 address the issue of durability (How long would it last?), and cover the interactions of mechanical, chemical, and thermal environments. Selected examples are used to illustrate the different cracking response of different material/environment combinations, and the influences of temperature, loading frequency, etc. The development of mechanistic understanding and modeling is an essential outcome of these studies. Chapter 10 illustrates the use of the forgoing mechanistically based models in the formulation of probability models in quantitative assessment of structural reliability and safety. It serves to demonstrate the need to transition away from the traditional empirically based design approaches, and the attendant uncertainties in their use in structural integrity, durability, and reliability assessments.

The book (along with the appended list of references) serves as a reference source for practicing engineers and scientists, in engineering, materials science, and chemistry, and as a basis for the formation of multidisciplinary teams. It may be used as a textbook for seniors and graduate students in civil and mechanical engineering, and materials science and engineering, and as a basis for the formation of multidisciplinary teams in industry and government laboratories.

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[3] Harlow, D. G., and Wei, R. P., “Probability Modeling and Statistical Analysis of Damage in the Lower Wing Skins of Two Retired B-707 Aircraft,” *Fatigue and Fracture of Engineering Materials and Structures*, 24 (2001), 523–535.

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2 Physical Basis of Fracture Mechanics

In this chapter, the classical theories of failure are summarized first, and their inadequacy in accounting for the failure (fracture) of bodies that contain crack(s) is highlighted. The basic development of fracture mechanics, following the concept first formulated by A. A. Griffith [1, 2], is introduced. The concepts of strain energy release rate and stress intensity factor, and their identification as the *driving force* for crack growth are introduced. The experimental determinations of these factors are discussed. Fracture behavior of engineering materials is described, and the importance of fracture mechanics in the design and sustainment of engineered systems is considered.

2.1 Classical Theories of Failure

Classical theories of failure are based on concepts of maximum stress, strain, or strain energy and assume that the material is homogeneous and free from defects. Stresses, strains, and strain energies are typically obtained through elastic analyses.

2.1.1 Maximum Principal Stress (or Tresca [3]) Criterion

The *maximum principal stress criterion* for failure simply states that failure (by yielding or by fracture) would occur when the maximum principal stress reaches a critical value (*i.e.*, the material's yield strength, σ_{YS}, or fracture strength, σ_f, or tensile strength, σ_{UTS}). For a three-dimensional state of stress, given in terms of the Cartesian coordinates x, y, and z in Fig. 2.1 and represented by the left-hand matrix in Eqn. (2.1), a set of principal stresses (see Fig. 2.1) can be readily obtained by transformation:

$$\begin{vmatrix} \sigma_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_{yy} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_{zz} \end{vmatrix} \Rightarrow \begin{vmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_3 \end{vmatrix} \tag{2.1}$$

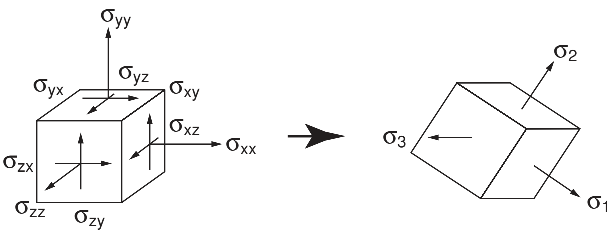

Figure 2.1. Transformation of stresses.

Assume that the largest principal stress is σ_1, the failure criterion is then given by Eqn. (2.2).

$$\sigma_1 = \sigma_{FAILURE} \ \ (\sigma_{YS} \text{ or } \sigma_f \text{ or } \sigma_{UTS});\ \sigma_1 > \sigma_2 > \sigma_3 \tag{2.2}$$

It is recognized that failure can also occur under compression. In that case, the strength properties in Eqn. (2.2) need to be replaced by the suitable ones for compression.

2.1.2 Maximum Shearing Stress Criterion

The *maximum shearing stress criterion* for failure simply states that failure (by yielding) would occur when the maximum shearing stress reaches a critical value (*i.e.*, the material's yield strength in shear). Taking the maximum and minimum principal stresses to be σ_1 and σ_3, respectively, then the failure criterion is given by Eqn. (2.3), where the yield strength in shear is taken to be one-half that for uniaxial tension.

$$\tau_{\max} = \tau_c = \frac{(\sigma_1 - \sigma_3)}{2} \quad \Rightarrow \quad \frac{\sigma_{YS}}{2} \text{ for uniaxial tension} \tag{2.3}$$

2.1.3 Maximum Principal Strain Criterion

The *maximum principal strain criterion* for failure simply states that failure (by yielding or by fracture) would occur when the maximum principal strain reaches a critical value (*i.e.*, the material's yield strain or fracture strain, ε_f). Again taking the maximum principal strain (corresponding to the maximum principal stress) to be ε_1, the failure criterion is then given by Eqn. (2.4).

$$\varepsilon_1 = \varepsilon_{FAILURE} \quad \Rightarrow \quad \frac{\sigma_{YS}}{E} \text{ or } \varepsilon_f \text{ for uniaxial tension} \tag{2.4}$$

2.1.4 Maximum Total Strain Energy Criterion

The *total strain energy criterion* for failure states that failure (by yielding or by fracture) would occur when the total strain energy, or total strain energy density u_T, reaches a critical value u_c. The total strain energy density may be expressed in terms