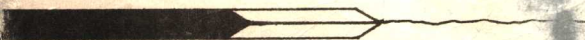
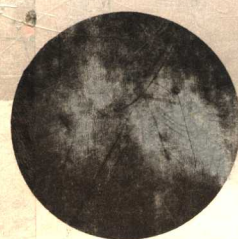
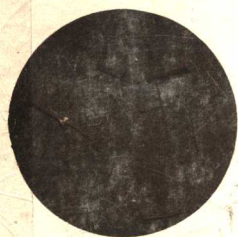


fracture mechanics



H.L. Edwards
R.J.H. Wanhill

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Fixed Grips and Constant Load

*Often we must show – to the best of our ability –
 That nothing can result in crack growth instability.
 Precision of analysis is unhappily elastic,
 Owing to the problem that most strains are really plastic.
 An added burden to each crack's calamitous position
 Is doubt about fixed grips and the constant load condition.
 U plus F is U_0 plus U_a plus U_γ
 This equation is so simple, we speak it without stammer.
 Now change the crack length slightly, increment da,
 At once we're not so certain of what we have to say.
 The energy release rate must always equal G,
 But positive or negative? It's difficult to see.
 So when you read our text on this in section four point two
 We hope there's not much trace of all that we have suffered through!*

R.J.H. Wanhill

Preface

While teaching a course on fracture mechanics at Delft University of Technology we discovered that although there are a few excellent textbooks, their subject matter covers developments only up to the early 1970s. Consequently there was no systematic treatment of the concepts of elastic-plastic fracture mechanics. Also the description of fracture mechanics characterization of crack growth needed updating, especially for sustained load fracture and unstable dynamic crack growth.

In the present textbook we have attempted to cover the basic concepts of fracture mechanics for both the linear elastic and elastic-plastic regimes, and three chapters are devoted to the fracture mechanics characterization of crack growth (fatigue crack growth, sustained load fracture and dynamic crack growth).

There are also two chapters concerning mechanisms of fracture and the ways in which actual material behaviour influences the fracture mechanics characterization of crack growth. The reader will find that this last topic is treated to some way beyond that of a basic course. This is because to our knowledge there is no reference work that systematically covers it. A consequence for instructors is that they must be selective here. However, any inconvenience thereby entailed is, we feel, outweighed by the importance of the subject matter.

This textbook is intended primarily for engineering students. We hope it will be useful to practising engineers as well, since it provides the background to several new design methods, criteria for material selection and guidelines for acceptance of weld defects.

Many people helped us during preparation of the manuscript. We wish to thank particularly J. Zuidema, who made vital contributions to uniform treatment of the energy balance approach for both the linear elastic and elastic-plastic regimes; R.A.H. Edwards, who assisted with the chapter on sustained load fracture; A.C.F. Hagedorn, who drew the figures for the first seven chapters; and the team of the VSSD, our publisher, whose patience was sorely tried but who remained unbelievably cooperative.

Finally, we wish to thank the National Aerospace Laboratory NLR and the Boiler and Pressure Vessel Authority 'Dienst voor het Stoomwezen' for providing us the opportunity to finish this book, which was begun at the Delft University of Technology.

The Authors
September 1983

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Part I Introduction

1. AN OVERVIEW

1.1. About this Course

This course is intended as a basic background in fracture mechanics for engineering usage. In order to compile the course we have consulted several textbooks and numerous research articles. In particular, the following books have been most informative and are recommended for additional reading:

- D. Broek, "Elementary Engineering Fracture Mechanics", Martinus Nijhoff (1982) The Hague.
- J.F. Knott, "Fundamentals of Fracture Mechanics", Butterworths, (1973) London.
- "A General Introduction to Fracture Mechanics", Institution of Mechanical Engineers (1978) London.

As indicated in the table of contents the course has been divided into several parts. Part I, consisting of this chapter, is introductory. In Part II the well established subject of Linear Elastic Fracture Mechanics (LEFM) is treated, and this is followed in Part III by the more recent and still evolving topic of Elastic-Plastic Fracture Mechanics (EPFM). In Part IV the applicability of fracture mechanics concepts to crack growth behaviour is discussed: namely subcritical, stable crack growth under cyclic loading (fatigue) or sustained load, and dynamic crack growth beyond instability. Finally, in Part V the mechanisms of fracture in actual materials are described together with the influence of material behaviour on fracture mechanics-related properties.

1.2. Historical Review

Strength failures of load bearing structures can be either of the yielding-dominant or fracture-dominant types. Defects are important for both types of failure, but those of primary importance to fracture differ in an extreme way from those influencing yielding and the resistance to plastic flow. These differences are illustrated schematically in figure 1.1.

For yielding-dominant failures the significant defects are those which tend to warp and interrupt the crystal lattice planes, thus interfering with dislocation glide and providing a resistance to plastic deformation that is essential to the strength of high strength metals. Examples of such defects are interstitial and out-of-size substitutional atoms, grain boundaries, coherent precipitates and dislocation networks. Larger defects like inclusions, porosity, surface scratches and small cracks may influence the effective net section bearing the load, but otherwise have little effect on resistance to yielding.

For fracture-dominant failures, i.e. fracture before general yielding of the net section, the size scale of the defects which are of major significance is essentially macroscopic, since general plasticity is not involved but only the local stress-strain fields associated with the defects. The minute lattice-related defects which control resistance to plastic flow are not of direct concern.

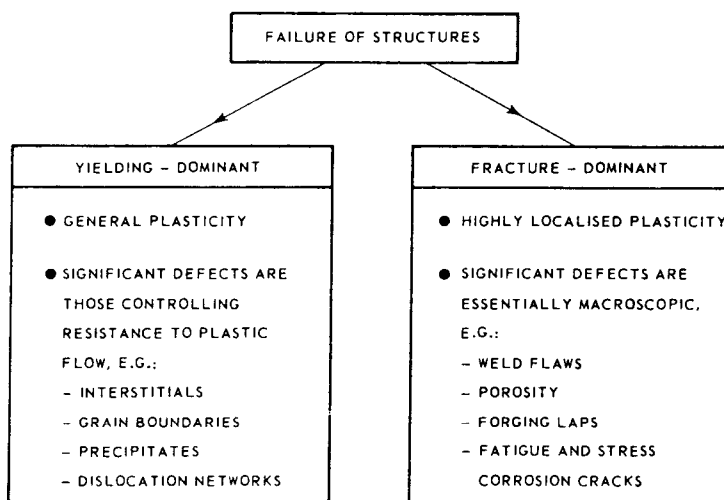


Figure 1.1. Types of structural failure.

They are important insofar as the resistance to plastic flow is related to the material's susceptibility to fracture.

Fracture mechanics, which is the subject of this course, is concerned almost entirely with fracture-dominant failure. The first successful analysis of a fracture-dominant problem was that of Griffith in 1920, who considered the propagation of brittle cracks in glass. Griffith formulated the now well-known concept that an existing crack will propagate if thereby the total energy of the system is lowered, and he assumed that there is a simple energy balance, consisting of a decrease in elastic strain energy within the stressed body as the crack extends, counteracted by the energy needed to create the new crack surfaces. His theory allows the estimation of the theoretical strength of brittle solids and also gives the correct relationship between fracture strength and defect size.

The Griffith concept was first related to brittle fracture of metallic materials by Zener and Hollomon in 1944. Soon after, Irwin pointed out that the Griffith-type energy balance must be between (1) the stored strain energy and (2) the surface energy plus the work done in plastic deformation. Irwin also recognized that for relatively ductile materials the energy required to form new crack surfaces is generally insignificant compared to the work done in plastic deformation, and he defined a material property G as the total energy absorbed during cracking per unit increase in crack length and per unit thickness. G is called the 'energy release rate' or 'crack driving force'.

In the middle 1950s Irwin contributed another major advance by showing that the energy approach is equivalent to a stress intensity (K) approach, according to which fracture occurs when a critical stress distribution ahead of the crack tip is reached. The material property governing fracture may therefore be stated as a critical stress intensity, K_c , or in terms of energy as a critical value G_c .

Demonstration of the equivalence of G and K provided the basis for development of the discipline of Linear Elastic Fracture Mechanics (LEFM). This is because the form of the stress distribution around and close to a crack tip is always the same. Thus tests on suitably shaped and loaded specimens to determine K_{Ic} make it possible to determine what flaws are tolerable in an actual structure under given conditions. Furthermore, materials can be compared as to their utility in situations where fracture is possible. It has also been found that the sensitivity of structures to subcritical cracking such as fatigue crack growth and stress corrosion can, to some extent, be predicted on the basis of tests using the stress intensity approach.

The beginnings of Elastic-Plastic Fracture Mechanics (EPFM) can be traced to fairly early in the development of LEFM, notably Wells' work on Crack Opening Displacement (COD), which was published in 1961. However, the greater complexity of the problems of analysis has necessarily led to somewhat slower progress. EPFM is still very much an evolving discipline.

1.3. The Significance of Fracture Mechanics

In the nineteenth century the Industrial Revolution resulted in an enormous increase in the use of metals (mainly irons and steels) for structural applications. Unfortunately, there also occurred many accidents, with loss of life, owing to failure of these structures. In particular, there were numerous accidents involving steam boiler explosions and railway equipment.

Some of these accidents were due to poor design, but it was also gradually discovered that material deficiencies in the form of pre-existing flaws could initiate cracking and fracture. Prevention of such flaws by better production methods reduced the number of failures to more acceptable levels.

A new era of accident-prone structures was ushered in by the advent of all-welded designs, notably the Liberty ships and T-2 tankers of World War II. Out of 2500 Liberty ships built during the war, 145 broke in two and almost 700 experienced serious failures. Many bridges and other structures also failed. The failures often occurred under very low stresses, for example even when

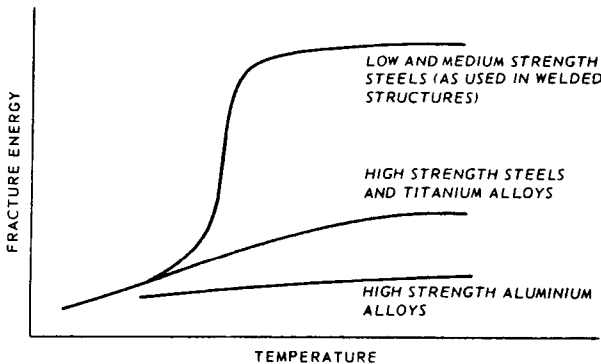


Figure 1.2. Schematic of the general effect of temperature on the fracture resistance of structural metals.

a ship was docked, and this anomaly led to extensive investigations which revealed that the fractures were brittle and that flaws and stress concentrations were responsible. It was also discovered that brittle fracture in the types of steel used was promoted by low temperatures. This is depicted in figure 1.2: above a certain transition temperature the steels behave in a ductile manner and the energy required for fracture increases greatly.

Current manufacturing and design procedures can prevent the intrinsically brittle fracture of welded steel structures by ensuring that the material has a suitably low transition temperature and that the welding process does not raise it. Nevertheless, service-induced embrittlement, for example irradiation effects in nuclear pressure vessels and corrosion fatigue in offshore platforms, remains a cause for concern.

Looking at the present situation it may be seen from figure 1.3 that since World War II the use of high strength materials for structural applications has greatly increased.

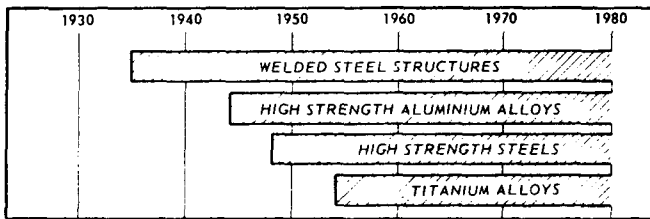


Figure 1.3. Introduction of high strength materials for structural applications.

These materials are often selected to obtain weight savings – aircraft structures are an obvious example. Additional weight savings have come from refinements in stress analysis, which have enabled design allowables to be raised. However, it was not recognized until towards the end of the 1950s that although these materials are not intrinsically brittle, the energy required for fracture is comparatively low, as figure 1.2 shows. The possibility, and indeed occurrence, of this low energy fracture in high strength materials stimulated the modern development of fracture mechanics.

The object of fracture mechanics is to provide quantitative answers to specific problems concerning cracks in structures. As an illustration, consider a structure containing pre-existing flaws and/or in which cracks initiate in service. The cracks may grow with time owing to various causes (for example fatigue, stress corrosion, creep) and will generally grow progressively faster, figure 1.4.a. The residual strength of the structure, which is the failure strength as a function of crack size, decreases with increasing crack size, as shown in figure 1.4.b. After a time the residual strength becomes so low that the structure may fail in service.

With respect to figure 1.4 fracture mechanics should attempt to provide quantitative answers to the following questions:

- 1) What is the residual strength as a function of crack size?
- 2) What crack size can be tolerated under service loading, i.e. what is the

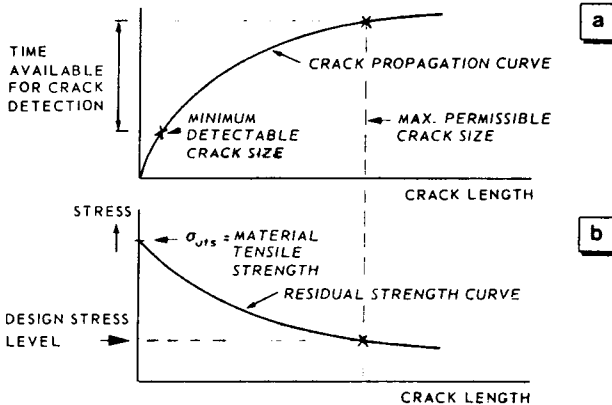


Figure 1.4. The engineering problem of a crack in a structure.

maximum permissible crack size?

- 3) How long does it take for a crack to grow from a certain initial size, for example the minimum detectable crack size, to the maximum permissible crack size?
- 4) What is the service life of a structure when a certain pre-existing flaw size (e.g. a manufacturing defect) is assumed to exist?
- 5) During the period available for crack detection how often should the structure be inspected for cracks?

This course is intended to show how fracture mechanics concepts can be applied so that these questions can be answered.

In the remaining sections 1.4 – 1.10 of this introductory chapter an overview of basic concepts and applications of LEFM are given in preparation for more detailed treatment in subsequent chapters.

1.4. The Griffith Energy Balance Approach

Consider an infinite plate of unit thickness that contains a through-thickness crack of length $2a$ and that is subjected to uniform tensile stress, σ , applied at infinity. Figure 1.5 represents an approximation to such a plate.

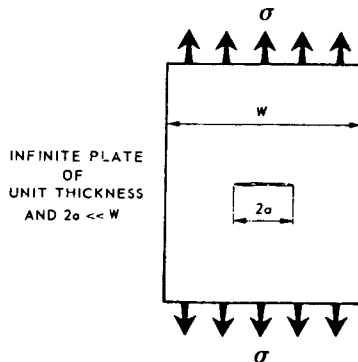


Figure 1.5. A through-cracked plate.