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FRACTURE MECHANICS

3.1 INTRODUCTION

The fatigue life of a component is made up of initiation and propagation stages. This is illustrated schematically in Fig. 3.1. The size of the crack at the transition from initiation to propagation is usually unknown and often depends on the point of view of the analyst and the size of the component being analyzed. For example, for a researcher equipped with microscopic equipment it may be on the order of a crystal imperfection, dislocation, or a 0.1 mm-crack, while to the inspector in the field it may be the smallest crack that is readily detectable with nondestructive inspection equipment. Nevertheless, the distinction between the initiation life and propagation life is important. At low strain amplitudes up to 90% of the life may be taken up with initiation, while at high amplitudes the majority of the fatigue life may be spent propagating a crack. Fracture mechanics approaches are used to estimate the propagation life.

Fracture mechanics approaches require that an initial crack size be known or assumed. For components with imperfections or defects (such as welding porosities, inclusions and casting defects, etc.) an initial crack size may be known. Alternatively, for an estimate of the total fatigue life of a defect-free material, fracture mechanics approaches can be used to determine propagation. Strain-life approaches may then be used to determine initiation life, with the total life being the sum of these two estimates.

In this chapter we briefly review the fundamentals of fracture mechanics and discuss the use of these concepts in applications to constant amplitude fatigue crack propagation analyses. In Chapter 4 we review fracture mechanics ap-

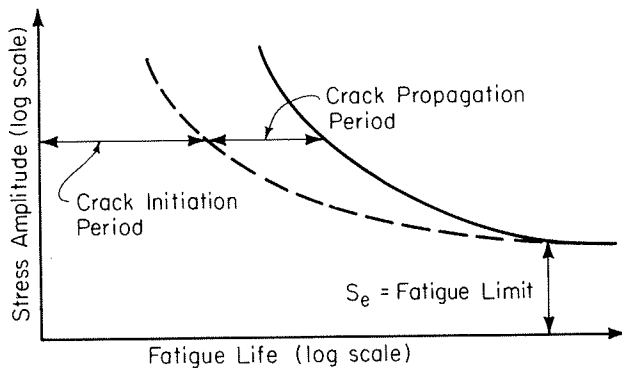


Figure 3.1 Initiation and propagation portions of fatigue life.

proaches for the analysis of notched components and in Chapter 5 discuss fracture mechanics approaches used to predict fatigue crack growth under variable amplitude loading.

3.2 LINEAR ELASTIC FRACTURE MECHANICS BACKGROUND

Linear elastic fracture mechanics (LEFM) principles are used to relate the stress magnitude and distribution near the crack tip to:

- Remote stresses applied to the cracked component
- The crack size and shape
- The material properties of the cracked component

3.2.1 Historical Overview

In the 1920s, Griffith [1] formulated the concept that a crack in a component will propagate if the total energy of the system is lowered with crack propagation. That is, if the change in elastic strain energy due to crack extension is larger than the energy required to create new crack surfaces, crack propagation will occur.

Griffith's theory was developed for brittle materials. In the 1940s, Irwin [2] extended the theory for ductile materials. He postulated that the energy due to plastic deformation must be added to the surface energy associated with the creation of new crack surfaces. He recognized that for ductile materials, the surface energy term is often negligible compared to the energy associated with plastic deformation. Further, he defined a quantity, G , the strain energy release rate or "crack driving force," which is the total energy absorbed during cracking per unit increase in crack length and per unit thickness.

In the mid-1950s, Irwin [3] made another significant contribution. He

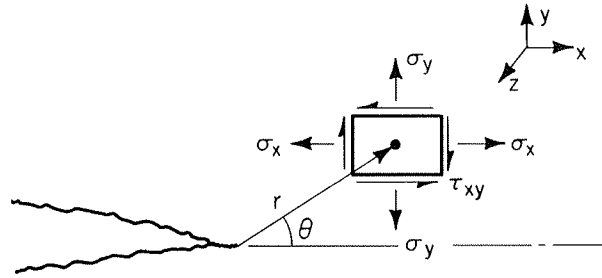


Figure 3.2 Location of local stresses near a crack tip in cylindrical coordinates.

showed that the local stresses near the crack tip are of the general form

$$\sigma_{ij} = \frac{K}{\sqrt{2\pi r}} f_{ij}(\theta) + \dots \quad (3.1)$$

where r and θ are cylindrical coordinates of a point with respect to the crack tip (see Fig. 3.2) and K is the stress intensity factor. He further showed that the energy approach (the “ G ” approach above) is equivalent to the stress intensity approach (described in Section 3.2.4) and that crack propagation occurs when a critical strain energy release rate, G_c (or in terms of a critical stress intensity, K_c) is achieved.

3.2.2 LEFM Assumptions

Linear elastic fracture mechanics (LEFM) is based on the application of the theory of elasticity to bodies containing cracks or defects. The assumptions used in elasticity are also inherent in the theory of LEFM: namely, small displacements and general linearity between stresses and strains.

The general form of the LEFM equations is given in Eq. (3.1). As seen, a singularity exists such that as r , the distance from the crack tip, tends toward zero, the stresses go to infinity. Since materials plastically deform as the yield stress is exceeded, a plastic zone will form near the crack tip. The basis of LEFM remains valid, though, if this region of plasticity remains small in relation to the overall dimensions of the crack and cracked body.

3.2.3 Loading Modes

There are generally three modes of loading, which involve different crack surface displacements (see Fig. 3.3). The three modes are:

- Mode I: opening or tensile mode (the crack faces are pulled apart)
- Mode II: sliding or in-plane shear (the crack surfaces slide over each other)
- Mode III: tearing or anti-plane shear (the crack surfaces move parallel to the leading edge of the crack and relative to each other)

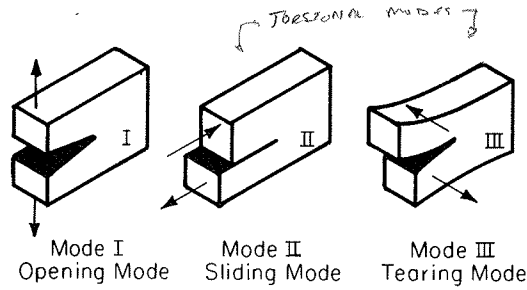


Figure 3.3 Three loading modes.

The following discussion deals with Mode I since this is the predominant loading mode in most engineering applications. Similar treatments can readily be extended to Modes II and III. Equations and additional details are found in Refs. 4 to 6.

3.2.4 Stress Intensity Factor

The stress intensity factor, K , which was introduced in Eq. (3.1), defines the magnitude of the local stresses around the crack tip. This factor depends on loading, crack size, crack shape, and geometric boundaries, with the general form given by

$$K = f(g)\sigma\sqrt{\pi a} \tag{3.2}$$

where σ = remote stress applied to component [not to be confused with the local stresses, σ_{ij} , in Eq. (3.1)]

a = crack length

$f(g)$ = correction factor that depends on specimen and crack geometry

Stress intensity factor solutions have been obtained for a wide variety of problems and published in handbook form [7-9]. Figure 3.4 gives the stress intensity relationships for a few of the more common loading conditions.

Stress intensity factors for a single loading mode can be added algebraically. Consequently, stress intensity factors for complex loading conditions of the same mode can be determined from the superposition of simpler results, such as those readily obtainable from handbooks.

One superposition method, the compounding technique, has been used to obtain relatively accurate approximations. The technique consists of reducing a complicated problem into a number of simpler configurations with known solutions. By superposition of these simpler K solutions, a stress intensity factor may be obtained for the complicated geometry. In equation form,

$$K_{tot} = K_0 + \left[\sum_{n=1}^N (K_n - K_0) \right] + K_e \tag{3.3}$$