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EXPERIMENTAL AND FINITE ELEMENT ANALYSIS OF CRACK DETECTION IN MATERIAL

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This project report, which entitled **"EXPERIMENTAL AND FINITE ELEMENT ANALYSIS OF CRACK DETECTION IN MATERIAL"** was prepared by Then Jip Chong as a partial fulfilment for the Degree of Bachelor (Honours) of Mechanical Engineering and Manufacturing System is hereby read and approved by:

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EXPERIMENTAL AND FINITE ELEMENT ANALYSIS OF CRACK DETECTION IN MATERIAL

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This project is submitted in partial fulfilment of the requirement for the Degree of Bachelor (Honours) of Mechanical Engineering and Manufacturing System

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Dedicated to beloved family

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ABSTRACT

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 of crack. Strain-life approaches may then be used to determine initiation life, with the total life being the sum of these two estimates. The prevention of failure in stressed structural components requires fracture mechanics based design parameter like critical load, critical crack-tip opening displacement or fracture toughness. Therefore, the intention of this paper is to study stress-strain response of thin mild steel sheet. Mode I fracture test was conducted based on Linear Elastic Fracture Mechanics (LEFM). In the fracture tests, three compact tension specimens were used in the T-L orientation, i.e. crack perpendicular to the rolling direction and load parallel to the rolling direction. Finite Element Analysis was performed to support the results on various fracture parameters. The magnitude of critical load was used as a fracture criterion for the thin sheets.

ABSTRAK

Pendekatan mekanik retakan memerlukan satu saiz retakan permulaan yang diketahui atau dianggap terlebih dahulu. Bagi komponen yang mengandungi ketidaksempurnaan atau kecacatan (seperti kekosongan, liang-liang kecil dalam kimpalan, dan kecacatan dalm pengacuanan, dll), saiz retakan permulaan mungkin boleh diketahui. Sebagai alternatif, anggaran jangka hayat kelesuan untuk sesuatu bahan yang tidak ada kecacatan, pendekatan mekanik retakan boleh digunakan untuk menentukan penyebaran retakan. Pendekatan jangka hayat ketegangan seterusnya digunakan untuk menentukan jangka hayat awal. Dengan itu, jangka hayat keseluruhan adalah hasil tambah kedua-dua anggaran. Pencegahan kegagalan dalam komponen berstruktur yang ditegangkan memerlukan parameter rekahan berdasarkan mekanik retakan seperti beban kritikal, pengambilalihan kritikal pembukaan hujung retakan ataupun kekuatan retakan. Dalam kerja ini, tumpuan diberikan kepada penyelidikan terhadap reaksi ketegasan-ketegangan kepingan keluli lembut yang nipis. Ujian retakan Mod I adalah berdasarkan Mekanik Retakan Keanjalan Linear. Dalam ujian retakan ini, tiga specimen digunakan adalah berorientasi L-T, iaitu retakan bersudut tepat kepada arah golekan dan beban adalah selari dengan arah golekan. Analisis Unsur Finit dilakukan untuk menyokong keputusan ke atas pelbagai parameter retakan. Magnitud beban kritikal dijadikan sebagai kriteria rekahan untuk kepingan nipis.

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CHAPTER 1

INTRODUCTION

1.0 Introduction

The static failure theories have assumed that materials are perfectly homogeneous and isotropic, thus free from any defects such as cracks, voids or inclusion, which could serve as stress-raisers. This is however seldom true for any real materials. In actual fact, all materials are considered to contain small flaws, which may vary from nonmetallic inclusions and microvoids to weld defects, grinding cracks, quench cracks, surface laps, etc. If stresses are high enough at the tip of a crack of sufficient size, a sudden, "brittle-like" failure can result, even in ductile materials under static loads[1].

According to Skinner[2], it has been suggested that 50 to 90 percent of all mechanical failures are due to fatigue, and the majority of these failures are unexpected. Fatigue causes failure in many common items such as door spring, toothbrushes, and tennis racquets as well as more complex components and structures in automobiles, ships and aircraft and any other device, which undergoes repeated loading.

Cracks commonly occur in welded structures, bridges, ships, aircraft, land vehicles, pressure vessels, etc. Several metallurgy investigations indicated that brittle fractures are resulted from a combination of factors. This cannot be eliminated in structures because of the interrelation among materials, design, fabrication, and loading. Although brittle fractures are not so common as fatigue, yielding, or buckling failures, there are more costly in terms of human life and/or property damage. These lead to researcher in seeking better failure theories, since the ones that are available could not adequately explained the observed phenomena[3].

To cope with these problems, it is important that the fracture behaviour of materials are characterised. Studies and researches of the phenomena as well as the properties of materials are still being carried out and are going on. In addition, precautions are to be taken to avoid or minimise damages that have been recommended; criteria for choice of materials and methods for estimation of durability of stressed components that have been developed[3].

Hence, periodic structural-safety inspections for cracks are required to verify the validity of structures, as in bridges, aircraft, etc. These inspections can be by X-ray, ultrasonic, or just visual inspection. When cracks are discovered, an engineering judgment must be made whether to repair or replace the flawed part, retire the assembly, or to continue it in service for a further time subject to more frequent inspection[1].

1.1 Project Objective

The purpose of this project is to study the stress-strain effects of compact tension specimen in Mode I (Tensile Mode), and determine the *critical stress intensity factors*, K_{IC}, of mild steel through experimentation and Finite Element Analysis (FEA). In addition to meet the purpose of the study, experiments are to be conducted for experiment's data and analysis. The relationship between crack displacements with increasing load is to be studied to estimate the greatest load for the mild steel sheet before which crack started to grow. Furthermore, the *critical stress intensity factor*, K_{IC}, of the mild steel sheet is to be determined.

Initially, Finite Element Analysis (FEA) is being used to predict the crack behaviour of a *4mm* mild steel sheet. This is achieved using a window-based commercial software called ANSYS. Once modelled, experiment will be conducted to obtain the actual values of critical load for the specimen. Furthermore, the prediction from ANSYS could be used to make a comparison with experimental results. This comparison is made to reveal the ability of finite element analysis method in simulating the problem area relative to conventional testing methods.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

Many researchers have investigated the fracture behaviour of structural materials in Mode I, i.e. the tensile mode. Some have attempted on experimental methods while others have attempted the Finite Element Analysis (FEA) methods. The following sections reveal the works presented by some researchers in terms of Mode I based on experimentation and two-dimensional (2D) modelling with FEA.

2.1 Griffith Theory

Griffith[3] formulated that a crack in a component will propagate if the total energy of the system is lowered with crack propagation. The analysis was based on the assumption that incipient fracture in ideally brittle materials occurs. 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. Therefore fracture is associated with the consumption of energy. The total potential energy of the system, U, may be written as

$$U = U_0 - U_a + U_\gamma \qquad (2.0)$$

where U : total potential energy of the system;

U_0: elastic energy of the uncracked plate;

U_a: decrease in the elastic energy caused by introducing the crack in the plate; and

U_γ: increase in the elastic-surface energy caused by the formation of the crack surfaces.

One such model that is used to demonstrate the propagation of a crack in a brittle material is called the *elastic strain energy model.*

$$\sigma = \sqrt{\frac{2E\gamma_e}{\pi a}} \qquad (2.1)$$

where E: modulus of elasticity;

γ_e: specific surface energy; and

a: one half the length of an internal crack.

2.2 Irwin Theory

Irwin[3] 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 recognised 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.

The modification recognised that a material's resistance to crack extension is equal to the sum of the elastic-surface energy and the plastic-strain work, γ_p, accompanying crack extension. Consequently, equation (2.1) was modified to

$$\frac{\pi\sigma^2 a}{E} = 2(\gamma_e + \gamma_p) \tag{2.2}$$

where γ_p is plastic deformation energy associate.

Since the left hand side of equation (2.2) is the strain energy release rate, G, and stress intensity factor, $K_I = \sigma\sqrt{\pi a}$ for plane-strain condition, the following relation exists between G and K_I:

$$\frac{\pi\sigma^2 a}{E} = G = \frac{K_I^2}{E}(1-\nu^2) \tag{2.3}$$

where G: energy release rate;

ν: Poisson's Ratio;

K_I: stress intensity factor for Mode I; and

E: modulus of elasticity.

2.3 Fracture Mechanics Theory

2.3.1 Definition of Fracture Mechanics

The presence of cracks may weaken materials such that fracture occurs at stresses much less than the yield or ultimate strengths. As defects always occur at a weld or at the heat affected zones in the base material, it is therefore essential to have acceptance fracture mechanics presumes the presence of a crack. Fracture mechanics is the methodology used to aid in selecting materials and designing components to minimize the possibility of fracture from cracks[4].

2.3.2 Modes of Crack Displacement

There are three types of relative movements of two fracture surfaces, namely Mode I (opening or tensile mode), Mode II (sliding or shearing mode), and Mode III (tearing mode). These displacement modes as shown in Figure 2.0 illustrate the local deformation in an infinitesimal element containing a crack front.

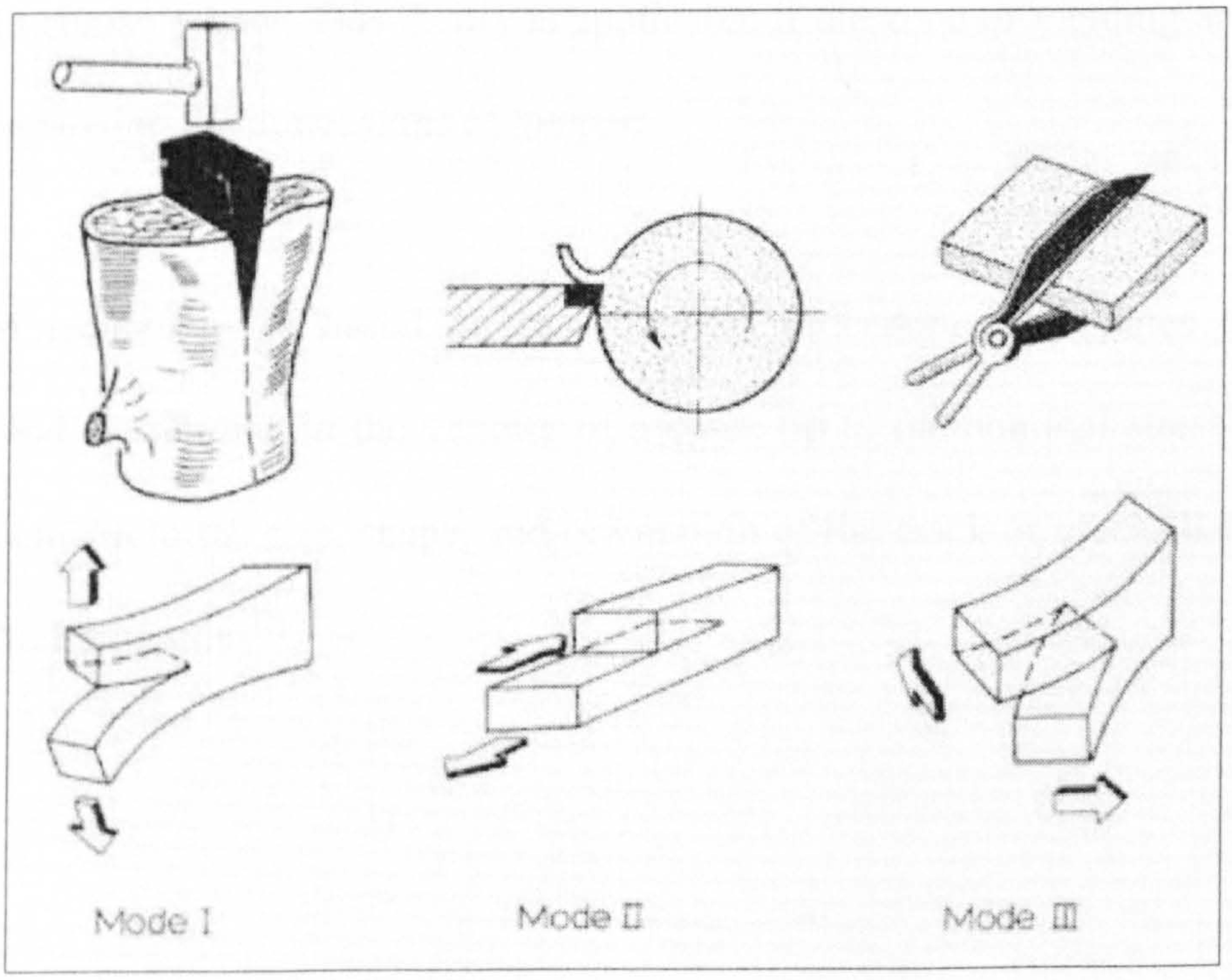

Figure 2.0: Modes of crack surface displacements. Mode I (opening or tensile mode), Mode II (sliding or shear mode), and Mode III (tearing mode).

2.3.3 Linear-Elastic Fracture Mechanics

Fracture mechanics has shown that fracture toughness, crack size and stress are the primary factors that determine the susceptibility of steel to fracture. Other contributing factors are service temperature, constraint, loading rate, cold working of the steel, and residual stresses. Brittle fractures may be analysed using linear elastic fracture mechanics (LEFM) principles[5].

The basic principle of LEFM is that incipient unstable crack growth will occur when the *stress intensity factor*, K_I, equals or exceeds the *critical stress intensity factor*, K_{IC}, i.e. $K_I \geq K_C$.

Norton[1] mentioned that LEFM assumes that the bulk of the material is behaving according to Hooke's Law. This theory is applicable if the zone of yielding around the crack is small compared to the dimensions of the part.

LEFM technology is based on an analytical procedure that relates the stress-field magnitude and distribution in the vicinity of a crack tip to the nominal stress applied to the structural member, to the size, shape, and orientation of the crack or crack-like discontinuity, and to material properties[3].

2.3.4 The Stress Intensity Approach

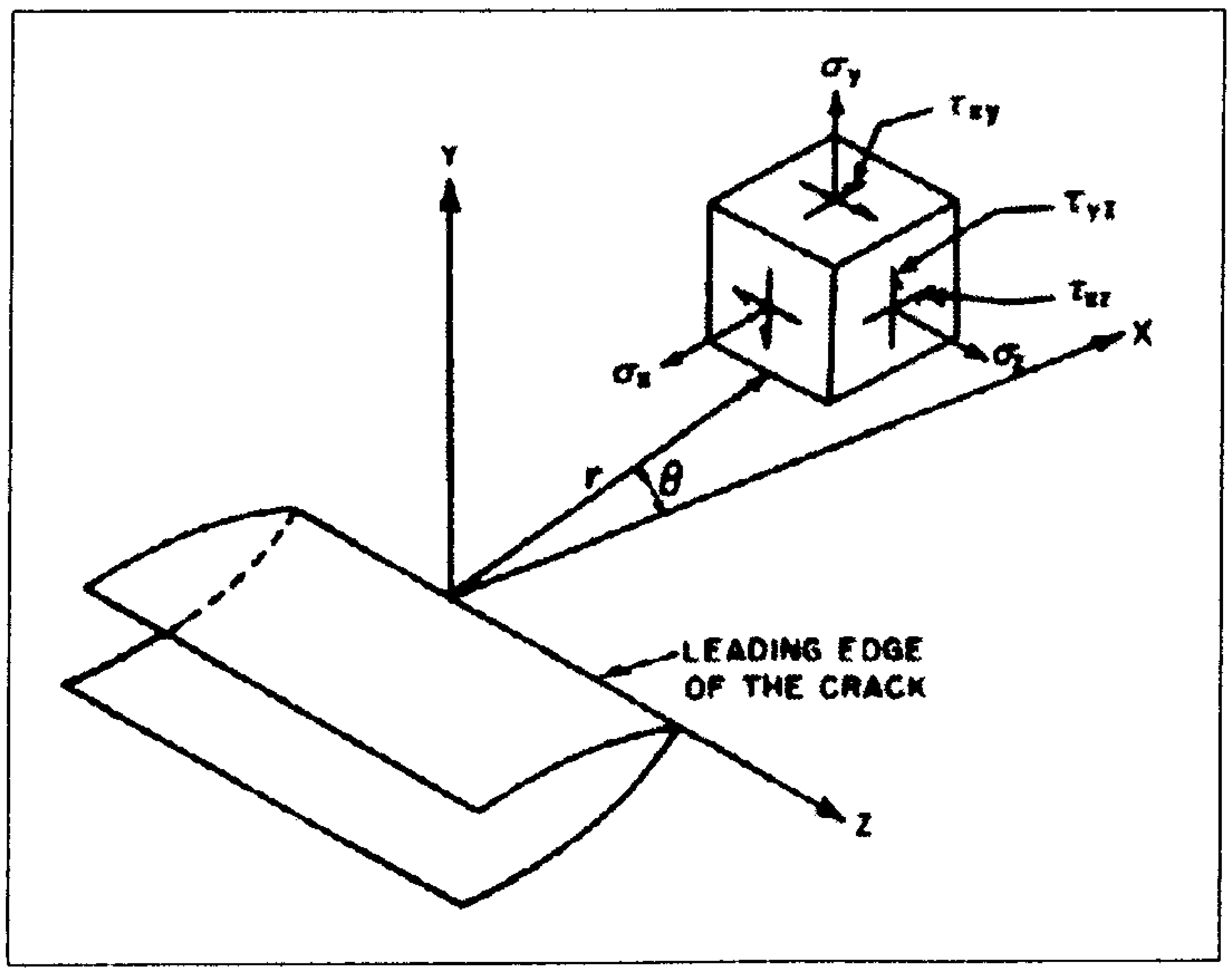

Figure 2.1 Coordinate system and stress components ahead of a crack tip.

The fundamental principle of fracture mechanics is that the stress field ahead of a sharp crack in a structural member can be characterised in terms of a single parameter, K, the *stress intensity factor*. This quantity, K, is related to both the nominal stress level (σ) in the member and the size of the crack present (a).

As shown in Figure 2.1, the stress and displacement field in the vicinity of crack tips subjected to the Mode I of deformation are given by[3]

$$\sigma_x = \frac{K_I}{\sqrt{2\pi r}}\cos\frac{\theta}{2}\left[1-\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right] \quad (2.4)$$

$$\sigma_y = \frac{K_I}{\sqrt{2\pi r}}\cos\frac{\theta}{2}\left[1+\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right] \quad (2.5)$$

$$\tau_{xy} = \frac{K_I}{\sqrt{2\pi r}}\sin\frac{\theta}{2}\cos\frac{\theta}{2}\cos\frac{3\theta}{2} \quad (2.6)$$

$$\sigma_z = \nu(\sigma_x + \sigma_y) \quad (2.7)$$

$$\tau_{xz} = \tau_{yz} = 0 \quad (2.8)$$

where σ_x: stress component at x direction;

σ_y: stress component at y direction;

K_I: stress intensity factor for Mode I;

r: radius from crack tip in the xy plane;

θ: angle from crack tip in the xy plane;

τ_{xy}: shear component at xy direction;

τ_{yx}: shear component at yx direction; and

ν: Poisson ratio.

2.4 Factors That Contribute to Brittle Fracture

Barson and Rolfe[3] have mentioned that research on brittle fracture in structures of all types has shown that various factors can contribute to brittle fracture in large welded structures. These factors are service temperature, material toughness, design, welding, residual stresses, fatigue, constraint, etc. However development of fracture mechanics has shown that there are three primary factors that control the susceptibility of a structure to brittle fracture. Among these are material toughness (K), crack size (a), and stress level (σ).

These three factors generally are the primary ones that control the susceptibility of a structure to brittle fracture. However, it is possible for brittle fractures to occur without all these factors being present if the other factors are sufficiently severe. These three primary factors are briefly described in the following subsection.

The material toughness can be defined as the ability to carry load or deform plastically in presence of a notch and can be described in terms of critical stress intensity factor under conditions of slow loading and linear-elastic behaviour. K_{Id} is a measure of the critical material toughness under condition of maximum constraint (plane strain) and impact or dynamic loading, also for linear-elastic behaviour.

Brittle fractures initiate from discontinuities of various kinds. These discontinuities can vary from extremely small cracks within a weld arc strike to a much larger weld or fatigue cracks. The original size and number of these discontinuities can be minimised but cannot be eliminated even though good fabrication practice and inspection were taken.

Tensile stresses (nominal, residual, or both) are necessary for brittle fracture to occur. As the imposed stress is raised, the stress intensity also increased. These stresses could be determined by conventional stress analysis techniques, i.e. the ratio of applied load over cross-sectional area.