CHAPTER 1

INTRODUCTION

Components and structures in the real world are subjected to different loads. The life assessment and their load carrying ability before fracture are design criteria to be quantified (Branco et al 2010). There is a separate field of engineering science pertaining to the assessment of load bearing ability and behaviour of components and structures with crack like defects.

1.1 FRACTURE MECHANICS

Fracture Mechanics deals with the potentiality of cracks present in a material and helps in designing components safely and conservatively. It involves the determination of the conditions necessary to avoid failure. This is usually given in terms of a critical load for fracture or a critical defect size. The use of fracture mechanics has been exploited usefully in the past (Adams et al 2009).

Usually, a crack front in an engineering component is a line of varying curvature (Prashant Kumar 2009). So, the state of stress close to the crack front varies from one point to another. A segment of the crack front can be divided into three basic modes as shown in Figure 1.1. Mode I is the opening mode and the displacement is normal to the crack surface. Mode II is sliding mode and the displacement is anti symmetric and the relative displacement is normal to the crack front. Mode III also produces sliding
motion but the displacement is parallel to the crack front, thereby causing tearing.

Figure 1.1 Three modes of fracture

1.2 MIXED-MODE FRACTURE

Mixed-mode fracture is a case where two or more modes are combined so as to produce a different effect on the behavior of the material. Though, the majority of fracture mechanics studies on the toughness of engineering materials have been performed under tensile loading, recently the research on mixed-mode (Zimmermann et al 2010, and Ayatollahi and Aliha 2009) has gained insight. Mode I fracture is the most occurring one and many researchers have worked on it. However, random cracks are also developed and they may lead to failure in different orientation other than those explained in Figure 1.1.

This type of cracks must be studied with the insights gained from the literature available on mixed-mode. Though number of studies is available on situations where Mode I and Mode II type fractures are acting together, there is ambiguity in the explanation of the effect of Mode II and III on
combined mode or mixed-mode. The effect of mode I decrease with increasing the crack distance to interface (Liviu Marsavina and Timea Piski 2010). Avci et al (2005) have investigated and quantified fracture toughness in Mode I and Mode III loading conditions, and they have demonstrated that fracture toughness in Mode I is highly dependent on the mode-mixity. Moreover, addition of Mode III to the system does not affect the critical fracture criterion. Under shear force, cracks tend to propagate in Mode I, Mode II and Mode III configuration. There were many attempts to apply fracture mechanics concepts to study mixed-mode failure and crack propagation by many researchers (Hafiz et al 2010, Zhuo Fu et al 2011).

1.3 IMPORTANCE OF FRACTURE MECHANICS

The power of fracture mechanics really lies in the fact that local crack tip phenomena can be characterized by relatively easily measured parameters, e.g. crack length and nominal global stress (calculated in the absence of the crack), together with finite geometry correction factors. Use of fracture mechanics in engineering critical assessment of defects has been codified in documents like British Standards (BS PD 6493, 1991) and American standards ASTM E399 (2005) and ASTM E1820(2001).

The fracture mechanics approach allows us to design and select materials while taking the presence of flaws into consideration. There are three variables to be considered while designing a component in fracture mechanics point of view: the elastic property of the material, the stress that the material must withstand, and the size of the flaw.

1.4 IMPORTANCE OF MIXED-MODE FRACTURE

Engineering structures are not only subjected to pure tension, pure shear or pure torsion. But, also they experience combination of any two or all
of tension, shear and torsion loading, leading to a mixed-mode interaction (Nestor Perez, 2004). Correspondingly, the stress state ahead of a crack is frequently based on mixed-mode I and II or I and III type of interactions. A mixed-mode interaction can also arise when crack branching occurs, that is, when a crack changes its direction in which the classical energy balance of Griffith can no longer be carried out in a simple manner since cracking is not collinear as in the case of pure mode I.

1.5 Historical Background

Foundational research on Fracture Mechanics was developed by Griffith and Irwin. Almost a century ago, Griffith (1921) developed a theory for an infinite plate containing a crack and subjected to uniform stress. Drawing upon the concept of potential energy, Griffith showed that for every level of applied stress, there is a critical value for the given crack length. At this value critical value of stress, the system is at a maximum of potential energy. If the stresses or the crack length are increased, the system will reduce its potential energy by increasing the crack length, basically developing a failure. A few decades later, Irwin (1948) introduced the concepts of stress intensity factor (K) and strain energy release rate (SERR or G), which are still used in fracture mechanics. Critical values of stress intensity factor and strain energy release rate are material attributes that characterize the resistance to elastic fracture.

The two concepts are widely used to analyze the correlation among crack growth, material properties, and input test parameters, which include the imposed displacements or loads (Kundu 2008, Miannay 1998). In a monolithic isotropic and homogeneous material with elastic modulus E and Poisson’s ratio ν, the two parameters G and K can be calculated as in Equation (1.1), where index i refers to the in-plane loading modes: I and II.
\[ G = \frac{K_{1c}^2}{E} \]  \hspace{1cm} (1.1)

where \( E' = E \) for plane stress condition \hspace{1cm} (1.2)

\[ E' = \frac{E}{(1 - \nu^2)} \] for plane strain condition \hspace{1cm} (1.3)

The concept of the SERR comes from an energetic approach with elastic deformation hypotheses (Irwin 1948, Orowan 1970). When external loads are applied to a cracked system and the crack propagates, part of the work given by the loads is stored in the system as elastic energy and part is spent in propagation of the crack. The available energy for crack propagation equals:

\[ G \cdot dA = dW - dU \] \hspace{1cm} (1.4)

where \( G \) is the applied or available SERR, \( dA \) the infinitesimal propagation of crack area, \( dW \) the work of the internal forces and \( dU \) the variation of stored elastic energy. The critical SERR, \( G_c \), is the amount of energy per unit of area required to create new crack area. If the crack growth is driven by a constant external load and in a system with linear force vs. displacement relation, \( G_c \) can be expressed as follows:

\[ G_c = \frac{P^2}{2} \frac{dC}{dA} \] \hspace{1cm} (1.5)

where \( P \) is the applied external load and \( C \) the specimen compliance.

A large amount of literature has described fracture in homogeneous and isotropic materials. Comprehensive reviews of the classical papers of Griffith (1921), Irwin (1948), newest approaches, and a description of state of the art testing techniques can be found in (Pook 2000, Dowling 2007, Anderson 1995). Fracture often occurs with the nucleation of a crack that
then grows and can lead the material to complete failure. Nucleation may occur at points with stress concentrations or singularities in the material; material properties, discontinuities and presence of voids, flaws and other irregularities also influence the nucleation and propagation phases.

Moreover, mixed-mode loading conditions are likely to occur in real applications, because of the loading orientation and the nature of both structural configuration. Other issues related to fracture mechanics during the crack growth, such as the direction of crack propagation, have been developed by Erdogan and Sih (1963), Cotterell and Rice (1980).

The critical SERR and $G$ often depend on the fracture mode that is present at the crack tip, where mode I, mode II, mode III, or combinations of these can cause the crack to propagate. The applied SERR can have components associated with each of the three fracture modes (Pocius 2002). This study focuses on in-plane loading conditions, as a first step for the characterization of generalized mixed-mode behaviors. In-plane loading conditions are defined by the presence of only mode I and mode II loads. In this case, the angle of mode-mixity is indicated with the letter $\beta$ and defined in the Equation (1.6).

$$\beta = \arctan \left( \frac{G_{II}}{G_I} \right)$$

(1.6)

where $G_I$ - Energy Release Rate under mode I loading

$G_{II}$ - Energy Release Rate under mode I loading

1.6 DIVISIONS AND TERMINOLOGY IN FRACTURE MECHANICS

Designers are always interested to know whether a crack is likely to grow if the geometry of a crack in a structural component, loads and other boundary conditions are known (Prashant Kumar 2009). Therefore, one or
several parameters are needed to measure crack extension force. These parameters are based on the two main branches in fracture mechanics.

The analysis of the two branches depends on the type of deformation experienced by the material during the test. The Linear Elastic Fracture Mechanics (LEFM) is based on the parameter \( K \). The LEFM analysis is for the case of linear elastic deformation and is relatively simple and quick to perform. When the deformation of the test specimen has plasticity, then a non-linear method is required. A non-linear fracture mechanics or Elastic Plastic Fracture Mechanics (EPFM) which uses several non-linear parameters, namely J-integral and crack-tip opening displacement, would serve the purpose of dealing with materials containing appreciable plasticity. EPFM methods are more complex than simple LEFM analysis. However, non-linear behavior is encountered often in the failures of many materials and structures. The linear elastic method is discussed here.

There are several parameters involved in studying the cracked elements. Stress Intensity Factor, J-integral and Crack Tip Opening Displacement (CTOD) are some of them. The Stress Intensity Factor (Gdoutus 2005) is a quantity which governs the stress field near the crack tip. The term stress intensity factor which is originally introduced by Irwin (1948), is useful in defining stress, \( \sigma \) and crack length, \( a \) in one parameter. Stress intensity factor in mode I (\( K_I \)) is presented below:

\[
K_I = \sigma \sqrt{\pi a}
\]

(1.7)

where the suffix I denotes mode I (opening mode)

\( \sigma \) - far field stress

\( a \) - crack length
$K_{lc}$, $J_{lc}$, J-R curve, CTOD$_c$ are some of the fracture toughness parameters. But $K_{lc}$ has some limitations and it is considered a LEFM fracture toughness parameter.

CTOD$_c$ needs to be evaluated carefully from the CMOD data available. And hence $J_{lc}$ and J-R curves are the most suitable and most used fracture toughness parameters to characterize the ductile materials.

### 1.6.1 Linear Elastic Fracture Mechanics (LEFM)

A brittle material is the one which remains elastic even at the crack tip where stresses are high. The analysis of cracks in such material is called Linear Elastic Fracture Mechanics.

The LEFM method is relatively simple and straightforward. One of the parameters for defining fracture in LEFM is $K$, the crack tip stress intensity factor. This parameter $K$ is called the fracture toughness ($K_{lc}$) at failure. The $K_{lc}$ is a material property and to be determined as per the guidelines given by ASTM standard E 399 (2005).

#### 1.6.1.1 Stress Intensity Factor

The linear elastic fracture mechanics says that the stresses at the crack tip reach infinity but in reality there is always a plastic zone at the crack tip that limits the stresses to finite values. It is very difficult to model and calculate the actual stresses in the plastic zone and compare them to the maximum allowable stresses of the material to determine whether a crack is going to grow or not.

A convenient parameter named Stress Intensity Factor, $K$, is used in fracture mechanics to more accurately predict the stress state ("stress
intensity") near the tip of a crack caused by a remote load or residual stresses. When this stress state(stress intensity) becomes critical, a small crack grows ("extends") in an unstable manner and the material fails. The critical value at which crack starts growing, is called critical stress intensity factor ($K_c$). According to linear elastic fracture mechanics, this $K_c$ is a material property.

1.6.2 Elastic Plastic Fracture Mechanics (EPFM)

Non-linear fracture includes the deformation from elastic-plastic components in fracture analysis. The non linear fracture mechanics methods are more complicated than LEFM methods. The incorporation of plasticity complicates the analysis. The fracture toughness parameters used for elastic plastic fracture are the $J$-integral, $J-\Delta a$ curve and Crack Tip Opening Displacement (CTOD). The evaluation of $J$ includes the determination of load, Crack Mouth Opening Displacement (CMOD) plot and crack length.

1.6.2.1 J-Integral

In structures with a crack, Rice (1973) introduced a path independent line integral, known as the J-integral. The present chapter is devoted to the theoretical foundation of the path independent J-integral and its use as a fracture criterion. The critical value of the opening of the crack faces near the crack tip is also introduced as fracture criterion.

The path independent nature of the integral allows the integration path to be taken close or far away from the crack tip. Although the J-integral is based on purely elastic (linear or nonlinear) analysis, its use for ductile materials has been supported by experimentation or numerical analysis. The limiting value of J-integral, beyond which crack initiation takes place, is critical value of J-integral. This value is a material property, called fracture
toughness $J_c$. This fracture toughness in mode I is called $J_{lc}$, which is critical value of J-integral in mode I.

### 1.6.2.2 Crack Tip Opening Displacement

Crack Tip Opening displacement (CTOD) is another parameter suitable to characterize a crack (Prashant Kumar 2009). Unlike parameters $G$ and $K$, it can be used for both linear elastic fracture mechanics (LEFM) and elastic plastic fracture mechanics (EPFM). The material cannot withstand very high stresses within the plastic zone, and the usual stress field of the square root singularity no longer exists. However, rigorous analysis being complex, designers are interested in exploring a simple model. The yielding of the material and the resulting rearrangement of the stresses around the crack tip can be accounted for by an effective crack, which is longer than the actual crack. The tip of the effective crack is located inside the plastic zone. Now, the linear equations of elasticity can be applied to the effective crack. One can then visualize that the effective crack has some finite opening at the location of the actual crack tip. The opening is defined as the Crack Tip Opening Displacement (CTOD) as shown in Figure 1.2. Also, the Crack Mouth Opening Displacement (CMOD) is described in the same Figure 1.2. The displacement at the mouth of a notch is called Crack Mouth Opening Displacement.
The basic fracture toughness characterization by the J-integral for ductile materials is the J-R curve, which is a plot of J vs. crack extension. Figure 1.3 shows a typical J-R curve. Often a single value of toughness is defined to simplify the analysis of fracture potential. To get single point toughness, a point on the J-R curve is determined by a construction procedure as given in ASTM E1820 (2001).
1.7 FRACTURE MECHANICS TESTING AND CHARACTERIZATION

In most of the real world problems, the material flaws can have an arbitrary orientation with respect to any general loading of a component or structure. Hence, this gives rise to mixed-mode fracture. In the past, a lot of attention in experimental fracture mechanics had been focused on mode I cases, in which the specimen geometry and loading conditions correspond to the opening mode. In recent years, there has been an increasing awareness of the importance on mixed-mode fracture.

The suitable specimens and loading for the determination of mixed-mode fracture properties of materials are

1. Three Point Bend specimen with asymmetric loading
2. Four Point Bend specimen with asymmetric loading
3. Compact Tension specimen with inclined cracks subjected to tensile loading.

4. Compact Tensile specimen with Arcan type test fixture.

1.7.1 Multiple Specimen Construction of J-R Curve

There are two different methods of determining R – curves. One is multiple specimen techniques and the other one, single specimen method. The multiple specimen technique involves testing five or more identical specimens with each specimen loaded to a different point on the load vs. displacement curve. The specimens are first loaded to an uppermost point, and then unloaded and finally the crack length is measured optically or using non destructive test techniques.

The J integral is evaluated from the load displacement diagram of these tests.

\[
J = \frac{1}{B} \frac{dU}{da}
\]  

where \(dU\)- strain energy released, in J

\(da\) – increase in crack length, in m

\(B\)- thickness, in m.

Since the experiments are expensive, it is desirable to use as few specimens as possible. For each test a specimen needs to be fabricated, pre-cracked and tested. The fabrication and pre-cracking of the specimens can take a considerable amount of time. The accuracy of the test also depends on the number of samples tested. The more samples tested, the Better will be the J result.
1.7.2 Single Specimen Construction of J-R Curve

The single specimen method for construction of J-R curves requires only one specimen to be prepared and tested. The machine must have either crack opening displacement (COD) or load – line displacement (LLP) equipment to read the corresponding displacement. The specimen undergoes continuous loading and unloading cycles. The compliances of the unloading cycles are determined from COD values and are used for the evaluation of crack length using the unloading compliance method as said by ASTM E1820 (2001).

Among the different single specimen methods for determining J-R curve, only the unloading compliance method is accepted by ASTM. This method uses unloading and reloading to develop elastic slopes. The inverse of the slopes called compliances are related to the crack length using compliance calibration equations.

Because of one point data collection and analysis, the elastic unloading compliance method is preferred. However, it needs good experimental setup and experience. The fixtures have to be aligned properly in order to get good results. There is possible noise from the testing equipment while gauging the compliance. Measuring the compliance requires that the gauges be very accurate. When bad alignment or noise interferes with the test, the crack length measurements may have a great deal of variability. The automated compliance method requires a good amount of experience. The J-R curve determined by these compliance measurements is used to determine the $J_Q$ value as per the analysis procedure in the standard ASTM E1820 (2001).
1.7.3 **The R Curve Shape and its Use**

A ductile material fails by coalescence of micro-voids. The development of the micro-voids causes an increase in the shape of the R curve.

The curve is used to determine the fracture toughness of a material. A point is selected on the $R$ curve as the fracture toughness value. When a single value of fracture toughness is determined for ductile fracture, the point is called $J_{lc}$. The $J_{lc}$ value is a point determined by a construction procedure on the J-R curve and initially is called $J_Q$ which is a trial or provisional value of $J_{lc}$. The $J_Q$ value has to meet specific criteria before the point is accepted as $J_{lc}$ value. The present method for determining $J_Q$ requires a detailed construction procedure as detailed by ASTM E1820 (2001).

1.8 **OBJECTIVES AND SCOPE OF THE PROBLEM**

The objectives of the present research work are:

(i) To investigate the fracture parameters on three point bend specimens with eccentric loading and to evaluate mixed-mode fracture toughness,

(ii) To study the effect of load inclination and notch inclination on the fracture parameters and evaluate mixed-mode fracture toughness for different thickness of specimens, and

(iii) To examine the effect of location of notch on the fracture properties using four point bend specimen.

Though many researchers have worked on brittle fracture (Taylor et al 2005 and Yosibash et al 2006, Jian Lu 2010), cracking analysis in ductile
fracture gains importance and recent research studies show that ductile fracture also is a growing research area.

Further in the case of ductile materials, the simple fabrication and testing resulted in extensive research being performed in mode I (Opening mode) fracture. This led to the development of many standards for conducting/performing fracture characterization testing (ASTM E399, 2005, ASTM E1820, 2001). But, in practice, the real fracture mode can have arbitrary orientation and this led to the rise of mixed-mode fracture, where the crack grows in a combination of shear, tension and/or tearing modes. This has been emphasized by Choupani (2008a), Rasmus Walter and John Olesen (2008), Luciani et al. (2009), Victor Kozhushko and Peter Hess (2010), Sharma et al (2011).

To characterize materials in mixed-mode, various configurations have been proposed and some of them used by researchers are arcan type fixture (Elmoiz Mahgoub et al 2003, Sutton et al 2003), Compact Tension specimen and bend specimens.

Brocks et al. (2010), Kamat and Hirth (1996a), Sha Jiangbo et al (2000) have analyzed mixed-mode I/II fracture using CT specimens. Avci et al (2005) and Srinivas et al (2007) have worked on bend specimen subjected to mixed-mode loading. But a bend specimen has been used only to a limited extent to develop and characterize mixed-mode loading and there is no sufficient literature on characterization of bend specimens subjected to mixed-mode loading. These gaps encouraged this research work on mixed mode fracture of bend specimens made of ductile materials i.e., Aluminum alloys.
1.9 HYPOTHESIS

It has been accepted that changing the orientation or location of loading or crack would result in a superimposition of two or more modes of fracture and it is called mixed-mode. Based on this concept, the following hypotheses were drawn. There are three parts in this research work. In the first part of research work, the hypotheses drawn are listed as below:

1. The mixed-mode fracture parameters could be determined for eccentrically bend specimens and could be validated using finite element method.

2. The mixed-mode fracture toughness would be influenced by the place of loading. There would be a decrease in mixed-mode fracture toughness with increase in eccentricity of loading in a three point bend specimens.

3. There would be some microscopic fracture mechanism responsible for mode I / mode II fracture in eccentrically loaded bend specimens.

In the second part of research, the orientation of loading and notch are varied in order to produce mode-mixity I/III. Here the following hypotheses were drawn:

4. It is expected to find whether thicker / thinner specimens have higher fracture toughness in mixed-mode I/III.

5. There could be significant difference between the mixed-mode I/III fracture toughness to be evaluated from notch inclination and load inclination methods.
In the third part of research, it was expected that the orientation of loading and location of crack in a four point bend specimen, would affect the fracture characteristics. Based on this assumption, the following hypotheses were made:

6. There would be significant influence of thickness on the fracture points in a fracture envelope of four points bend specimens subjected to asymmetric loading.

7. There would be some relationship between maximum hoop stress criterion and the kind of fracture for the three different thicknesses of the specimens chosen.

8. There would be significant relationship between the critical energy release rate and mode-mixity.

1.10 METHODOLOGY

1.10.1 Phase I: Mixed-mode I/II Fracture Characterization of Aluminum Alloys 5083 and 7075 using Three Point Bend Specimens

The bend specimens are normally tested by keeping the notch and precrack inclined at an angle to the loading as done by Mahanty and Savant (1992). This work analyses the case of bend specimen subjected to eccentric load and provides an estimation procedure to determine Mixed-mode J-resistance curves for SE(B) fracture specimens using the unloading compliance technique. A summary of the methodology upon which J and Δa are derived, sets the necessary framework to determine crack resistance data from the measured load vs. displacement curves. Laboratory testing of SE(B) specimens of 5083 and 7075 grade aluminum alloys at room temperature provides the load–displacement data needed to verify the estimation
procedure for measuring the crack growth resistance curve for the material. The results presented here produce a representative set of solutions which lend strong support to develop new standard test procedures for SE(B) specimens with eccentric load.

1.10.2 Phase II: Mixed-mode I/III Fracture Characterization of Aluminum Alloys 5083 and 7075 using Three Point Bend Specimens

Here two configurations for determining mixed-mode I/III fracture toughness are experimented. One is load inclination, in which the specimen is subjected to load inclination and the other is notch inclination, in which, a specimen is machined with inclined notch is used for fracture characterization.

Two aluminum grade alloys 5083 and 7075 are chosen for this study. Usually, three point bend specimens are fabricated and precracked for \( a/W > 0.45 \) (where \( a \) denotes crack length and \( W \), the width of the specimen). By keeping the load inclined to the transverse axis of the specimen, the precracked specimens are tested using unloading compliance method as detailed in ASTM E1820 (2001). The load displacement curves plotted are used to find the specimen compliance for each loading cycle. A set of crack lengths were found using finite element method software, ANSYS. The experimentally obtained J-integral values versus load applied data were compared with finite element results. In the same configuration, two specimen thicknesses were used for experimentation in Al 5083 material.

In the second configuration, the specimens were fabricated with notches inclined to the transverse direction. They were precracked for \( a/W=0.5 \). Then, the specimens were loaded with straight transverse loads and tested using unloading compliance method as detailed in ASTM E1820.
The load displacement curves plotted are used to find the specimen compliance for each loading cycle.

1.10.3 Phase III: Mixed-mode I/II on Fracture Analysis of Aluminum Alloy 5083 using Four Point Bend Specimens

A series of mixed mode fracture experiments were conducted on a type of aluminum 5083 grade using the four point bend specimen.

Totally 15 specimens were chosen with different notch configuration. They correspond to 3 different thicknesses and 5 states of different crack distances from the middle of the specimen, S. The three thickness groups with thicknesses 6.35 mm, 9.6 mm and 12.7 mm were called 1T, 1.5 T and 2T respectively. All specimens were cut from one rectangular plate with thickness of 25.4 mm.

Then an edge notch having a length of 11 mm was created in the centre line of each test specimen using a wire cut machine. For each desired mode mixity, the specimen was placed in a suitable location inside the loading fixture and then was loaded until the final fracture. The servo hydraulic test machine of make BISS was used for fracture tests.

The loading and unloading rates for all tests were 0.05 mm/sec. The load-displacement history for each test was recorded during the test using a computerized data logger. The critical stress intensity factors for each loading condition were calculated as given in Shahani and Tabatabaei (2008) and the stress intensity factors in mode I and mode II were obtained using the data and methods suggested by Murukami (1987) and He and Hutchinson (2000).
1.11 THE APPLICATIONS OF FRACTURE TOUGHNESS UNDER MIXED-MODE CONDITIONS

Though experiments on specimens under the mode I loading is more common, the real life practical applications, state the need of mixed-mode fracture characterization and analysis. The following applications are found in literature.


2. Cortical bones due to loading or shape and orientation of the bone (Analysed by Zimmermann et al (2009))

3. Fighter aircraft turbine blades (Recho et al (2004)).

4. Engine component failures (Analysed by Nalla et al (2002)).

5. Structure containing weld defects of specific size and orientation as suggested by Kardomateas and McClintock (1987)