CHAPTER 2

LITERATURE REVIEW

In this chapter, theoretical of project will be discussed further to get basic understanding of the project.

2.1 Linear Elastic Fracture Mechanics (LEFM)

Linear Elastic Fracture Mechanics (LEFM) assumes that the material is isotropic and linear elastic. Based on the assumption, the stress field near the crack tip is calculated using the theory of elasticity. When the stresses near the crack tip exceed the material fracture toughness, the crack will grow. In LEFM, most formulas are derived for either plane stress or plane strain associated with the three basic modes of loadings on a cracked body which are Mode I (opening), Mode II (sliding), and Mode III (tearing). LEFM is also valid only when the inelastic deformation is small compared to the size of the crack. If large zones of plastic deformation develop before the crack grows, Elastic Plastic Fracture Mechanics (EPFM) must be used. All of the terms mention will be detail discuss in this chapter.

2.2 Stress Intensity Factor, *K*

Stress intensity factor is defined as factor of the singular stress at the crack tip. It is used in fracture mechanics to more accurately predict the stress state or stress intensity near the tip of a crack caused by a remote load or residual stresses. When this stress state becomes critical, a small crack grows and the material fails. The load at which this failure occurs is referred to as the fracture strength.

The stress intensity factor also is a function of geometry of the cracked body and associated loading and is used to determine the fracture toughness of most materials. The stress intensity factor presented by the following equation 2.1 [1]:

$$K = \sigma\sqrt{\pi a} \tag{2.1}$$

σ = Applied stress, MPa

a = Crack size, m

2.3 Fracture Toughness, K_{IC}

The critical stress intensity factor is referred to as fracture toughness. Empirically, it is found that this approach works well, because the assumptions inherent with linear elastic fracture mechanics are satisfied. In linear elastic fracture mechanics, instead of comparing the maximum stress value with a critical stress value, the material failure is predicted by comparing the stress intensity factor with some critical value.

Fracture toughness of a material is defined as the amount of stress required or energy resistance of a material to propagate a preexisting flaw which can lead to material failure. The energy required of a particular flaw to cause failure depends on the fracture toughness of the material, the location, crack size, thickness, width, magnitude and distribution of the loads imposed on the solid. It can be calculate by the following equation 2.2:

$$K_{IC} = Y\sigma\sqrt{\pi}a \tag{2.2}$$

Where,

Y = dimensionless parameter that depends on both the specimen and crack geometry

σ = Applied stress,MPa

a = Crack size, m

If a material have a large value of fracture toughness it will probably undergo ductile fracture while if the material have low value of fracture toughness it can be characteristic as brittle fracture [2].

2.4 Modes

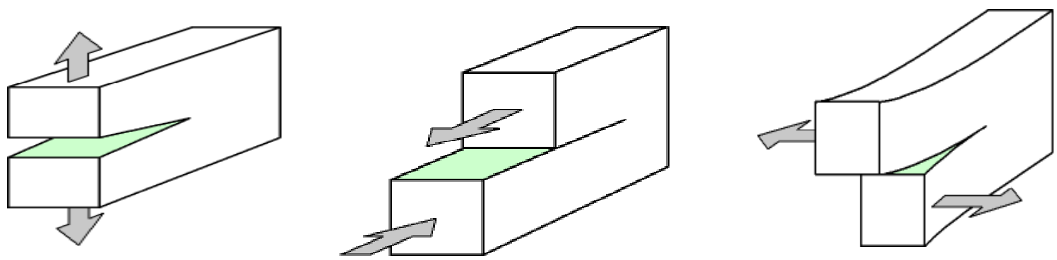

Figure 2.1: Modes I, Modes II and Modes III that applied on crack

There are three loading modes as shown in Figure 2.1 that considered can be applied to the cracks which are Modes I (opening), Mode II (forward shear) and Mode III (ant plane shear). The anti plane shear mode plane does not occur in the plane problem of elasticity [3]. The opening mode of deformation is by far the most important mechanism controlling failure of homogenous and isotropic materials. For this project, the emphasis will be on the development of linear elastic fracture mechanic for opening mode deformation. To differentiate the stress intensity factor with respect to its mode, they were denoted as K_I for Modes I, K_{II} for Mode II and K_{III} for Mode III. Most material is more susceptible to fracture by normal tensile stresses (opening mode) than by shear stress (shear mode).

2.5 Effect of loading modes

Critical stress intensity factor or fracture toughness for a given mode is a material constant and it is varies with the loading mode as shown in equation 2.3:

$$K_{IC} \neq K_{IIC} \neq K_{IIIC} \tag{2.3}$$

Most material is more susceptible to fracture by normal tensile stresses than by shear stresses. Consequently, mode I loading am more important than others. Mode II and mode III loading usually do not lead to fracture. This also can be said that K_{IIC} and K_{IIIC} is greater than K_{IC}. This project only considers Mode I and the other Mode become important when they are applied to a weak interface in the material [2].

2.6 Stress analysis of crack

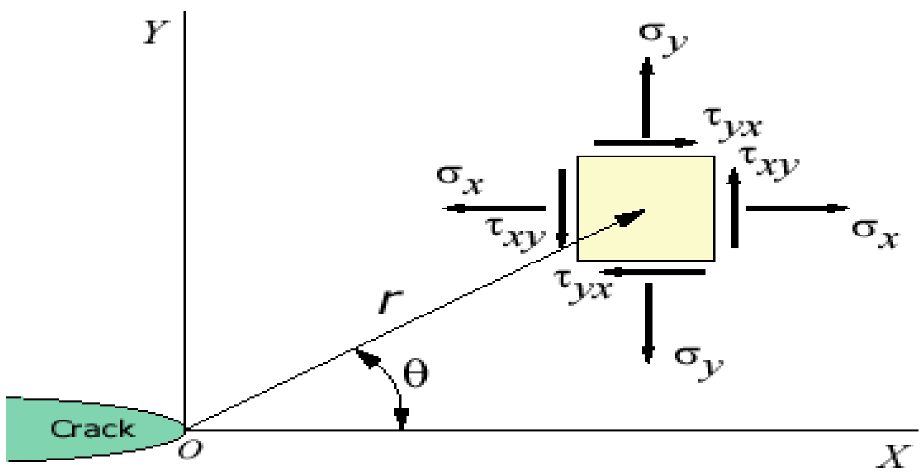

Figure 2.2: Distribution of stresses at the vicinity crack tip

Figure 2.2 schematically shows an element near the crack tip of a crack in an elastic material, together with the in plane stresses on this element. Every stress components are proportional to stress intensity factor. Stress intensity factor is a unique design parameter which represents the magnitude of stress field severity near a crack tip and the limit show by equation 2.4. If this constant is known, the entire stress distribution equation show in equation 2.5 can be computed.

Besides that, stress intensity factor gives a measure of strength of singularity controlling stresses at the crack tip. Crack tips produce a $1/\sqrt{r}$ singularity. As distance from crack, *r* approach zero, equation 2.5 will approaches infinity. But the other terms will remain finite or approach zero. The stress near crack tip will varies with $1/\sqrt{r}$, regardless of the configuration of the cracked body [4].

The stress fields near a crack tip of an isotropic linear elastic material as shows in figure 2.2 can be expressed as a product of $1/\sqrt{r}$ and a function of θ with a scaling factor *K* by equation 2.3 and 2.4:

$$\lim_{r \to 0} \sigma_{ij}^{(I)} = \frac{K_I}{\sqrt{2\pi r}} f_{ij}^{(I)}(\theta) \tag{2.4}$$

In this study, mode I will be used and to make a clearer view that stress become singular at the crack, Irwin had come out with this result:

$$\begin{aligned}
\sigma_{xx} &= \frac{K_I}{\sqrt{2\pi r}} \cos\left(\frac{\theta}{2}\right)\left[1-\sin\left(\frac{\theta}{2}\right)\sin\left(\frac{3\theta}{2}\right)\right] & \tau_{yz} &= 0 \\
\sigma_{yy} &= \frac{K_I}{\sqrt{2\pi r}} \cos\left(\frac{\theta}{2}\right)\left[1+\sin\left(\frac{\theta}{2}\right)\sin\left(\frac{3\theta}{2}\right)\right] & \tau_{yz} &= 0 \\
\sigma_{zz} &= \begin{cases} 0 & \text{(Plane Stress)} \\ \nu\left(\sigma_{xx}+\sigma_{yy}\right) & \text{(Plane Strain)} \end{cases} & \tau_{zx} &= 0
\end{aligned} \tag{2.5}$$

From the equation 2.5 it is clear that stresses become singular at the crack tip. K_I control the magnitude of stresses at any point in a small neighborhood around the crack tip. Far away from the crack tip, Irwin's equation does not apply [4].

2.7 Plane stress versus plane strain

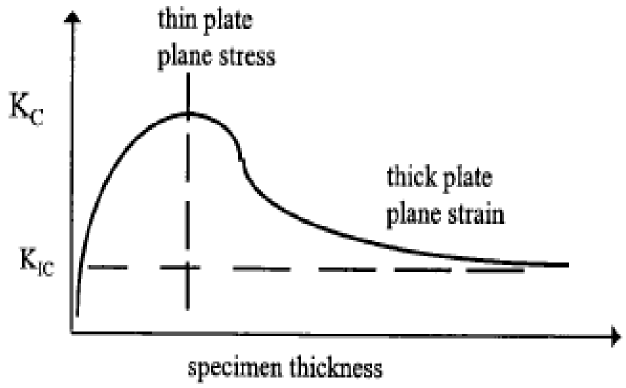

Figure 2.3: effect of thickness in fracture toughness

The definition of plane strain is a condition in a body in which the displacements of all points in the body are parallel to a given plane, and the values of this displacement do not depend on the distance perpendicular to the plane. While, plane stress can be define as a condition of a body in which the state of stress is such that two of the principle stresses are always parallel to a given plane and are constant in the normal direction [5].

When a material with a crack is loaded in tension, the materials develop plastic strains as the yield stress is exceeded in the region near the crack tip. Material within the crack tip stress field, situated close to a free surface, can deform laterally (in the z-direction of the specimen) because there can be no stresses normal to the free surface. This condition is called plane-stress and it occurs in relatively thin bodies where the stress through the thickness cannot vary appreciably due to the thin section.

However, material away from the free surfaces of a relatively thick component is not free to deform laterally as it is constrained by the surrounding material. The stress state under these conditions tends to triaxial and there is zero strain perpendicular to both the stress axis and the direction of crack propagation when a material is loaded in tension [2]. This condition is called plane-strain and is found in thick plates. These assumptions had been shown in figure 2.3.Under plane-strain conditions, materials behave essentially elastic until the fracture stress is reached and then rapid fracture occurs.

2.8 Numerical method

Numerical method based on finite element method requires a careful choice of elements to model the geometry. The final goal of such method is to extract the singular field near the crack tip. If the stress, σ_y is extracted ahead of the crack tip then stress intensity factor can be calculated by the limit in equation 2.6:

$$K = \lim_{r \to 0} \sigma\sqrt{2\pi r} \tag{2.6}$$

K_I can also be extracted by examining displacement behind the crack tip as equation 2.7 [6]:

$$K = \frac{2G}{\alpha + 1} \lim_{r \to 0} v \sqrt{\frac{2\pi}{r}} \tag{2.7}$$

Where,

v = displacement at Y-direction
G = strain energy changes
r = the distance from the crack tip to the first node

2.9 Compact tension specimen (CTS)

For this project, compact tension specimen had been chosen as the test piece. This is because this specimen is commonly used in fracture toughness evaluation related to Modes I. The configuration and specification of CTS is as mentioned in ASTM E-399-90 (Approved 1997): Standard Test Method for Plane – Strain Fracture Toughness of Metallic Material. Figure 2.4 indicate the fix dimension of CTS.

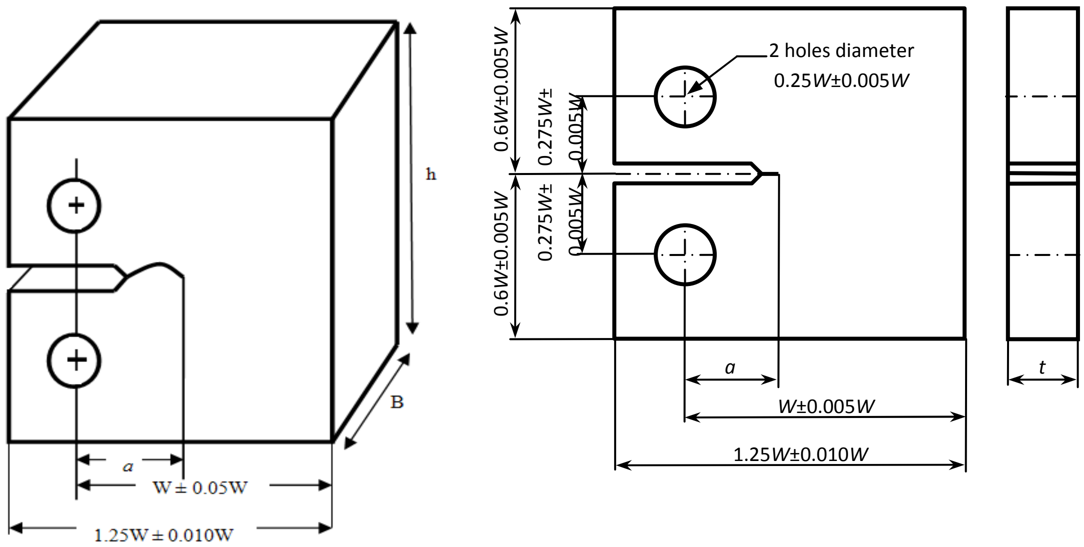

Figure 2.4: Compact Tension Specimen (CTS) adapted from ASTM E-399-90

Note that, dimension W is not the actual width of the specimen. The actual width of the specimen is 1.25W. Stress intensity factor can be determined by applying empirical expression. The empirical expression of CTS was included in ASTM E-399-90 (Approved 1997) testing procedure as in equation 2.8 and 2.9 [7]:

$$K = \frac{\mathrm{P}}{\mathrm{B}\sqrt{\mathrm{W}}} \cdot f\left(\frac{a}{W}\right) \qquad (2.8)$$

$$f\left(\frac{a}{W}\right) = \left(2 + \frac{a}{W}\right)\left[0.866 + 4.64\frac{a}{W} - 13.32\frac{a^2}{W} + 14.72\frac{a^3}{W} - 5.6\frac{a^4}{W}\right] \qquad (2.9)$$

P = Load, *N*

B = specimen thickness, m

W = specimen width, m

a = crack length, m

The main specimen dimensions are the crack length,*a* and the width,*W*. Other dimensions are automatically fixed as indicated in the figure. The specimen thickness,*B* is sufficiently large in comparison with the plastic zone size to ensure plane strain testing conditions.

2.10 Limits to the validity of LEFM

Because of strict size requirement, ASTM E399-90 recommends that the author perform preliminary validity check to determine the appropriate specimen dimension. The size requirement for valid fracture toughness is represent by equations 2.10, 2.11 and 2.12 [7]:

$$a, B > 2.5\left(\frac{K_{IC}}{Y}\right)^2 \tag{2.10}$$

$$0.45 \leq \frac{a}{W} \leq 0.55 \tag{2.11}$$

$$2 \leq \frac{W}{B} \leq 4 \tag{2.12}$$

In order to determine the required specimen dimensions, rough estimation of anticipated fracture toughness should be done. Such an estimate can come from data from similar material.

All equations give requirement for plane strain and linear elastic fracture mechanics. A valid fracture toughness result is a material property that does not depend on the size or geometry of the cracked body. Plain strain condition are use to measure a valid fracture toughness and the lack of plain strain does not necessarily invalidate linear elastic fracture mechanics. As long as the in plane dimensions are sufficiently large to confine the plastic zone to the singularity dominated zone, the stress intensity factor is a valid crack tip characterizing parameter.

2.11 PROPERTIES OF MATERIAL

To meet the above requirement, it is necessary to estimate critical stress intensity factor and also to know the yield strength of the material. So in this study, Aluminum 7075-T6 had been chosen. Table 2.1 shown the material properties for Aluminum7075-T6 [8]:

Table 2.1: Material properties for Aluminum 7075-T6

Properties	**Value**
Modulus of Elasticity	69GPa
Poisson’s Ratio	0.33
Yield Strength	495MPa
Critical Stress Intensity Factor	24MPa.m $^{1/2}$