# CHAPTER 1

# PROJECT BACKGROUND

## 1.1 BACKGROUND OF STUDIES

Failure of engineering structures through fracture can be fatal. Engineers found that most failure began with cracks. Often engineering structures which contains crack can lead to major disasters—arising either these cracks may be caused by material defects, discontinuities in assembly and/or design, harsh environments and damages in service. Most microscopic cracks are arrested inside the material but it takes one run-away crack to destroy the whole structure.

The stress intensity factor, K, defines the magnitude of the local stresses around the crack tip. This factor depends on loading, crack size, crack shape, and geometric boundaries. Engineers are interested with the stress near the crack tip as either the maximum stress either exceeds the fracture toughness of the material or not. In this study, the stress intensity factor (SIF) will be investigated using ANSYS Software.

## 1.2 PROBLEM STATEMENT

It is well known that fatigue cracks often initiate at geometrical discontinuities, such as notches. Near the notch tip the line of force a relatively close together and this leads to a concentration of the local stress hence induce large stress gradients. A large portion of the fatigue life of a notched component may be spent on the propagation of relatively small fatigue cracks. Therefore, it is important to perform stress analysis within the region of influence of a stress raiser. The stress intensity factor (SIF) characterizes the crack tip condition and this concept has proven to be an effective tool for fatigue crack growth analysis.

A finite element analysis is needed to perform in order to determine the stress intensity factor at the edge of the notched tip. Results from the analysis will be used in order to perform simulation to replace the experimental work in the real case studies. Even though results from simulation may contain error and not accurate but it may helps us get the overview of what will happen in the real cases.

## 1.3 OBJECTIVES

1. To investigate and determine the stress intensity factor of single edge notch bend specimen
2. To simulate the finite element analysis of the stress intensity factor using ANSYS Software.
3. To compared and discussed the results obtained from finite element analysis with analytical analysis

## 1.4 SCOPE OF STUDIES

In this study, a bend test analytical and finite element analysis simulations of stress intensity factor will be presented. The test piece will be subjected to a pre-determined loading and boundary condition. The modeling of test piece and simulation will be conducted using ANSYS. The stress intensity factor of the bend test piece will be determined and discussed. It will be validate with J-Integral method or analytical solution. The results from the analysis will be used to simulate the real case studies.

# CHAPTER 2

# LITERATURE REVIEW

## 2.3 LINEAR ELASTIC FRACTURE MECHANICS

Linear elastic fracture mechanics (LEFM) is based on the application of the theory of elasticity to bodies containing cracks or defects. It first 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 Linear Elastic Fracture Mechanics, most formulas are derived for either plane stresses or plane strains, associated with the three basic modes of loadings on a cracked body: opening, sliding, and tearing.

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. If large zones of plastic deformation develop before the crack grows, Elastic Plastic Fracture Mechanics (EPFM) must be used.

## 2.2 INDEPENDENT MODES OF CRACK DEFORMATION

There are 3 independent modes of crack deformation which is Opening Mode (Mode I), Forward Shear Mode (Mode II) and Anti Plane Shear Mode (Mode III) [6].

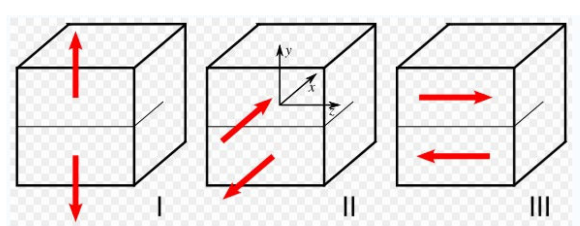


Fig 2.1: Independent modes of crack deformation

## 2.3 PLANE STRAIN FRACTURE TOUGHNESS STANDARD TESTING

It has been found that the value of the plane strain fracture toughness $K_{Ic}$ is a geometry independent material property in certain conditions [1]. The $K_{Ic}$ test was the first material property test based on fracture mechanics to be standardized. The complexity of material behavior makes the $K_{Ic}$ test difficult to standardize. In order to obtain reproducible results test procedures must be strictly controlled. The need to obtain reasonably reproducible results and the need to avoid making the test unnecessarily difficult and expensive compromised the limitations imposed in standards. There is no guarantee that particular tests is carefully conducted and give useful data. However, there are few requirements to be fulfilled to obtain a plane strain condition. A specimen must be thick enough and large enough in its other dimension in order to avoid large scale yielding. Figure 2.3 below show the effect of thickness on Kc behaviour

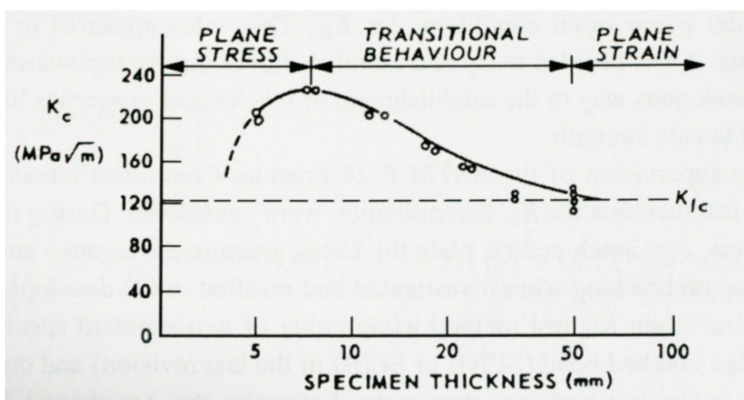


Figure 2.3Effect of thickness on Kc behaviour

In order to ensure that cracking occurs at the right place, the specimens have to be provided with a fatigue crack. In thick members, fatigue crack usually start at a corner. Such cracking behavior results in irreproducible, curved crack front, not suitable for the standard test. It can be avoided by providing the specimens with a chevron notch. This notch forces initiation of the crack in the centre, which enhances the probability of a relatively straight crack front, and it has the additional advantage that the fatigue crack starts almost immediately upon cycling.

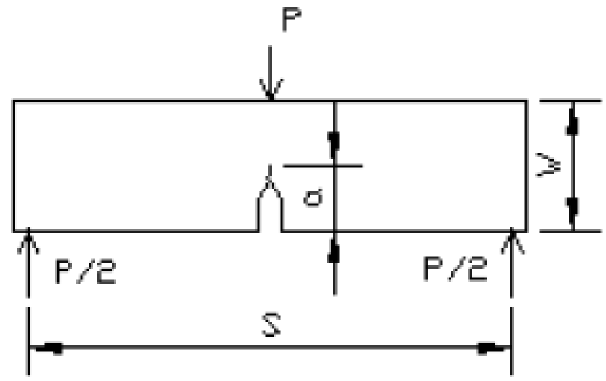


Figure 2.2: Highlighted in figure, chevron notched initiation of crack in the centre, which enhances the probability of a relatively straight crack front.

## 2.4 EFFECT OF THICKNESS ON FRACTURE TOUGHNESS

Most fracture toughness tests on metallic materials are carried out using constant thickness. In general, a material's fracture toughness depends on the thickness of the specimen used [6].

At above a critical thickness, $B_c$, full through thickness constraint s developed in the vicinity of the crack tip, and $K_c$, is constant at a minimum value. The minimum value of $K_c$ is the plane strain fracture toughness $K_{Ic}$ This is a material property in the sense that it is independent of geometry, but may depend on factors such temperature and loading rate. At thickness below $B_c$, $K_c$ tends to increase as the thickness decreases. High values of $K_c$ are usually associated with the slant crack growth often observed in thin sheets.

## 2.5 SOLID95 MESH ELEMENT OPTION IN ANSYS

SOLID95 is a higher order version of the 3-D 8-node solid element SOLID45. It can tolerate irregular shapes without as much loss of accuracy. SOLID95 elements have compatible displacement shapes and are well suited to model curved boundaries.

The element is defined by 20 nodes having three degrees of freedom per node: translations in the nodal x, y, and z directions. The element may have any spatial orientation. SOLID95 has plasticity, creep, stress stiffening, large deflection, and large strain capabilities.

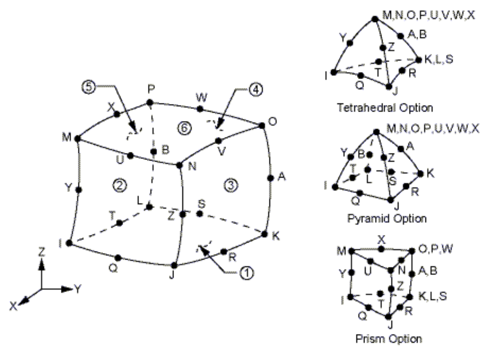


Figure2.4: Solid95 Mesh element

## 2.6 ASTM E399 EMPIRICAL EXPRESSION TO DETERMINE THE STRESS INTENSITY FACTOR

For calculation of K, the unit is in MPa.√m. The equation of the calculation of K is as follows:

$$K = \frac{PS}{BW^{\frac{3}{2}}}\left[\frac{3\left(\frac{a}{W}\right)^{\frac{1}{2}}\left[1.99 - \frac{a}{W}\left(1 - \frac{a}{W}\right)\left(2.15 - 3.93\frac{a}{W} + 2.7\,{a^2}/{W^2}\right)\right]}{2\left(1 + 2\frac{a}{W}\right)\left(1 - \frac{a}{W}\right)^{\frac{3}{2}}}\right]$$

Where:

a = effective crack length

W = Width of test piece

B = Thickness of test piece

S = Span length

# CHAPTER 3

# METHODOLOGY

## 3.1 RESEARCH FLOW

Throughout the research, there will be no physical experiment done in order to determine the Stress Intensity Factor, K. All the analysis will be done using ANSYS Software. The overall of the research methodology is according to the process flow as in Figure 3.1:

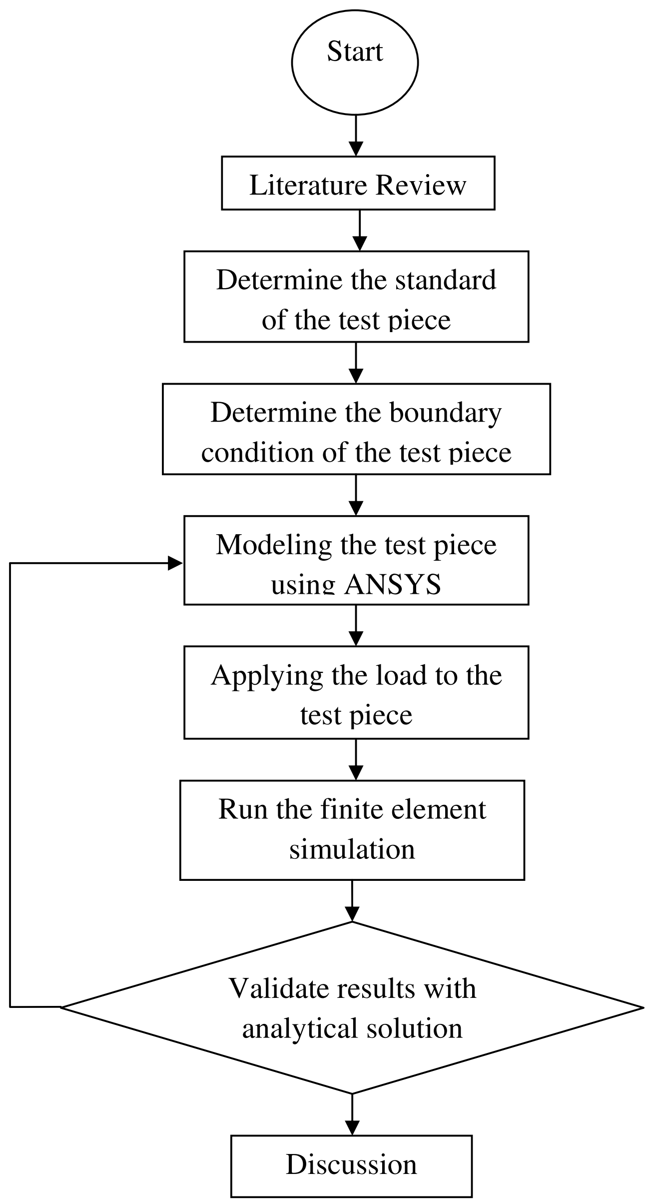


Figure 3.1: Research process flow

## 3.2 PROJECT ACTIVITIES

We use KCALC command for plane strain in ANSYS, in order to obtain the FEA analysis of the test piece. The analyzing procedures are as follow:

### 3.2.1 Analyzing Procedure using ANSYS

In order to using KCALC command for plane strain analysis. Several steps and procedures must be followed in order to conduct the analysis. The steps are as follows:

1. **Preprocessing**

- Give the jobname for the analysis

  a. **Utility menu > File > Change Jobname. Insert jobname**

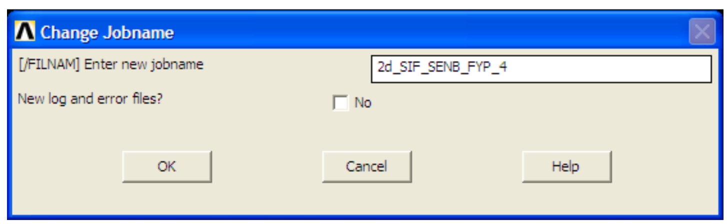


Figure 3.2 Change Jobname of analysis

- Define element type

  a. **Main Menu > Preprocessor > Element Type > Add/Edit/Delete**

  b. **Select <u>PLANE82</u> and <u>SOLID95</u>**

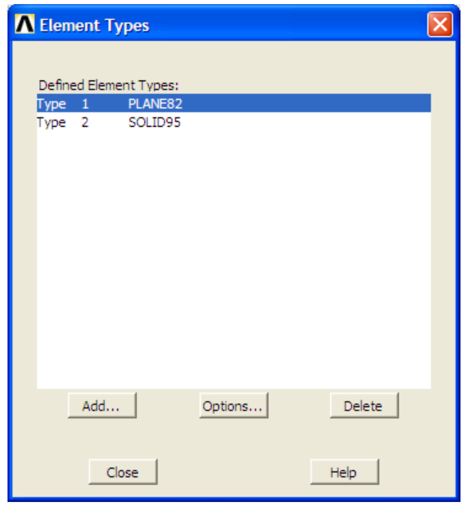


Figure 3.3 Selecting Element Types

c. **Click Options and <u>select Plane Strain</u> for <u>Element behavior K3</u>**

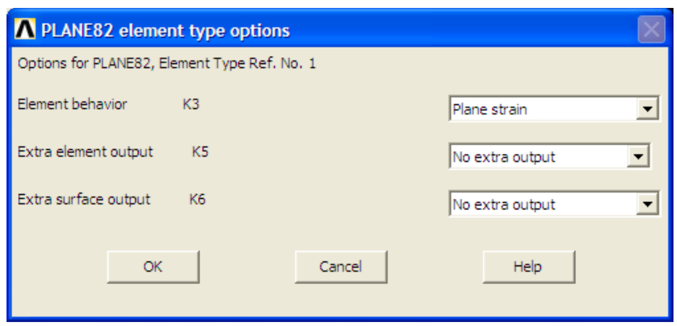


Figure 3.4 Plane element type options

- Define material properties

a. **Main Menu > Preprocessor > Material Props > Material Models**

b. **Structural > Linear > Elastic > Isotropic. <u>Insert the material properties</u> of Young Modulus (EX) and Poisson's Ratio (PRXY)**

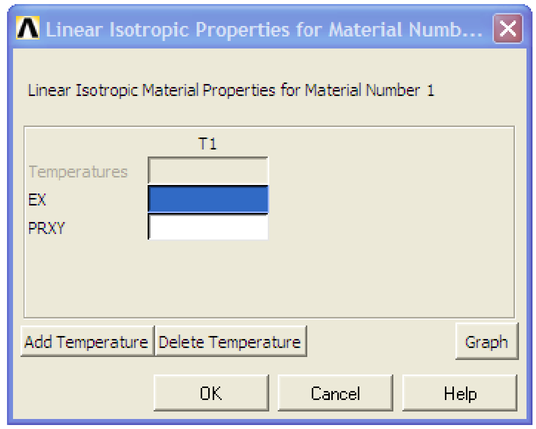


Figure 3.5 Material Properties

- Define key points

  a. **Main Menu > Preprocessor > Modeling > Create > Keypoints > In Active CS**

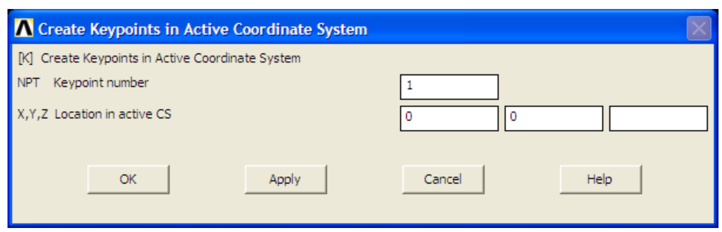


Figure 3.6 Creating key-points by coordinate

  b. **<u>Insert key-points</u> coordinate according to the model**

- Define line segments

  a. **Main Menu > Preprocessor > Modeling > Create > Lines**

  b. **Connect each keypoints with the lines. Click <u>OK</u>**

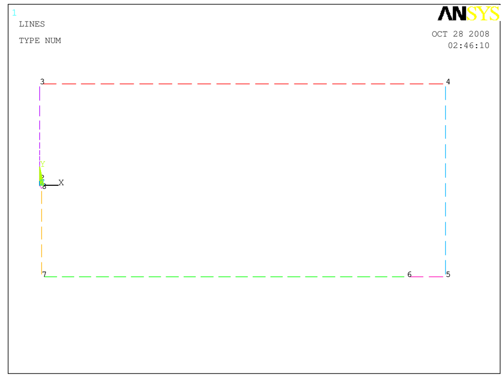


Figure 3.7 Complete lines through Key-points

- Create the Area

  a. **Main Menu > Preprocessor > Modeling > Create > Areas > Arbitrary > By Lines**

  b. **Pick all lines. Click <u>OK</u>**

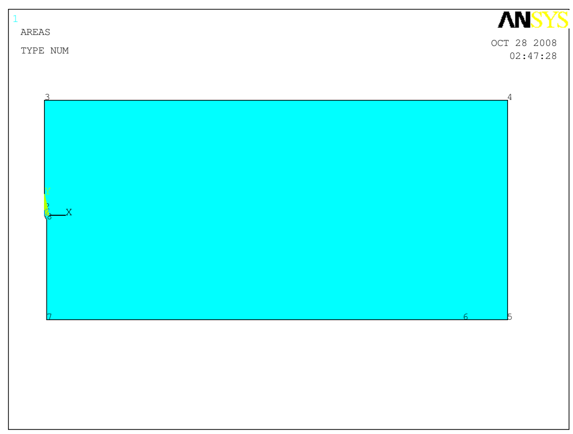


Figure 3.8 Model Area

- Meshing the Area

  a. **Main Menu > Preprocessor > Meshing > Size Cntrls > Concentrated KPs**. **Pick <u>crack tip key-point</u>. Fill in the appropriate value. Click <u>OK</u>**

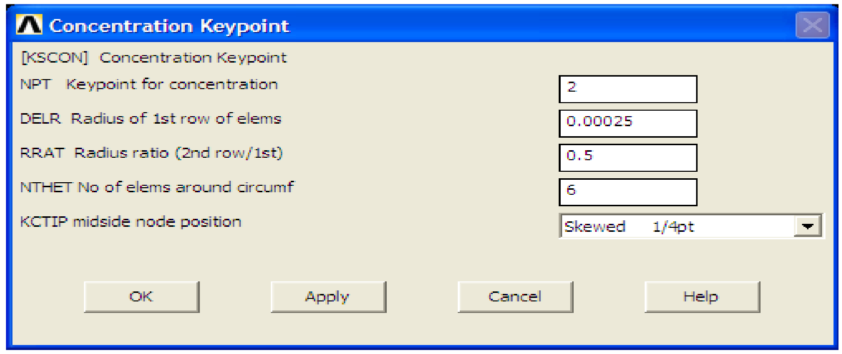


Figure 3.9 Concentration key-point

b. **Main Menu > Preprocessor > Meshing > Size cntrls > Manual Size > Global > Size**

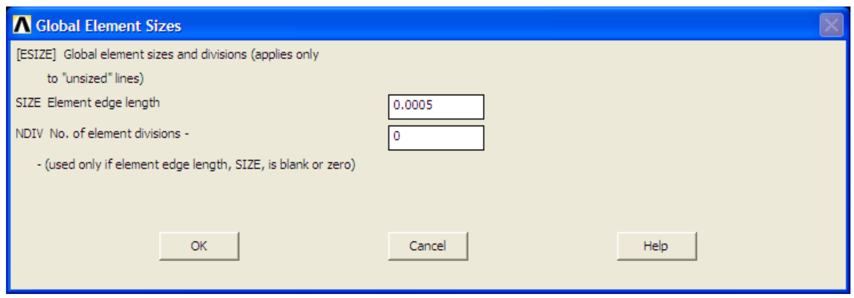


Figure 3.10 Setting element size of the test-piece

c. **Put the element size. Click OK**

d. **Main Menu > Preprocessor > Meshing > Mesh > Areas > Free**

e. **Select the area to be meshed. Click OK**

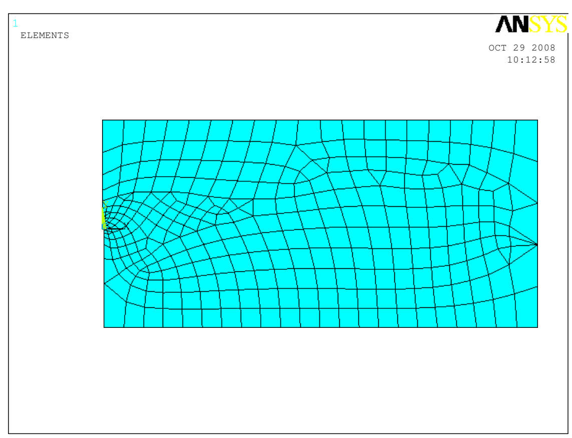


Figure: 3.11 Meshed Areas

- Extrude Area

a. **Main Menu > Preprocessor > Modeling > Operate > Extrude > Element Ext Opts**

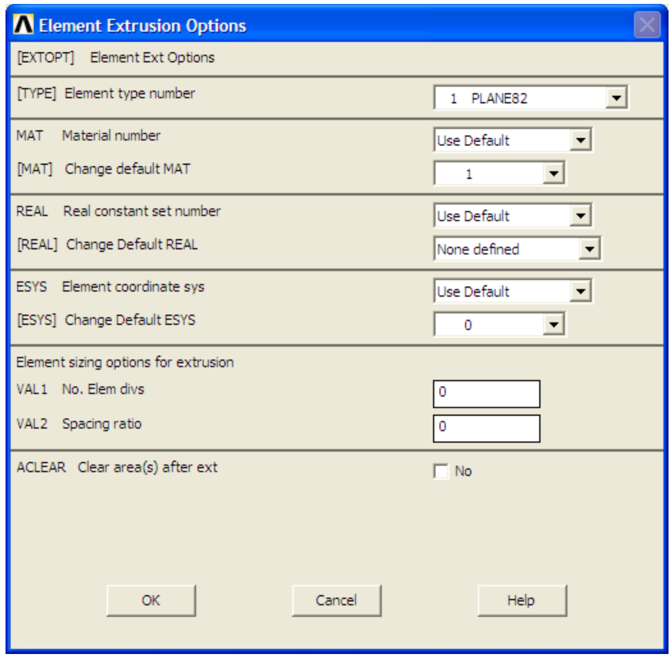


Figure 3.12 Element extrusion option

b. **Put No of element division and spacing ratio**

c. **Main Menu > Preprocessor > Modeling > Operate > Extrude > Areas > Along Normal**

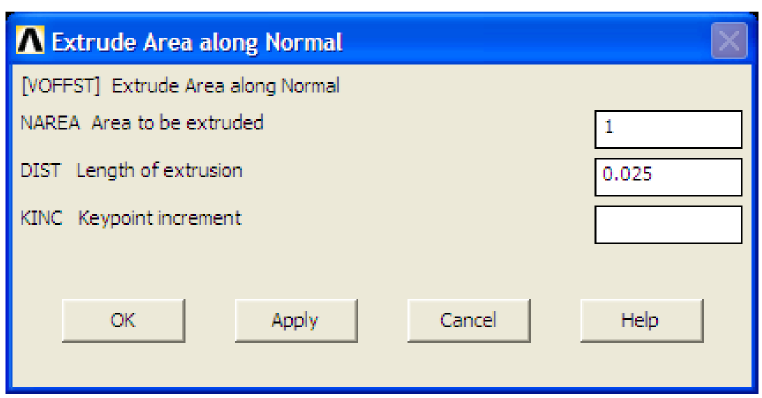


Figure 3.13 Extruding area along normal option

d. **Put thickness value. Click OK**

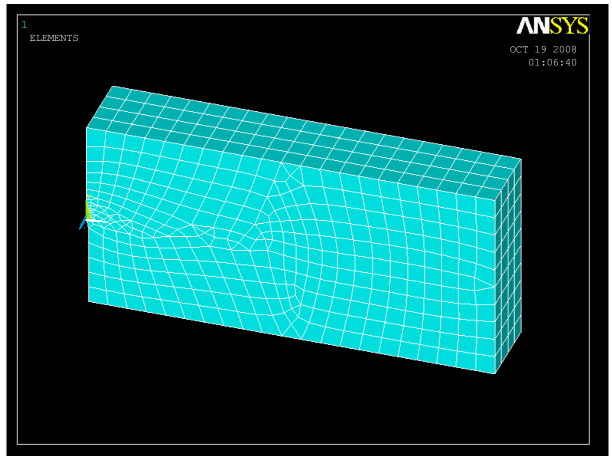


Figure 3.14 Meshed Volume

e. **Main Menu > Preprocessor > Meshing > Clear > Areas. Select the front area of meshed volume. Click OK**

## 2. Solving

- Define Loads and boundary condition

a. **Main Menu > Solution > Define Loads > Apply > Structural > Displacements > On Lines. Pick lines which is fixed during the test. Click OK. Select <u>All DOF</u> for the constrained and put <u>0</u> as displacement value**

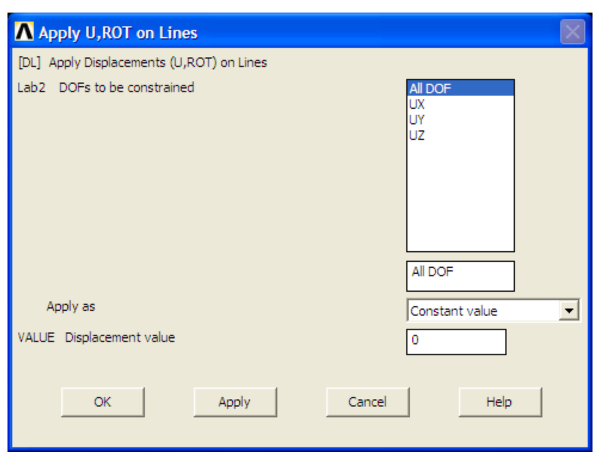


Figure 3.15 Displacement value is set for 0 for all DOF

b. **Main Menu > Solution > Define Loads > Apply > Structural > Displacements > Symmetry B.C > On Areas**. **Pick areas where symmetrical boundary condition applied. Click <u>OK</u>**

c. **Main Menu > Solution > Define Loads > Apply > Structural > Force/Moment > On Lines. Select Load direction. Put force value.**

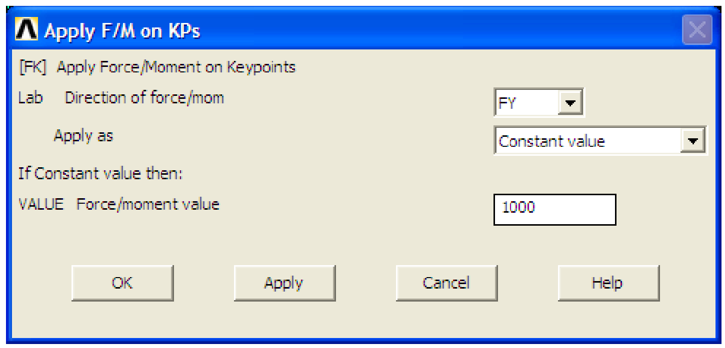


Figure 3.16 Applying load at Y direction

d. **Main Menu > Solution > Solve > Current LS. Click OK. Ignore any warning.**

**3. General Postprocessor**

- Solve analysis

a. **Main Menu > General Postproc > Define Path > By Nodes**

b. **Select 3 nodes of crack from the crack tip to the direction of the crack. Click OK.**

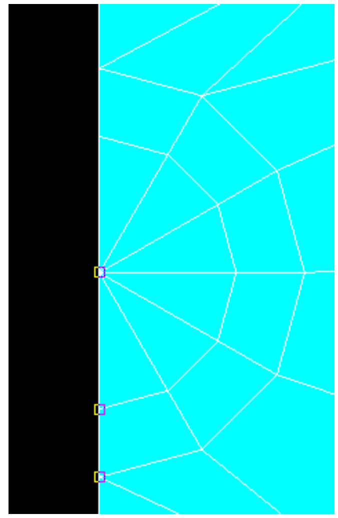

Figure 3.17 Select nodes at crack tip which is in the direction from crack tip to the crack

c. **Define the path name as K1. Click OK**

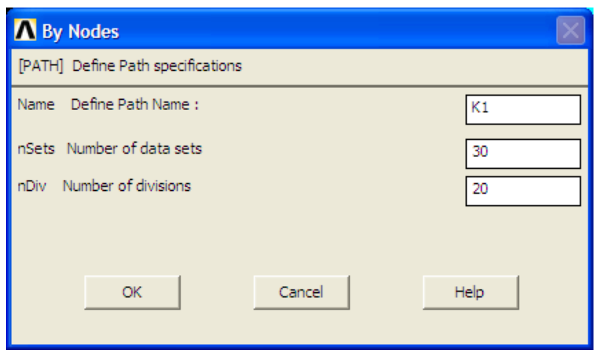


Figure 3.18 Define pathname of the path

d. **Utility Menu > Workplane > Local Coordinate System > Create local CS > by 3 nodes. Select 3 nodes at the crack tip. Click OK**

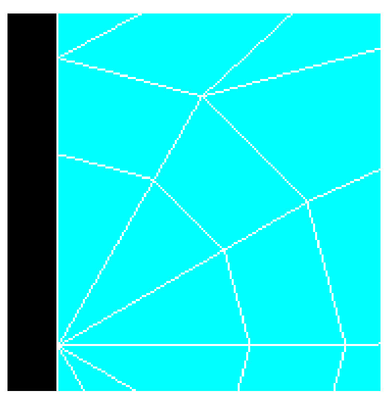

Figure 3.19 Selecting nodes at the crack tip

e. **Set the reference number as 11.Click OK**

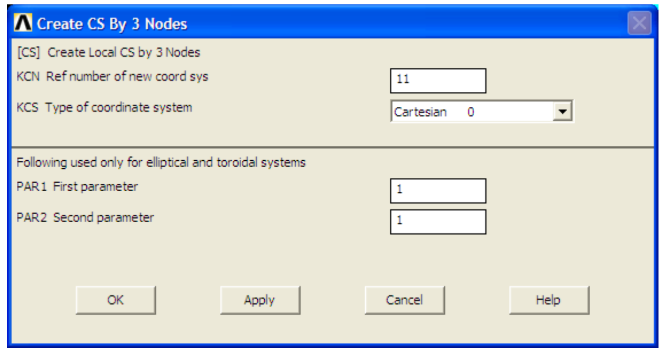


Figure 3.20 Set reference number

f. **Utility Menu > Workplane > Change Active CS to > Specified Coord Sys. <u>Set Coordinate system</u> number as <u>11</u>.**

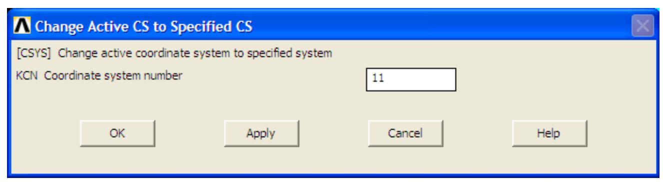


Figure 3.21 Setting the coordinate system

g. **Main Menu > General Postproc > Opt of Outp**. **Set Result Coord system to <u>Local system</u> and reference no of <u>11</u>**

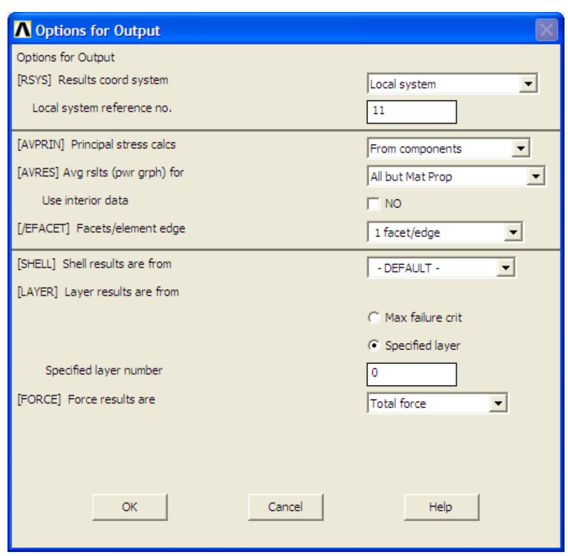


Figure 3.22 Option for Output.

h. **Main Menu > General Postproc > Nodal Calc > Stress Int Factor. Click OK**

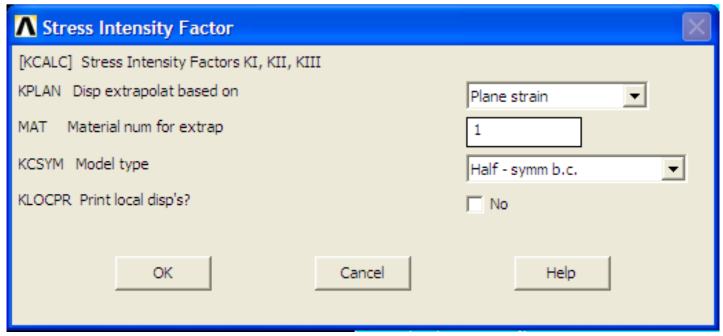


Figure: 3.23 KCALC Stress intensity factor.

i. **The result will appear at bottom left of the window.**

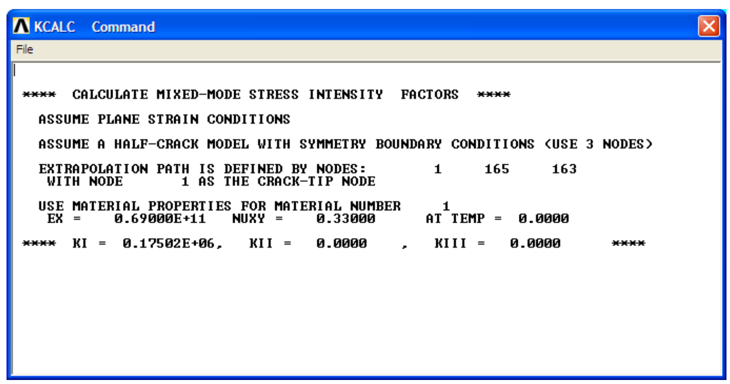


Figure 3.24 Stress intensity factor KCALC results

## 3.3 GANTT CHART

In order to make the research work is done properly and manageable. a schedule of the research project is prepared. The purposes of preparing the schedule are to plan all the research activities and to ensure that all the activities can be done in the time frame for the 2 semesters. Gantt chart is used to list all activities and mark the entire major milestone achieved during completing the project. Figure 3.25 and Figure 3.26 below shows the Gantt chart constructed during completing this project

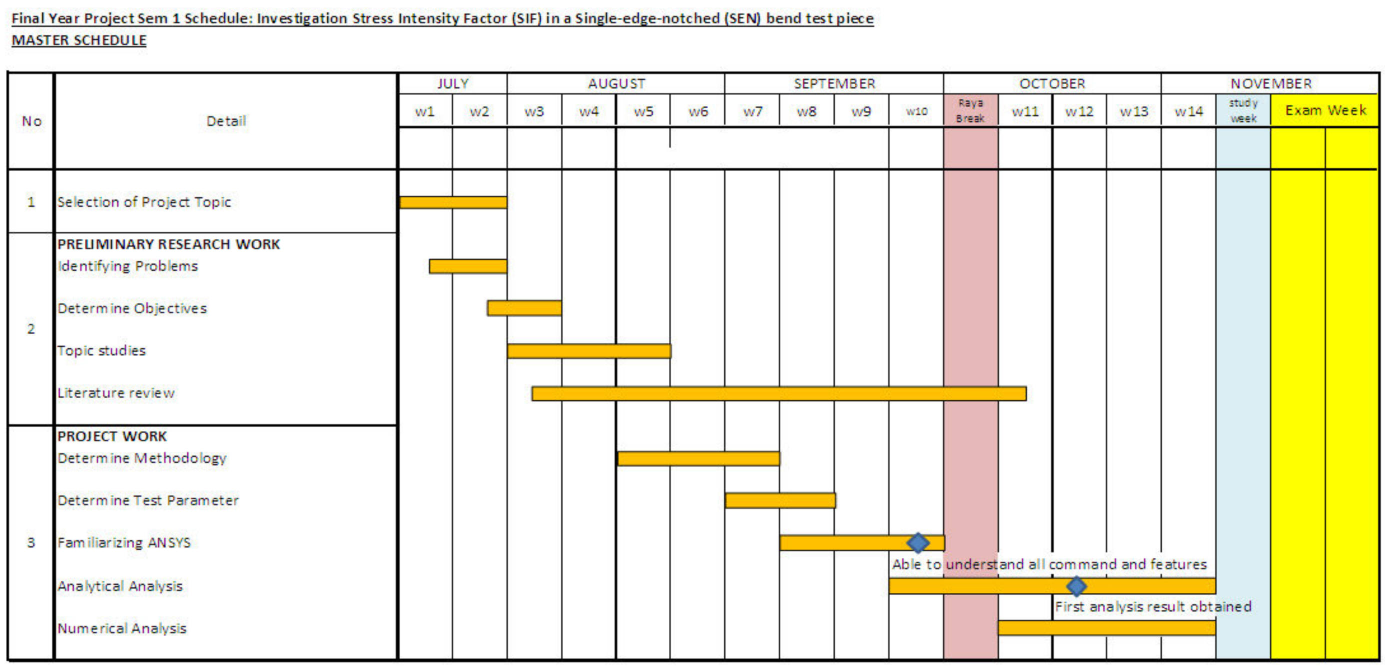


Figure 3.25: Gantt Chart for all activities for semester 1

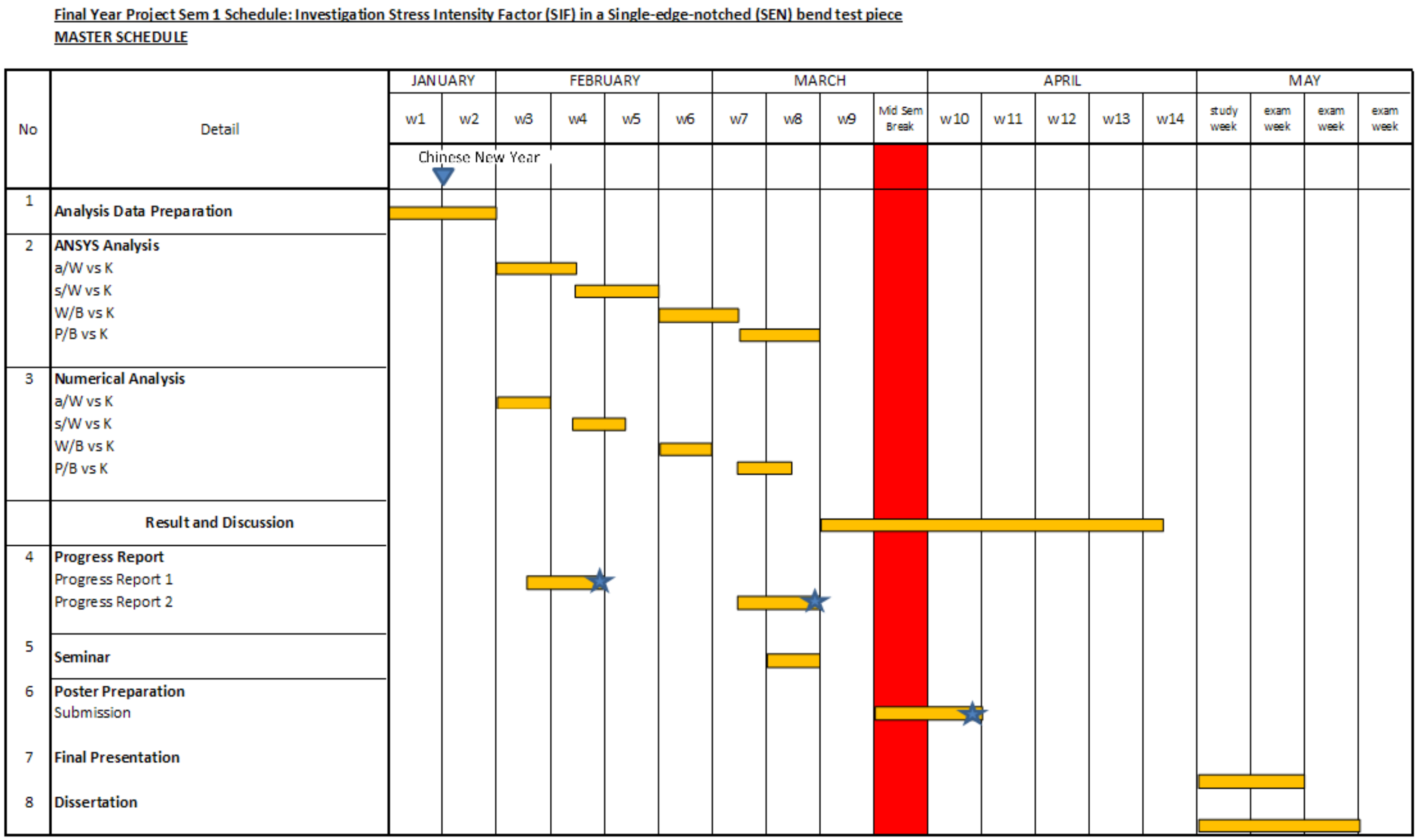


Figure 3.25: Gantt Chart for all activities for semester

# CHAPTER 4

# RESULT AND DISCUSSION

## 4.1 SPECIAL REQUIREMENT FOR THE TESTING OF BEND SPECIMEN

### 4.1.1 ASTM E399-90(2001) Standard Test Method for Plain-Strain Fracture Toughness of Metallic Material

According to ASTM E399 – 90 (2001), the standard beam specimen is a single edge notched and fatigue cracked beam loaded in three-point bending with support span, S. The overall dimension of the test piece is shown in figure 4.1 below.

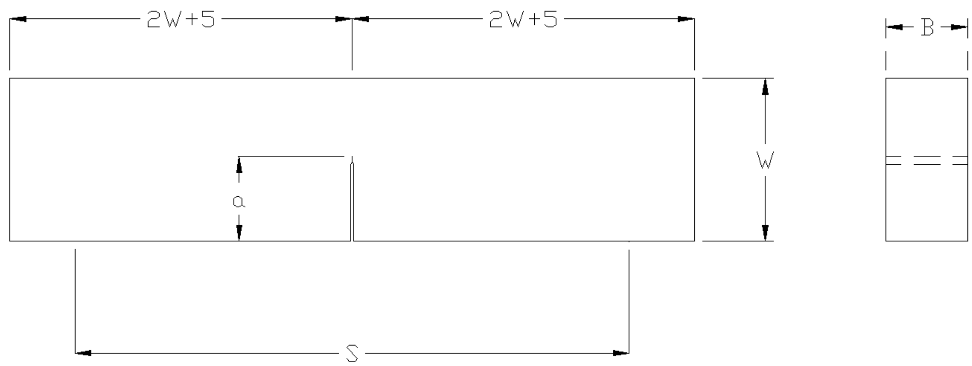


Figure 4.1 Single Edge Notched Bend Specimen – Standard Proportions and Tolerances according to ASTM E399 – 90 Standard Test Method

Where:
a = effective crack length

W = Width of test piece

B = Thickness of test piece

S = Span length

This test method covers the determination of the plane-strain fracture toughness (Kic) of metallic materials by tests using a variety of fatigue-cracked specimens having a 1.6mm or greater.

## 4.2 MATERIAL USED IN THE TEST

This testing used Aluminum 7075-T6 (ASTM 2001) as the bend test piece material. The physical properties of the material are as follows:

Table 4.1: Physical Properties of Aluminum 7075-T6 (ASTM 2001)

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

## 4.3 APPROACH OF DETERMINING STRESS INTENSITY FACTOR IN ANSYS

The objective of this analysis is to investigate the how value of SIFs are effected by span length ratio (s/W) and thickness ratio (w/B) with different crack depth ratio (a/W) in a single edge notched bend test piece. For this analysis, a 3-D pre-cracked bend test piece is modeled as in the figure. The analysis is using Linear Elastic Fracture Mechanics (LEFM) assumption, and Plane Strain Problem condition.

To find the the analytical value for K-expression for bend test piece, the analytical expression is used based on ASTM E399 (2001) as below.

$$K = \frac{PS}{BW^{\frac{3}{2}}} \cdot f(^{a}/_{W}) \qquad \ldots\ldots.\ 1$$

Where

$$f(^{a}/_{w}) = \left[\frac{3\left(\frac{a}{W}\right)^{\frac{1}{2}}\left[1.99-\frac{a}{W}\left(1-\frac{a}{W}\right)\left(2.15-3.93\frac{a}{W}+2.7^{a^2}/_{W^2}\right)\right]}{2\left(1+2\frac{a}{W}\right)\left(1-\frac{a}{W}\right)^{\frac{3}{2}}}\right] \qquad \ldots\ldots.2$$

We put equation 2 into equation 1, hence:

$$K = \frac{PS}{BW^{\frac{3}{2}}}\left[\frac{3\left(\frac{a}{W}\right)^{\frac{1}{2}}\left[1.99-\frac{a}{W}\left(1-\frac{a}{W}\right)\left(2.15-3.93\frac{a}{W}+2.7^{a^2}/_{W^2}\right)\right]}{2\left(1+2\frac{a}{W}\right)\left(1-\frac{a}{W}\right)^{\frac{3}{2}}}\right] \qquad \ldots\ldots.3$$

From previous analysis, the results show a large variation between the analytical and finite element analysis. After some revision and consultation, author finds that a meshing problem is the cause of large variation. Hence several modifications and correction to the analysis model have been made to solve the problem.

According to ASTM Standard, in experimental analysis, a pre-cracked test piece must have a notch of 60º as a crack starter and to ensure that the crack path is straight and occurs at the right place during the test, but in ANSYS, the crack path is treated to be straight. There are no needs to have a large notch. Hence author reduces the notched and also reduced the crack width from 1mm to 0.5mm to enable author create a necessary mesh around the crack tip

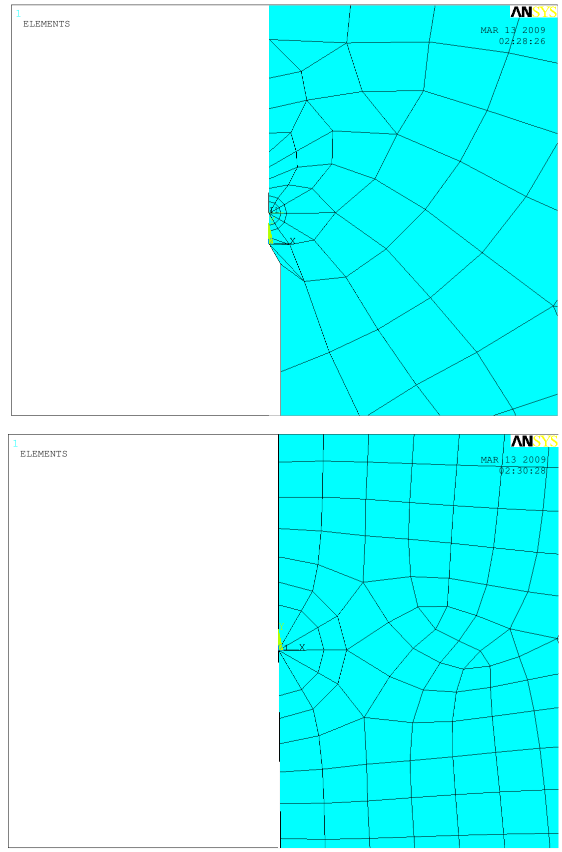


Figure 4.2 Meshing before correction and after correction. A larger radius of crack-tip mesh is necessary in order to compute the K accurately at the crack tip

The approach manages to significantly reduce the error variation from around 16% to around 3% to 0.1%.

## 4.4 RESULTS

During the analysis, only half of the test piece is modeled because of its symmetrical shape of the test piece and for ease of modeling. Overall test piece boundary conditions and the crack length to width ratio, a/W of the finite element analysis are as below:

Table 4.2 Boundary condition of the FEA

| | |
|---|---|
| Element Type | Plane82, Solid95 |
| Element Radius at the crack tip | 0.0005m |
| No of element around the crack tip | 6 |
| Radius Ratio | 0.5 |
| Crack Width | 0.001m |
| Load Exerted | 40kN |

**Analysis of K vs B/W ratio**

Table 4.3: Overall dimensions for each test piece (All dimension in meter) for Stress Intensity Factor, K vs B/W from a/W 0.50 to a/W 0.44

| P | a | B | s | s/2 | W |
|---|---|---|---|---|---|
| 4.00E+04 | 2.50E-02 | 2.40E-02 | 1.90E-01 | 9.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.50E-02 | 2.60E-02 | 1.90E-01 | 9.00E-02 | 5.00E-02 |
| 4.00E+04 | 2.50E-02 | 2.80E-02 | 1.90E-01 | 8.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.50E-02 | 3.00E-02 | 1.90E-01 | 8.00E-02 | 5.00E-02 |
| 4.00E+04 | 2.50E-02 | 3.20E-02 | 1.90E-01 | 7.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.50E-02 | 3.40E-02 | 1.90E-01 | 7.00E-02 | 5.00E-02 |
| 4.00E+04 | 2.40E-02 | 2.40E-02 | 1.90E-01 | 9.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.40E-02 | 2.60E-02 | 1.90E-01 | 9.00E-02 | 5.00E-02 |
| 4.00E+04 | 2.40E-02 | 2.80E-02 | 1.90E-01 | 8.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.40E-02 | 3.00E-02 | 1.90E-01 | 8.00E-02 | 5.00E-02 |
| 4.00E+04 | 2.40E-02 | 3.20E-02 | 1.90E-01 | 7.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.40E-02 | 3.40E-02 | 1.90E-01 | 7.00E-02 | 5.00E-02 |
| 4.00E+04 | 2.30E-02 | 2.40E-02 | 1.90E-01 | 9.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.30E-02 | 2.60E-02 | 1.90E-01 | 9.00E-02 | 5.00E-02 |
| 4.00E+04 | 2.30E-02 | 2.80E-02 | 1.90E-01 | 8.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.30E-02 | 3.00E-02 | 1.90E-01 | 8.00E-02 | 5.00E-02 |
| 4.00E+04 | 2.30E-02 | 3.20E-02 | 1.90E-01 | 7.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.30E-02 | 3.40E-02 | 1.90E-01 | 7.00E-02 | 5.00E-02 |
| 4.00E+04 | 2.20E-02 | 2.40E-02 | 1.90E-01 | 9.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.20E-02 | 2.60E-02 | 1.90E-01 | 9.00E-02 | 5.00E-02 |
| 4.00E+04 | 2.20E-02 | 2.80E-02 | 1.90E-01 | 8.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.20E-02 | 3.00E-02 | 1.90E-01 | 8.00E-02 | 5.00E-02 |
| 4.00E+04 | 2.20E-02 | 3.20E-02 | 1.90E-01 | 7.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.20E-02 | 3.40E-02 | 1.90E-01 | 7.00E-02 | 5.00E-02 |

Table 4.4: Overall dimensions for each test piece (All dimension in meter) for Stress Intensity Factor, K vs B/W from a/W 0.42 to a/W 0.36

| P | a | B | s | s/2 | W |
|---|---|---|---|---|---|
| 4.00E+04 | 2.10E-02 | 2.40E-02 | 1.90E-01 | 9.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.10E-02 | 2.60E-02 | 1.90E-01 | 9.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.10E-02 | 2.80E-02 | 1.90E-01 | 9.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.10E-02 | 3.00E-02 | 1.90E-01 | 9.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.10E-02 | 3.20E-02 | 1.90E-01 | 9.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.10E-02 | 3.40E-02 | 1.90E-01 | 9.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.00E-02 | 2.40E-02 | 1.90E-01 | 9.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.00E-02 | 2.60E-02 | 1.90E-01 | 9.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.00E-02 | 2.80E-02 | 1.90E-01 | 9.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.00E-02 | 3.00E-02 | 1.90E-01 | 9.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.00E-02 | 3.20E-02 | 1.90E-01 | 9.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.00E-02 | 3.40E-02 | 1.90E-01 | 9.50E-02 | 5.00E-02 |
| 4.00E+04 | 1.90E-02 | 2.40E-02 | 1.90E-01 | 9.50E-02 | 5.00E-02 |
| 4.00E+04 | 1.90E-02 | 2.60E-02 | 1.90E-01 | 9.50E-02 | 5.00E-02 |
| 4.00E+04 | 1.90E-02 | 2.80E-02 | 1.90E-01 | 9.50E-02 | 5.00E-02 |
| 4.00E+04 | 1.90E-02 | 3.00E-02 | 1.90E-01 | 9.50E-02 | 5.00E-02 |
| 4.00E+04 | 1.90E-02 | 3.20E-02 | 1.90E-01 | 9.50E-02 | 5.00E-02 |
| 4.00E+04 | 1.90E-02 | 3.40E-02 | 1.90E-01 | 9.50E-02 | 5.00E-02 |
| 4.00E+04 | 1.80E-02 | 2.40E-02 | 1.90E-01 | 9.50E-02 | 5.00E-02 |
| 4.00E+04 | 1.80E-02 | 2.60E-02 | 1.90E-01 | 9.50E-02 | 5.00E-02 |
| 4.00E+04 | 1.80E-02 | 2.80E-02 | 1.90E-01 | 9.50E-02 | 5.00E-02 |
| 4.00E+04 | 1.80E-02 | 3.00E-02 | 1.90E-01 | 9.50E-02 | 5.00E-02 |
| 4.00E+04 | 1.80E-02 | 3.20E-02 | 1.90E-01 | 9.50E-02 | 5.00E-02 |
| 4.00E+04 | 1.80E-02 | 3.40E-02 | 1.90E-01 | 9.50E-02 | 5.00E-02 |

**Analysis of K vs S/W ratio**

Table 4.5: Overall dimensions for each test piece (All dimension in meter) for Stress Intensity Factor, K vs s/W from a/W 0.50 to a/W 0.47

| P | a | B | s | s/2 | W |
|---|---|---|---|---|---|
| 4.00E+04 | 2.50E-02 | 2.50E-02 | 1.90E-01 | 9.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.50E-02 | 2.50E-02 | 1.80E-01 | 9.00E-02 | 5.00E-02 |
| 4.00E+04 | 2.50E-02 | 2.50E-02 | 1.70E-01 | 8.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.50E-02 | 2.50E-02 | 1.60E-01 | 8.00E-02 | 5.00E-02 |
| 4.00E+04 | 2.50E-02 | 2.50E-02 | 1.50E-01 | 7.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.50E-02 | 2.50E-02 | 1.40E-01 | 7.00E-02 | 5.00E-02 |
| 4.00E+04 | 2.45E-02 | 2.50E-02 | 1.90E-01 | 9.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.45E-02 | 2.50E-02 | 1.80E-01 | 9.00E-02 | 5.00E-02 |
| 4.00E+04 | 2.45E-02 | 2.50E-02 | 1.70E-01 | 8.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.45E-02 | 2.50E-02 | 1.60E-01 | 8.00E-02 | 5.00E-02 |
| 4.00E+04 | 2.45E-02 | 2.50E-02 | 1.50E-01 | 7.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.45E-02 | 2.50E-02 | 1.40E-01 | 7.00E-02 | 5.00E-02 |
| 4.00E+04 | 2.40E-02 | 2.50E-02 | 1.90E-01 | 9.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.40E-02 | 2.50E-02 | 1.80E-01 | 9.00E-02 | 5.00E-02 |
| 4.00E+04 | 2.40E-02 | 2.50E-02 | 1.70E-01 | 8.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.40E-02 | 2.50E-02 | 1.60E-01 | 8.00E-02 | 5.00E-02 |
| 4.00E+04 | 2.40E-02 | 2.50E-02 | 1.50E-01 | 7.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.40E-02 | 2.50E-02 | 1.40E-01 | 7.00E-02 | 5.00E-02 |
| 4.00E+04 | 2.35E-02 | 2.50E-02 | 1.90E-01 | 9.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.35E-02 | 2.50E-02 | 1.80E-01 | 9.00E-02 | 5.00E-02 |
| 4.00E+04 | 2.35E-02 | 2.50E-02 | 1.70E-01 | 8.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.35E-02 | 2.50E-02 | 1.60E-01 | 8.00E-02 | 5.00E-02 |
| 4.00E+04 | 2.35E-02 | 2.50E-02 | 1.50E-01 | 7.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.35E-02 | 2.50E-02 | 1.40E-01 | 7.00E-02 | 5.00E-02 |

Table 4.6: Overall dimensions for each test piece (All dimension in mm) for Stress Intensity Factor, K vs s/W from a/W 0.50 to a/W 0.47

| P | a | B | s | s/2 | W |
|---|---|---|---|---|---|
| 4.00E+04 | 2.30E-02 | 2.50E-02 | 1.90E-01 | 9.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.30E-02 | 2.50E-02 | 1.80E-01 | 9.00E-02 | 5.00E-02 |
| 4.00E+04 | 2.30E-02 | 2.50E-02 | 1.70E-01 | 8.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.30E-02 | 2.50E-02 | 1.60E-01 | 8.00E-02 | 5.00E-02 |
| 4.00E+04 | 2.30E-02 | 2.50E-02 | 1.50E-01 | 7.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.30E-02 | 2.50E-02 | 1.40E-01 | 7.00E-02 | 5.00E-02 |
| 4.00E+04 | 2.25E-02 | 2.50E-02 | 1.90E-01 | 9.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.25E-02 | 2.50E-02 | 1.80E-01 | 9.00E-02 | 5.00E-02 |
| 4.00E+04 | 2.25E-02 | 2.50E-02 | 1.70E-01 | 8.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.25E-02 | 2.50E-02 | 1.60E-01 | 8.00E-02 | 5.00E-02 |
| 4.00E+04 | 2.25E-02 | 2.50E-02 | 1.50E-01 | 7.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.25E-02 | 2.50E-02 | 1.40E-01 | 7.00E-02 | 5.00E-02 |
| 4.00E+04 | 2.20E-02 | 2.50E-02 | 1.90E-01 | 9.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.20E-02 | 2.50E-02 | 1.80E-01 | 9.00E-02 | 5.00E-02 |
| 4.00E+04 | 2.20E-02 | 2.50E-02 | 1.70E-01 | 8.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.20E-02 | 2.50E-02 | 1.60E-01 | 8.00E-02 | 5.00E-02 |
| 4.00E+04 | 2.20E-02 | 2.50E-02 | 1.50E-01 | 7.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.20E-02 | 2.50E-02 | 1.40E-01 | 7.00E-02 | 5.00E-02 |
| 4.00E+04 | 2.15E-02 | 2.50E-02 | 1.90E-01 | 9.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.15E-02 | 2.50E-02 | 1.80E-01 | 9.00E-02 | 5.00E-02 |
| 4.00E+04 | 2.15E-02 | 2.50E-02 | 1.70E-01 | 8.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.15E-02 | 2.50E-02 | 1.60E-01 | 8.00E-02 | 5.00E-02 |
| 4.00E+04 | 2.15E-02 | 2.50E-02 | 1.50E-01 | 7.50E-02 | 5.00E-02 |
| 4.00E+04 | 2.15E-02 | 2.50E-02 | 1.40E-01 | 7.00E-02 | 5.00E-02 |

Results

For the FEA using ANSYS, Figure 4.3 shows the stress field at the crack tip. We can see that the high stress concentration at crack tip. Table 4.7 to Table 4.10 shows the overall results of the tests. From the table 4.7 to Table 4.10, graph at Figure 4.4 to 4.7 is constructed

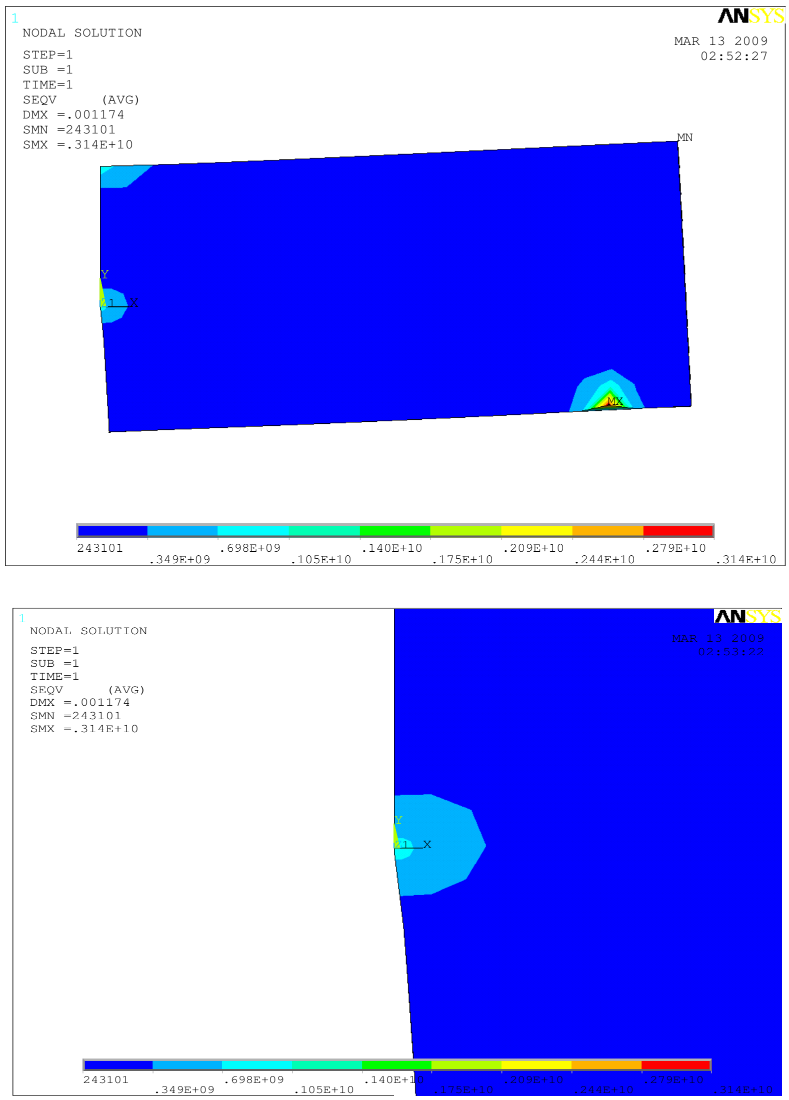


Figure 4.3: Stress region at the crack tip.

Table 4.7: Results for Stress Intensity Factor, K vs B/W from a/W 0.50 to a/W 0.44

| a/W | B/W | ANSYS K | Empirical K | Error | % Error |
|---|---|---|---|---|---|
| 0.5 | 0.48 | 7.75E+07 | 75411393 | 2.08E+06 | 2.760336 |
| 0.5 | 0.52 | 7.07E+07 | 69610516 | 1.13E+06 | 1.618267 |
| 0.5 | 0.56 | 6.50E+07 | 64638336 | 3.45E+05 | 0.533218 |
| 0.5 | 0.6 | 6.00E+07 | 60329114 | 2.95E+05 | 0.489173 |
| 0.5 | 0.64 | 5.62E+07 | 56558544 | 3.88E+05 | 0.685209 |
| 0.5 | 0.68 | 5.24E+07 | 53231571 | 8.32E+05 | 1.562177 |
| 0.48 | 0.48 | 7.30E+07 | 70845102 | 2.13E+06 | 3.000769 |
| 0.48 | 0.52 | 6.66E+07 | 65395479 | 1.22E+06 | 1.872486 |
| 0.48 | 0.56 | 6.16E+07 | 60724373 | 9.10E+05 | 1.49796 |
| 0.48 | 0.6 | 5.70E+07 | 56676082 | 2.96E+05 | 0.522122 |
| 0.48 | 0.64 | 5.29E+07 | 53133827 | 2.13E+05 | 0.400548 |
| 0.48 | 0.68 | 4.94E+07 | 50008307 | 6.35E+05 | 1.270404 |
| 0.46 | 0.48 | 6.88E+07 | 66680381 | 2.16E+06 | 3.246261 |
| 0.46 | 0.52 | 6.33E+07 | 61551121 | 1.71E+06 | 2.779607 |
| 0.46 | 0.56 | 5.82E+07 | 57154612 | 1.01E+06 | 1.767815 |
| 0.46 | 0.6 | 5.38E+07 | 53344305 | 4.30E+05 | 0.805513 |
| 0.46 | 0.64 | 5.00E+07 | 50010286 | 5.33E+04 | 0.106549 |
| 0.46 | 0.68 | 4.71E+07 | 47068504 | 3.65E+04 | 0.077538 |
| 0.44 | 0.48 | 6.55E+07 | 62867256 | 2.59E+06 | 4.120975 |
| 0.44 | 0.52 | 5.98E+07 | 58031313 | 1.79E+06 | 3.078832 |
| 0.44 | 0.56 | 5.50E+07 | 53886219 | 1.12E+06 | 2.081758 |
| 0.44 | 0.6 | 5.09E+07 | 50293805 | 5.68E+05 | 1.129752 |
| 0.44 | 0.64 | 4.73E+07 | 47150442 | 1.08E+05 | 0.228117 |
| 0.44 | 0.68 | 4.41E+07 | 44376887 | 2.77E+05 | 0.623943 |

Table 4.8: Results for Stress Intensity Factor, K vs B/W from a/W 0.42 to a/W 0.36

| a/W | B/W | ANSYS | Empirical | Error | % Error |
|---|---|---|---|---|---|
| 0.42 | 0.48 | 6.16E+07 | 59363286 | 2.25E+06 | 3.793109 |
| 0.42 | 0.52 | 5.63E+07 | 54796879 | 1.49E+06 | 2.710229 |
| 0.42 | 0.56 | 5.21E+07 | 50882816 | 1.21E+06 | 2.374443 |
| 0.42 | 0.6 | 4.82E+07 | 47490629 | 6.82E+05 | 1.436855 |
| 0.42 | 0.64 | 4.48E+07 | 44522464 | 2.44E+05 | 0.546995 |
| 0.42 | 0.68 | 4.20E+07 | 41903496 | 1.28E+05 | 0.30428 |
| 0.4 | 0.48 | 5.84E+07 | 56132095 | 2.27E+06 | 4.047425 |
| 0.4 | 0.52 | 5.37E+07 | 51814242 | 1.88E+06 | 3.629809 |
| 0.4 | 0.56 | 4.94E+07 | 48113225 | 1.28E+06 | 2.662003 |
| 0.4 | 0.6 | 4.57E+07 | 44905676 | 7.80E+05 | 1.737695 |
| 0.4 | 0.64 | 4.25E+07 | 42099072 | 3.64E+05 | 0.864457 |
| 0.4 | 0.68 | 3.99E+07 | 39622656 | 2.52E+05 | 0.636869 |
| 0.38 | 0.48 | 5.57E+07 | 53142199 | 2.61E+06 | 4.905331 |
| 0.38 | 0.52 | 5.10E+07 | 49054338 | 1.92E+06 | 3.917415 |
| 0.38 | 0.56 | 4.69E+07 | 45550457 | 1.35E+06 | 2.96933 |
| 0.38 | 0.6 | 4.34E+07 | 42513760 | 8.78E+05 | 2.065779 |
| 0.38 | 0.64 | 4.03E+07 | 39856650 | 4.81E+05 | 1.207704 |
| 0.38 | 0.68 | 3.79E+07 | 37512141 | 3.73E+05 | 0.993969 |
| 0.36 | 0.48 | 5.30E+07 | 50366038 | 2.60E+06 | 5.160148 |
| 0.36 | 0.52 | 4.84E+07 | 46491727 | 1.95E+06 | 4.19058 |
| 0.36 | 0.56 | 4.46E+07 | 43170889 | 1.41E+06 | 3.261713 |
| 0.36 | 0.6 | 4.13E+07 | 40292830 | 9.57E+05 | 2.375534 |
| 0.36 | 0.64 | 3.84E+07 | 37774528 | 5.80E+05 | 1.536675 |
| 0.36 | 0.68 | 3.60E+07 | 35552497 | 4.77E+05 | 1.340279 |

Table 4.9: Results for Stress Intensity Factor, K vs s/W from a/W 0.50 to a/W 0.47

| a/W | s/W | ANSYS K | Empirical K | Error | % Error |
|---|---|---|---|---|---|
| 0.5 | 3.8 | 7.53E+07 | 72394937 | 2.86E+06 | 3.95064 |
| 0.5 | 3.6 | 7.10E+07 | 68584677 | 2.43E+06 | 3.549369 |
| 0.5 | 3.4 | 6.56E+07 | 64774417 | 8.73E+05 | 1.34711 |
| 0.5 | 3.2 | 6.15E+07 | 60964157 | 5.19E+05 | 0.851062 |
| 0.5 | 3 | 5.73E+07 | 57153898 | 1.66E+05 | 0.290623 |
| 0.5 | 2.8 | 5.32E+07 | 53343638 | 1.87E+05 | 0.349878 |
| 0.49 | 3.8 | 7.18E+07 | 70151603 | 1.62E+06 | 2.305574 |
| 0.49 | 3.6 | 6.77E+07 | 66459413 | 1.26E+06 | 1.901291 |
| 0.49 | 3.4 | 6.37E+07 | 62767224 | 9.10E+05 | 1.449445 |
| 0.49 | 3.2 | 5.96E+07 | 59075034 | 5.57E+05 | 0.942811 |
| 0.49 | 3 | 5.56E+07 | 55382845 | 2.04E+05 | 0.368626 |
| 0.49 | 2.8 | 5.15E+07 | 51690655 | 1.49E+05 | 0.287586 |
| 0.48 | 3.8 | 6.97E+07 | 68011298 | 1.65E+06 | 2.43004 |
| 0.48 | 3.6 | 6.57E+07 | 64431756 | 1.30E+06 | 2.016465 |
| 0.48 | 3.4 | 6.18E+07 | 60852214 | 9.47E+05 | 1.555877 |
| 0.48 | 3.2 | 5.79E+07 | 57272672 | 5.93E+05 | 1.03597 |
| 0.48 | 3 | 5.39E+07 | 53693130 | 2.41E+05 | 0.448605 |
| 0.48 | 2.8 | 5.00E+07 | 50113588 | 1.11E+05 | 0.220675 |
| 0.47 | 3.8 | 6.77E+07 | 65967230 | 1.69E+06 | 2.564561 |
| 0.47 | 3.6 | 6.38E+07 | 62495271 | 1.34E+06 | 2.140529 |
| 0.47 | 3.4 | 6.00E+07 | 59023311 | 9.85E+05 | 1.668305 |
| 0.47 | 3.2 | 5.62E+07 | 55551352 | 6.33E+05 | 1.138853 |
| 0.47 | 3 | 5.24E+07 | 52079392 | 2.80E+05 | 0.536888 |
| 0.47 | 2.8 | 4.85E+07 | 48607433 | 7.14E+04 | 0.146958 |

Table 4.10: Results for Stress Intensity Factor, K vs s/W from a/W 0.46 to a/W 0.43

| a/W | s/W | ANSYS | Empirical | Error | % Error |
|---|---|---|---|---|---|
| | | K | K | | |
| 0.46 | 0.5 | 6.20E+07 | 60644052 | 1.36E+06 | 2.250754 |
| 0.46 | 0.5 | 5.83E+07 | 57274938 | 1.01E+06 | 1.768771 |
| 0.46 | 0.5 | 5.46E+07 | 53905824 | 6.61E+05 | 1.22654 |
| 0.46 | 0.5 | 5.08E+07 | 50536710 | 3.10E+05 | 0.61399 |
| 0.46 | 0.5 | 4.71E+07 | 47167596 | 3.96E+04 | 0.083947 |
| 0.45 | 0.5 | 6.39E+07 | 62143372 | 1.77E+06 | 2.852481 |
| 0.45 | 0.5 | 6.03E+07 | 58872668 | 1.42E+06 | 2.412549 |
| 0.45 | 0.5 | 5.67E+07 | 55601964 | 1.07E+06 | 1.920859 |
| 0.45 | 0.5 | 5.30E+07 | 52331261 | 7.16E+05 | 1.367709 |
| 0.45 | 0.5 | 4.94E+07 | 49060557 | 3.64E+05 | 0.742843 |
| 0.45 | 0.5 | 4.58E+07 | 45789853 | 1.41E+04 | 0.030895 |
| 0.44 | 0.5 | 6.21E+07 | 60352566 | 1.80E+06 | 2.97491 |
| 0.44 | 0.5 | 5.86E+07 | 57176115 | 1.44E+06 | 2.527078 |
| 0.44 | 0.5 | 5.51E+07 | 53999664 | 1.09E+06 | 2.024709 |
| 0.44 | 0.5 | 5.16E+07 | 50823213 | 7.43E+05 | 1.461511 |
| 0.44 | 0.5 | 4.80E+07 | 47646762 | 3.92E+05 | 0.82322 |
| 0.44 | 0.5 | 4.45E+07 | 44470312 | 4.37E+04 | 0.098242 |
| 0.43 | 0.5 | 6.05E+07 | 58635866 | 1.82E+06 | 3.110952 |
| 0.43 | 0.5 | 5.70E+07 | 55549768 | 1.47E+06 | 2.653894 |
| 0.43 | 0.5 | 5.36E+07 | 52463670 | 1.12E+06 | 2.141158 |
| 0.43 | 0.5 | 5.02E+07 | 49377571 | 7.73E+05 | 1.566356 |
| 0.43 | 0.5 | 4.67E+07 | 46291473 | 4.25E+05 | 0.917073 |
| 0.43 | 0.5 | 4.33E+07 | 43205375 | 7.76E+04 | 0.179665 |

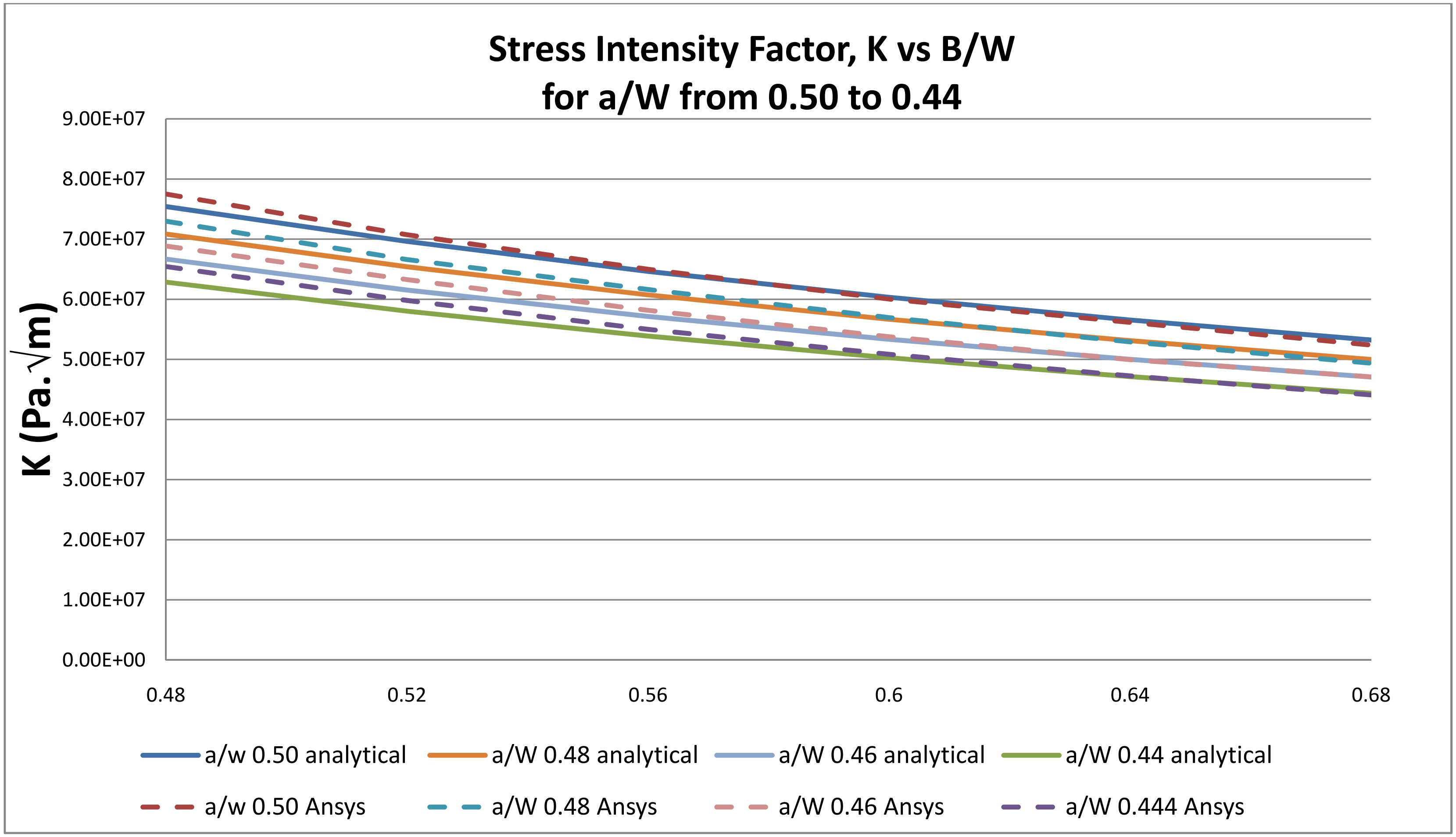


Figure 4.4: Graph of Stress Intensity Factor, K vs Thickness to width ratio B/W for a/W 0.50 to 0.44

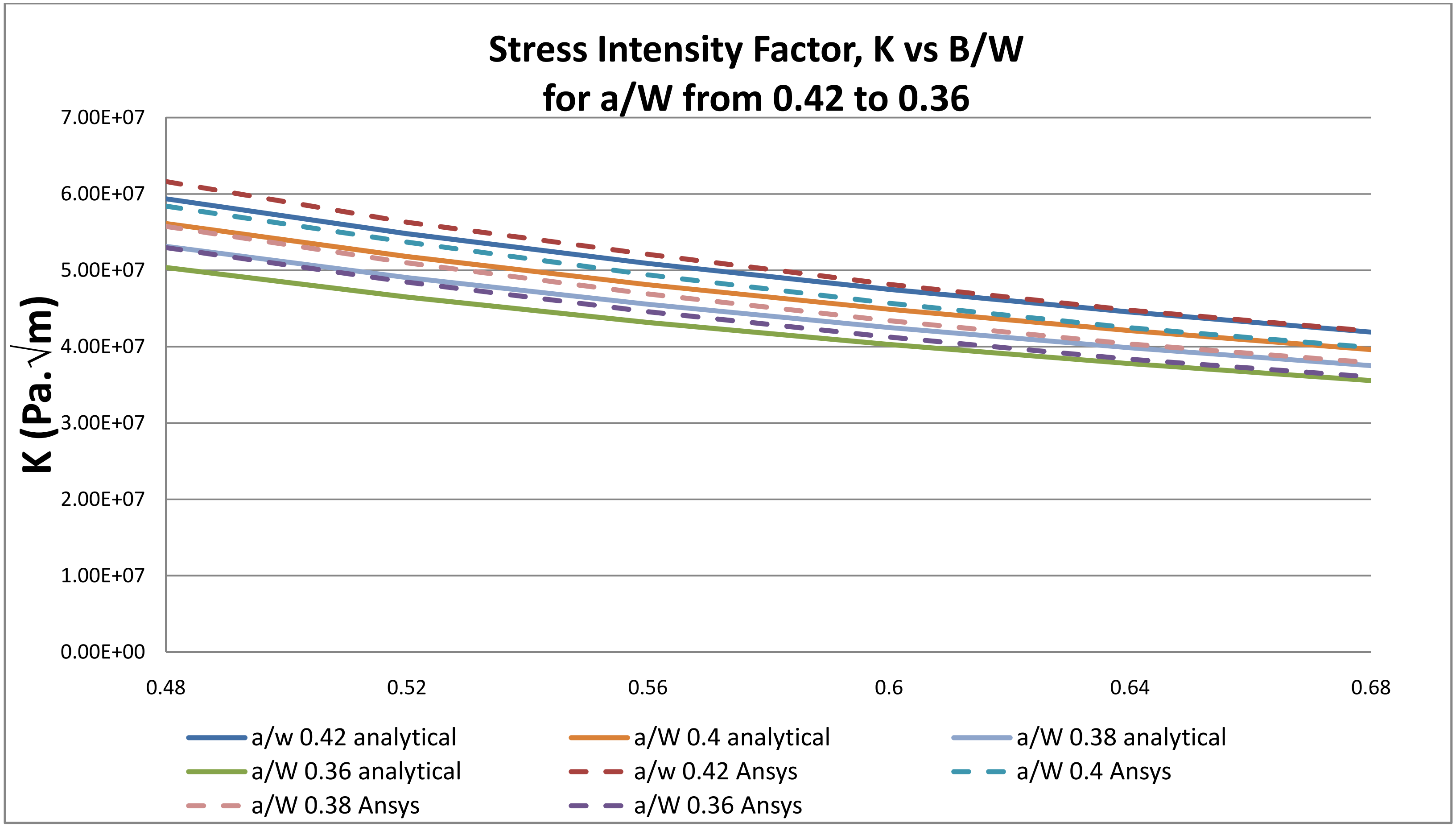


Figure 4.5: Graph of Stress Intensity Factor, K vs Thickness to width ratio B/W for a/W 0.42 to 0.36

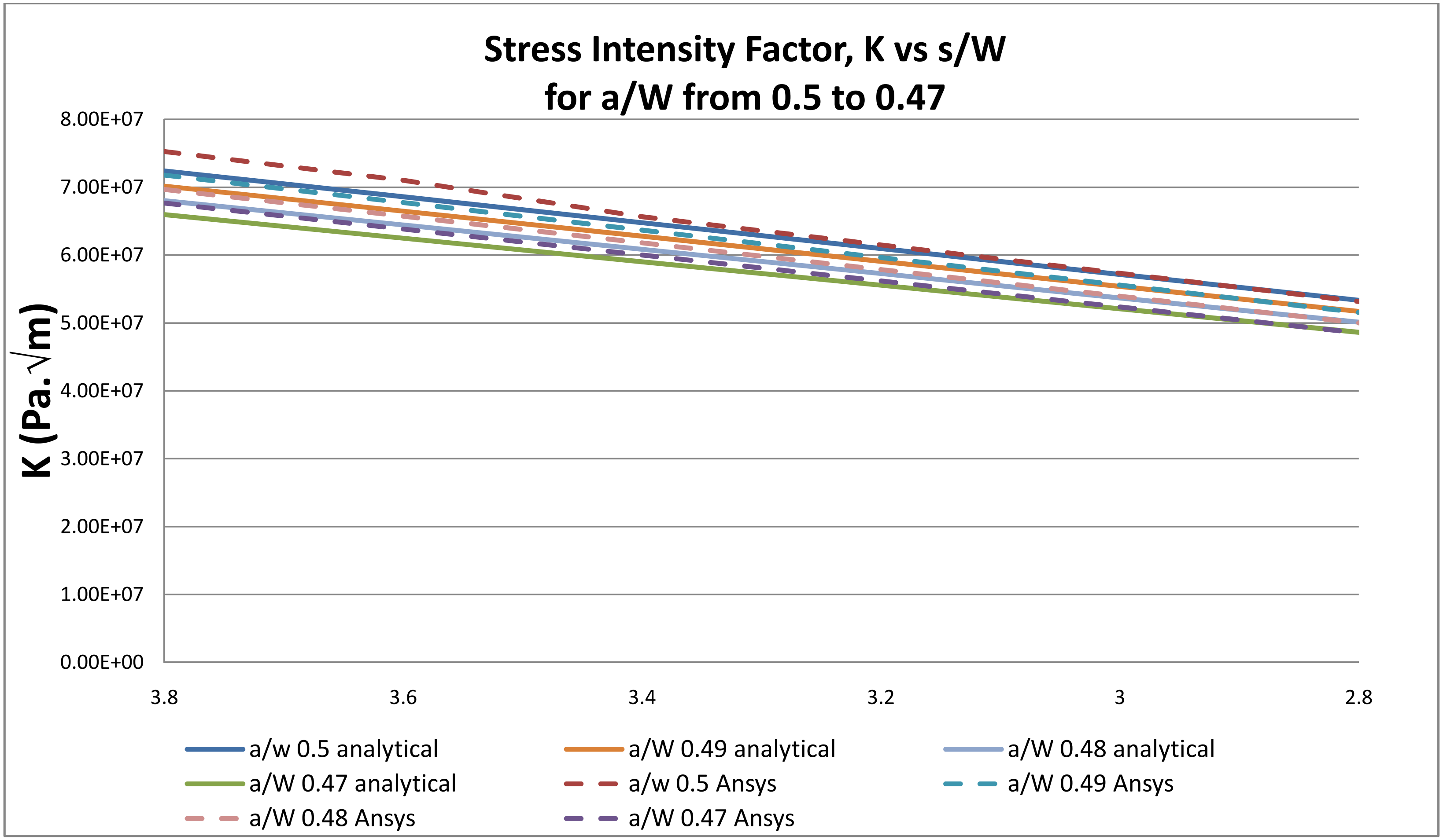


Figure 4.6: Graph of Stress Intensity Factor, K vs Span length to width ratio, s/W for a/W 0.50 to 0.44

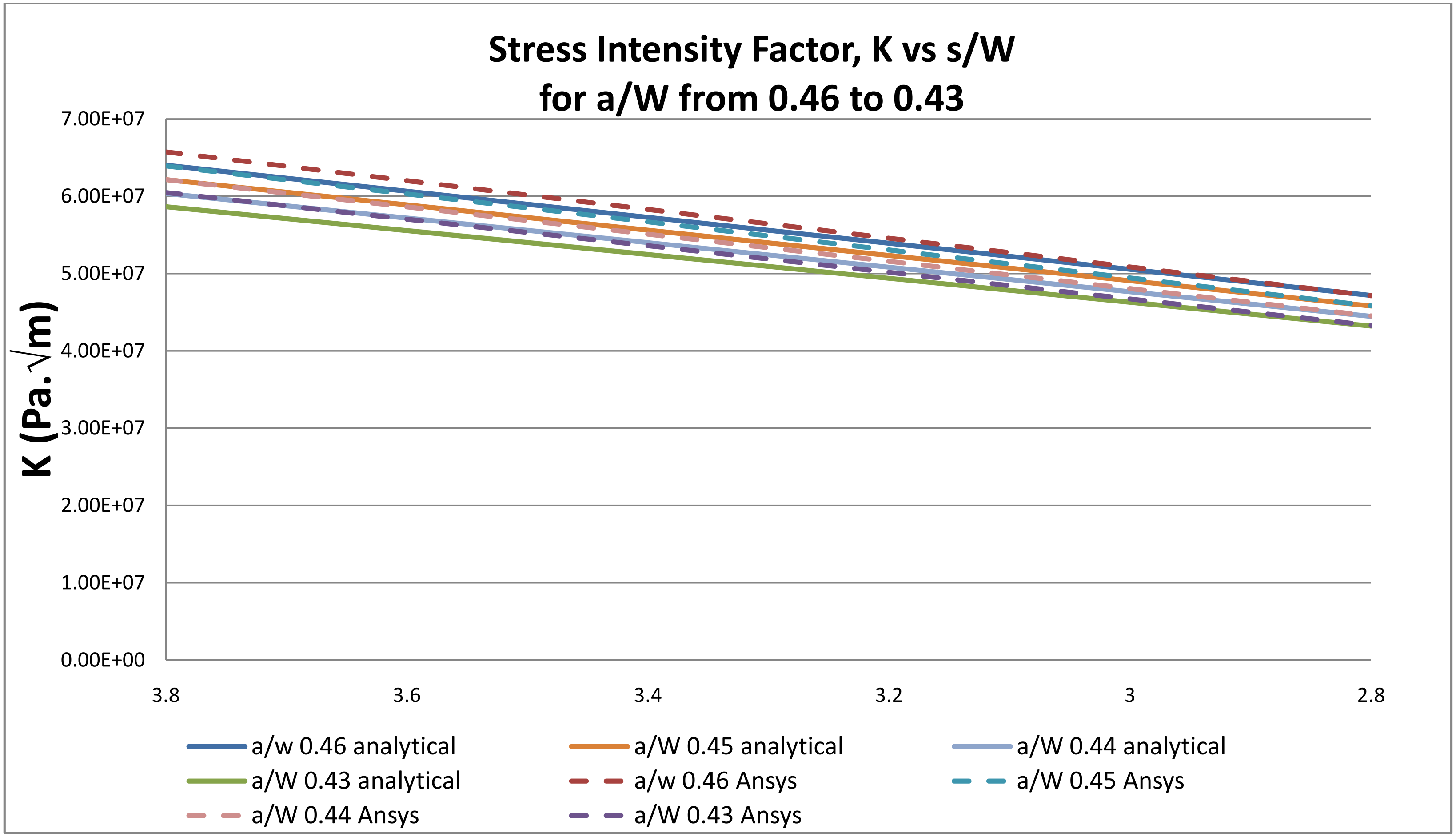


Figure 4.7: Graph of Stress Intensity Factor, K vs Span length to width ratio s/W for a/W 0.50 to 0.44

## 4.5 DISCUSSION

Table 4.4 and 4.5 shows the result obtained for Stress Intensity Factor, K vs. thickness to width ratio, B/W while Table 4.6 and 4.7 shows the result obtained for Stress Intensity Factor; K vs span length to width ratio, s/W from both empirical analysis and FEA. From the table, graphs obtained from both cases, graphs of Figure 4.4 to 4.5 were plotted.

From the graph from figure 4.4 and 4.5, we can understand that K behavior towards different value of B/W and crack length ratio, a/W. As a/W value increase, K increased. But the as value of B/W decreased, K decreased. We can say that the B/W ratio is inversely proportional to the stress intensity. There are some differences between FEA analysis and empirical analysis. The error between the both FEA and empirical is decreased as the B/W increased. We can see that at B/W of 0.68, there are only about 2% to 1% only. But at graph 4.4, the error can be reduced down to 0.2 % at B/W of 0.64. But we can't conclude that the error is decreased when ratio of B/W increased. There are possibilities that the FEA analysis might slightly have lower gradient for the greater B/W ratio because we didn't have the analysis of 0.68 onwards.

For the graph of Stress Intensity Factor, K vs Span length to width ratio s/W, the results yields almost as same pattern as B/W ratio but compared to B/W, graph of s/W has linear pattern. The error between both FEA and empirical also decreased as the s/W increased. From the graph we can see that the error variation between both FEA and empirical is about 3% to 1% with the lowest error variation for this analysis is at s/W 3.8.

There are differences between FEA and empirical value because of many factors such as the ANSYS environment and meshing of the analysis model. Several corrective actions have been taken in order to reduce the variation between both analysis and increase the results accuracy.

# CHAPTER 5

# CONCLUSION

From the graph obtained, we can conclude that Stress Intensity Factor, K is inversely proportional with span length to width ratio, s/W and thickness to width ratio, B/W while it is proportional to the crack length ratio, a/W. It is proved from all the results and graphs obtained. But s/W ratio is directly proportional from the straight line obtained compared to B/W ratio. As the B/W ratio and the s/W ratio increased, the variation between FEA and empirical analysis is decreased. But it is not sure whether the decreasing errors for both analyses are due to different line gradient or the error itself reduced because of the set of data limitation. Further analysis can be made to confirm the hypothesis. From the results the error variations between analytical analysis and FEA is around 3% to 0.1% only. From the corrective actions taken by the author, we can understand that the meshing, test pieces modeling and ANSYS environment contribute to the variation between FEA and empirical analysis.

# REFERENCES


1. Anon, Standard Test Method for Plane-Strain Fracture Toughness of Metallic Material, ASTM E399, 2001
2. B. Gross, J. E. Srawley, Stress Intensity Factor for Three-Point Bend Specimen by Boundary Collocation, NASA Technical Note, 1965
3. E.F. Gdoutos, C.A. Rodopoulos, J.R. Yates Problems of Fracture Mechanics and Fatigue: A Solution Guide, Kluwer Academic Publisher, 2003
4. G. Pluvinage, Fracture and Fatigue Emanating from Stress Concentrators, Kluwer Academic Publisher, 2003
5. J. Helena, Lu W. Y, H. Soonsung, Connelly K, Fracture Behavior of Polyurethane Foams, Society for Experimental Mechanics, Inc, 2007
6. L. P. Pook, Linear *Elastic Fracture Mechanics For Engineers: Theory and Application*, WIT Press, 2000
7. M. Janssen, J. Zuidema, R. Wanhill, *Fracture Mechanics 2nd Edition*, Spon Press, 2004
8. R.J Sanford, Principles of Fracture Mechanics, Prentice Hall, 2003
9. S. Samaringhe, D. Kulasiri, Stress Intensity Factor of Wood From Crack Tip Displacement Fields Obtained from Digital Image Processing, Silva Fennica Research Articles, 2004
10. Y. Hiroshi, Mode II Fracture Mechanics Properties of Wood measured by the Asymmetric Four-Point Bending Test Using a Single-Edge-Notched Specimen, Elsevier Ltd, 2008
11. http://www.efunda.com/formulae/solid_mechanics/fracture_mechanics/
12. http://www.matweb.com/index.aspx
13. *http://en.wikipedia.org/wiki/Stress_intensity_factor*

# APPENDIXES