Evaluation of Stress Intensity Factor for mode I using Finite Element Analysis for 304 stainless steel

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***Abstract* - The aim of this research is to determine the mode I Stress Intensity Factor and characterize the fatigue crack growth behaviour of structural steel alloy and 304 grade stainless steel specimens for cryogenic pressure vessel application. Compact Tension (CT) specimens found in the literature were used to calculate the geometric and mechanical parameters. CATIA V5 is being used to model the CT specimen. For the geometric parameters employed in this study, the theoretical value of KI is calculated using the ASTM E-399-83 formulation for measuring stress intensity factor. Analysis is carried out to solve the CT specimen problem using finite element analysis. The pre-meshed crack is generated at the crack front by creating the local coordinate system. Then the obtained analysis results are compared with the theoretical results. Different crack lengths are considered in this study. Overall, promising results were produced, with a good argument when compared to the theoretical result. The stress intensity factor values of 304 grade stainless steel is less than the SIF values of structural steel for respective crack length. Therefore 304 grade stainless steel is preferred for the cryogenic pressure vessel.**

***keywords* - Stress intensity factor, Linear elastic fracture mechanics, Fracture toughness, CT specimen, structural steel, 304 stainless steel, stress analysis.**

I. INTRODUCTION

Mechanics is a field of science that studies the behaviour of objects in motion or at rest. Fracture is a failure mechanism caused by fracture propagation that is unstable due to applied stress. Fracture mechanics is a branch of engineering that deals with the prediction, prevention, and control of fracture in materials, components, and structures that are subjected to static, dynamic, and sustained loads.

Fracture occurs when an object or material breaks into two or more pieces as a result of stress. Fracture mechanics has evolved into a valuable tool for predicting the strength and longevity of broken structures. Fracture mechanics is the study of how a crack spreads in a material Fracture mechanics has evolved into a valuable tool for analyzing broken structures in today's world.

Damage tolerance design methodology starts with a fracture mechanics study. The determination of (1) Stress intensity factor (K), (2) Energy release rate (G), (3) Path independent integral (J), (4) Crack tip Opening displacement (CTOD), and prediction of (1) Mixed mode fracture, (2) Residual strength, and (3) Crack growth life are all goals of fracture mechanics analysis.

On a crack body, there are three forms of loading: mode I, mode II, and mode III as shown in Figure 1. The load is applied normal to the fracture plane in Mode I, which tends to open the crack. Sliding or in-plane shear loading is referred to as Mode II. Out-of-plane loading or tearing is represented by Mode III.

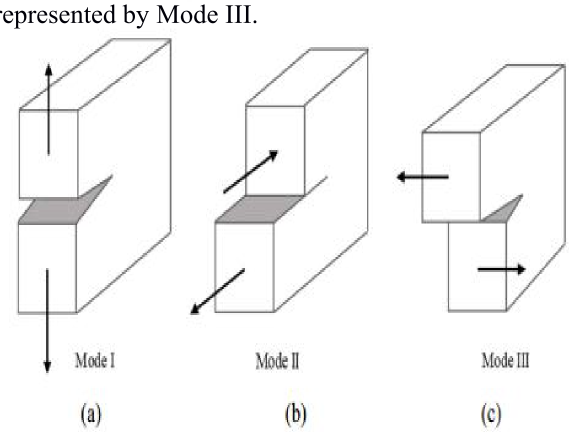


Figure 1: Fracture modes; (a) mode I- Opening mode, (b) mode II – Sliding mode, (c) Mode III – Shearing mode.

1.1 Stress intensity factor:

Irwin first proposed the stress intensity factor to determine the stress distribution around the fracture tip region, and it is now utilised to predict fatigue crack propagation. Stress intensity factor is the quantity that characterizes the driving force for fracture.

$K_I = \sigma \sqrt{\pi a}$

SIF has been calculated using a variety of numerical approaches, including the Finite Difference Method (FDM), Finite Element Method (FEM), and Boundary Element Method (BEM).

1.2 CT specimen:

To measure the fracture toughness of a material, the compact tension specimen (CT specimen) shown in Figure.1 is commonly used. Fracture toughness is a material attribute obtained in a static test on a CT- specimen with a fatigue fracture, commonly designated by the symbol (I for opening mode, c for critical). The critical value is the K-value calculated for the failure load at the time of failure.

Fracture toughness is a material attribute that reflects how sensitive a material is to cracks when subjected to static loading. This feature is used to calculate the residual strength of a cracked structure when it is subjected to static loading.

Experiments on fatigue crack growth also use the CT-specimen. The K-value of the CT-specimen equation is a curve fit to FE analysis data.

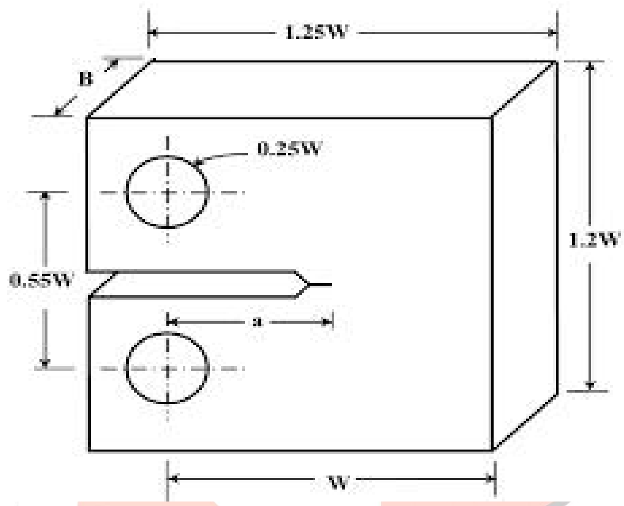


Figure 2: CT Specimen.

In fracture mechanics, the stress intensity factor (K) concept is extensively used to estimate the condition of stress (stress intensity) near the tip of a crack generated by an inaccessible load or residual stresses.

2. Calculation of stress intensity factor (SIF):

The relevant equation to compute the mode I SIF range for a CT specimen can take the following form, according to ASTM E399 International (Standard Test Method for Measurement of Fatigue Crack Growth Rates).

$K = (P/BW^{1/2}).f\,(a/W)$

Where

$$f(a/W) = \frac{(2+a/W)(0.886+4.64(a/W)-13.32(a/W)^2+14.72(a/W)^3-5.64(a/W)^4)}{(1-a/W)^{3/2}}$$

The above relation is valid for a/W >0.2 Notice that a single CT specimen was loaded in which SIF could be evaluated for several crack growth measurements. In the above equation P is load, W is the specimen width, B is the thickness and "a" distance between load line and the crack tip.

Let W= 25.4mm

B = 6.35mm

P = 10 N

For a crack length of 1mm

a/W= 0.0393

f(a/W) = 2.2719

K_I = 0.710 MPa √mm

Similarly for the crack length of a=2mm,3mm, 4mm, 5mm are tabulated below Table:1

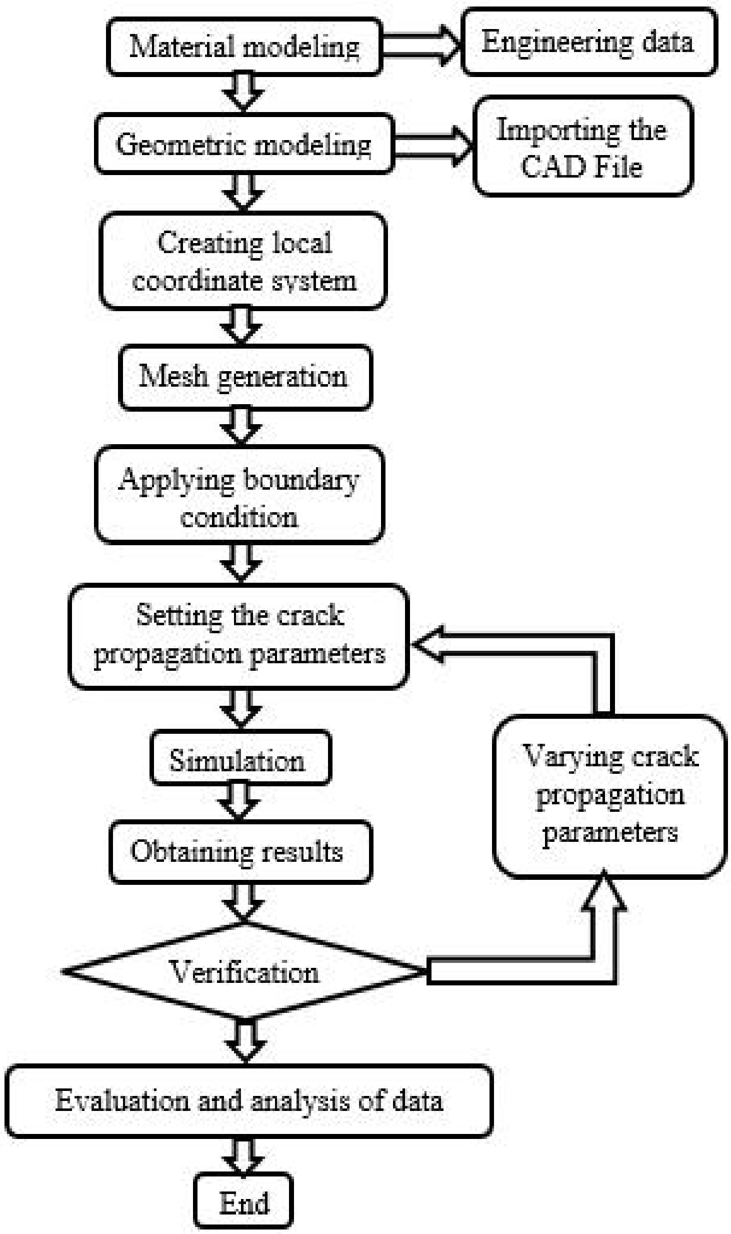
a in mm	K in MPa √mm

1	0.710
2	0.864
3	1.016
4	1.168
5	1.323

Table -1: calculated stress intensity factor for different crack length

3. Finite element analysis:

The methodology followed while doing analysis in FEA is as shown below flowchart.



3.1 CAD modeling:

By using the standard dimensions the CAD model of the CT specimen is created in the part design of the CATIA V5.the 3D cad model of the CT specimen is as shown in the figure 4.

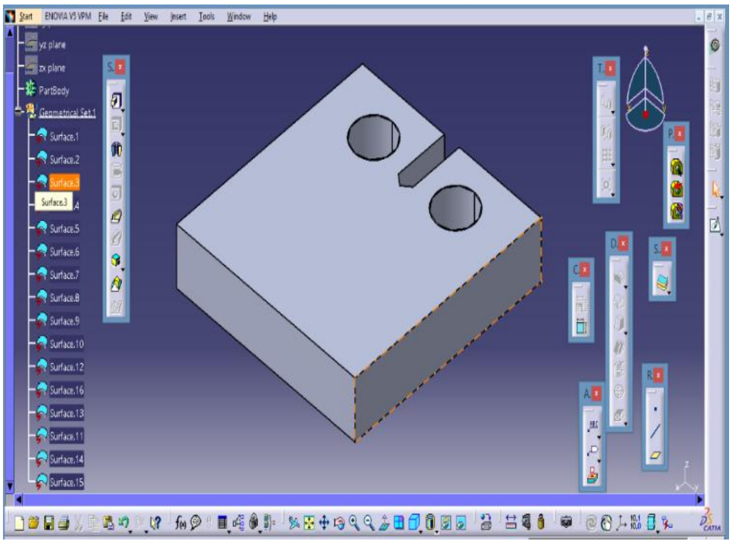


Figure 4: 3D CAD model of the CT specimen

Static structural analysis is used in the project work to fracture analysis of the CT specimen. Static structural analysis is used determine the stress, strains, deformation, displacements, forces and fracture criteria in the structure caused by the application of loads.

3.2 Coordinate system:

Coordinate systems is one of thing that is fundamental to Finite Element Analysis. The local coordinate system created at the tip of the crack on the CT specimen in as shown in the figure 5.

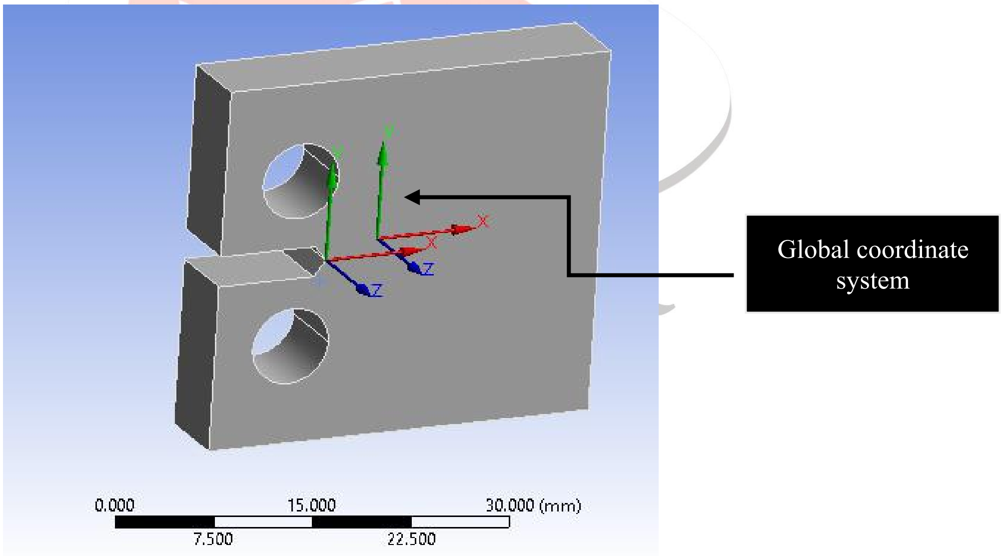


Figure 5: creating local coordinate system.

3.2 mesh generation:

Any continuous object has an infinite degree of freedom, making it impossible to solve the problem. The finite element approach uses discretization to reduce the degree of freedom from infinite to finite.
Meshing method used while doing the analysis is patch conforming meshing. In Ansys only tetrahedron elements are used to analyze the crack using premeshed crack as shown in Figure 6
The size of the element for the whole body: 1mm
The size of the element around the crack tip: 0.1mm

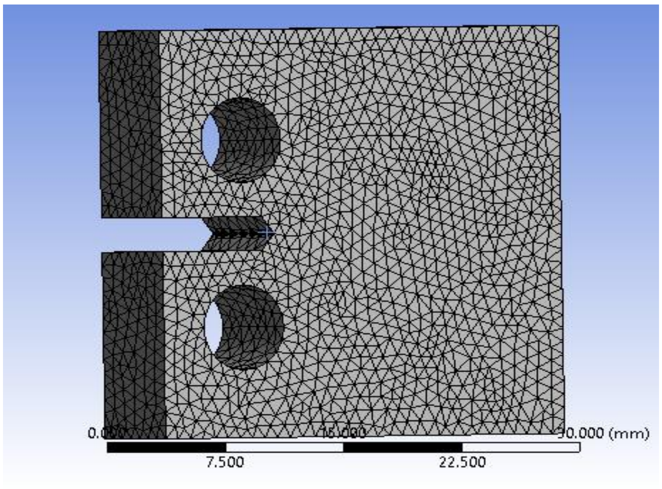


Figure 6: meshing of CT specimen using tetrahedron element

3.3 Applying the boundary condition:

Two boundary conditions applied in the analysis of the CT specimen.

1. fixed support : fixed support is applied on the faces of the lower hole (figure 7)
2. Force : force of 10N is applied on the surfaces of the top hole along the y-direction in vertically upwards(figure 8)

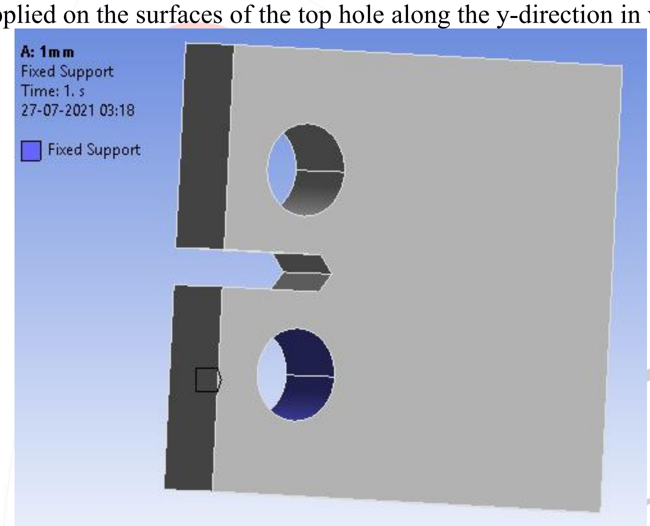


Figure 7: applying fixed support on the lower hole

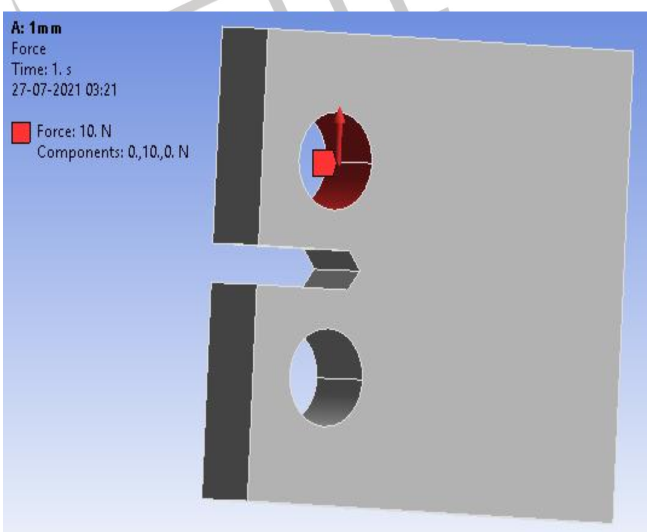


Figure 8: applying force on the upper hole

3.4 crack generation:

The CAD model of the CT specimen after applying the premeshed crack by selecting method as named selection and local coordinate system as shown in the figure 9.

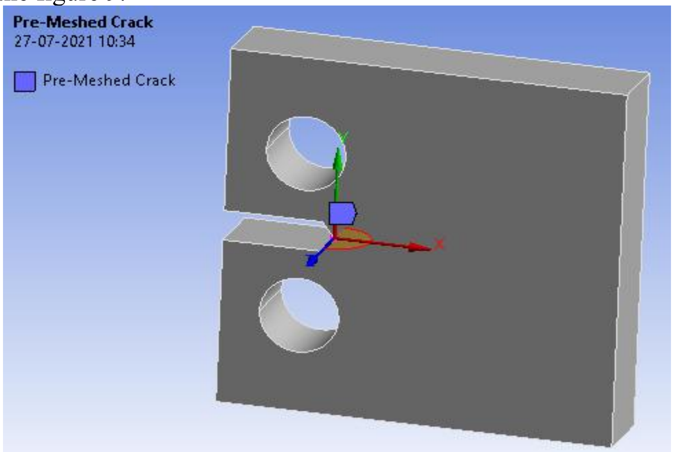


Figure 9: Pre-meshed crack of the CT specimen

4. RESULTS AND DISCUSSIONS:

4.1 Comparison of theoretical results with analysis results of structural steel.

Due to the application of boundary condition ie fixed support on the lower hole and force of 10N on the upper hole. The stress intensity factor for mode I generated at the crack front of the CT specimen of the premeshed crack is 0.799MPa √mm as shown in the below figure 10.

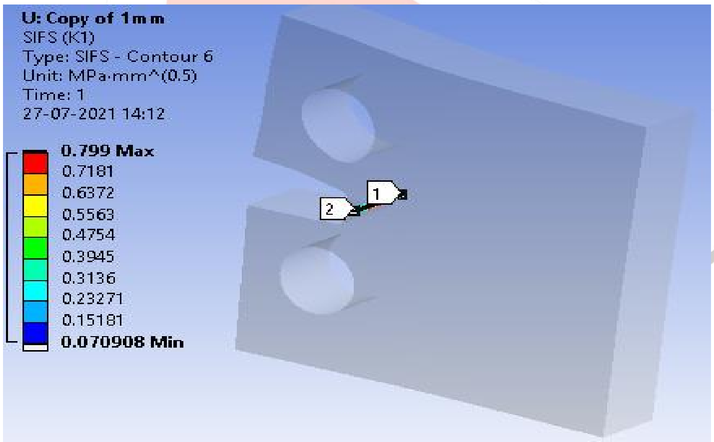


Figure 10: Stress Intensity Factor in the Structural Steel Specimen

By following the above procedure the stress intensity factor is obtained using Ansys workbench by varying the crack length and keeping the other parameters constant and it is seen that as the crack length increases SIF factor also increases .The comparison of stress intensity factor obtained by using empirical formula with analysis results obtained are tabulated below in table 2.The error between them is very less and shows the good argument for the present work.

a in mm	Theoretical SIF in MPa √mm	Analysis SIF in MPa √mm	Error in %
1	0.710	0.799	11.14
2	0.864	0.857	0.813648
3	1.016	0.928	9.546421
4	1.168	1.055	10.757
5	1.323	1.160	14.06251

Table 2: Comparison of SIF for 304 Structural steel obtained using theoretical Formula and Analysis

The below graph (figure 11) is plotted by taking stress intensity factor calculated using empirical formula and analysis for structural steel is plotted along y-axis and crack length is plotted along x-axis. From graph we can say that as crack length increases, SIF also increases and stress intensity factor value obtained using empirical formula and analysis are almost similar with least error.

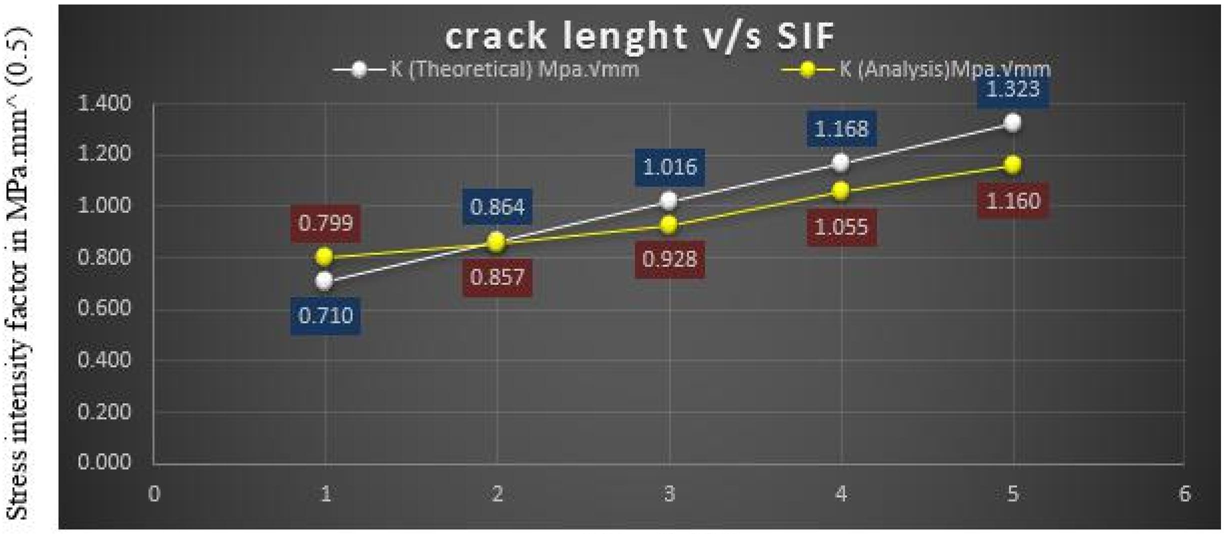


Figure 11 : graph plotted by taking crack length (a) v/s SIF

4.2 Comparison of theoretical results with analysis results of 304 stainless steel.

Due to the application of boundary condition ie fixed support on the lower hole and force of 10N on the upper hole. The stress intensity factor for mode I generated at the crack front of the CT specimen of the premeshed crack is 0.796MPa.√mm as shown in figure 12.

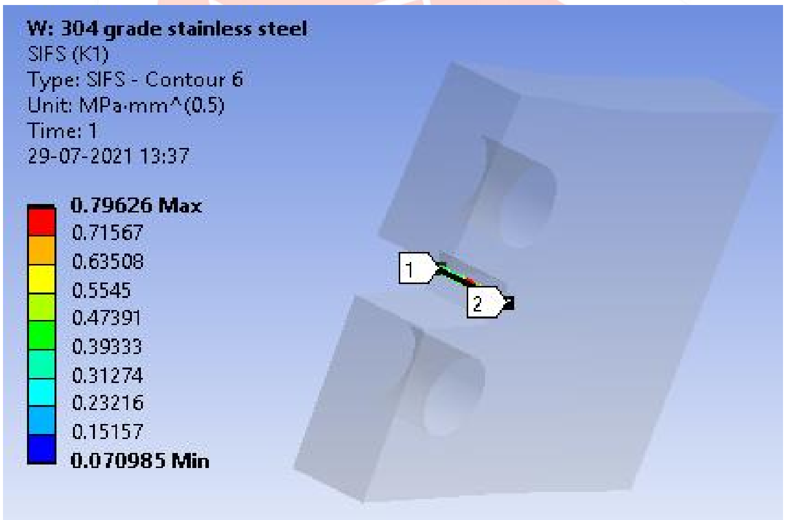


Figure 12: Stress Intensity Factor in 304 Stainless Steel Specimen

By following the above procedure the stress intensity factor is obtained using analysis by varying the crack length and keeping the other parameters constant and it is seen that as the crack length increases SIF factor also increases .The comparison of stress intensity factor obtained by using empirical formula with analysis results obtained are tabulated below in table 3.The error between them is very less and shows the good argument for the present work.

a in mm	Theoretical SIF in MPa √mm	Analysis SIF in MPa √mm	Error in %
1	0.710	0.796	10.81
2	0.864	0.8543	1.109
3	1.016	0.9243	9.926
4	1.168	1.052	11.073
5	1.323	1.1561	14.428

Table 3: Comparison of SIF for 304 Stainless Steel obtained using theoretical Formula and Analysis

The below graph (figure 13) is plotted by taking stress intensity factor calculated using empirical formula and analysis for stainless steel is plotted along y-axis and crack length is plotted along x-axis. From graph we can say that as crack length increases, SIF also increases and stress intensity factor value obtained using empirical formula and analysis are almost similar with least error.

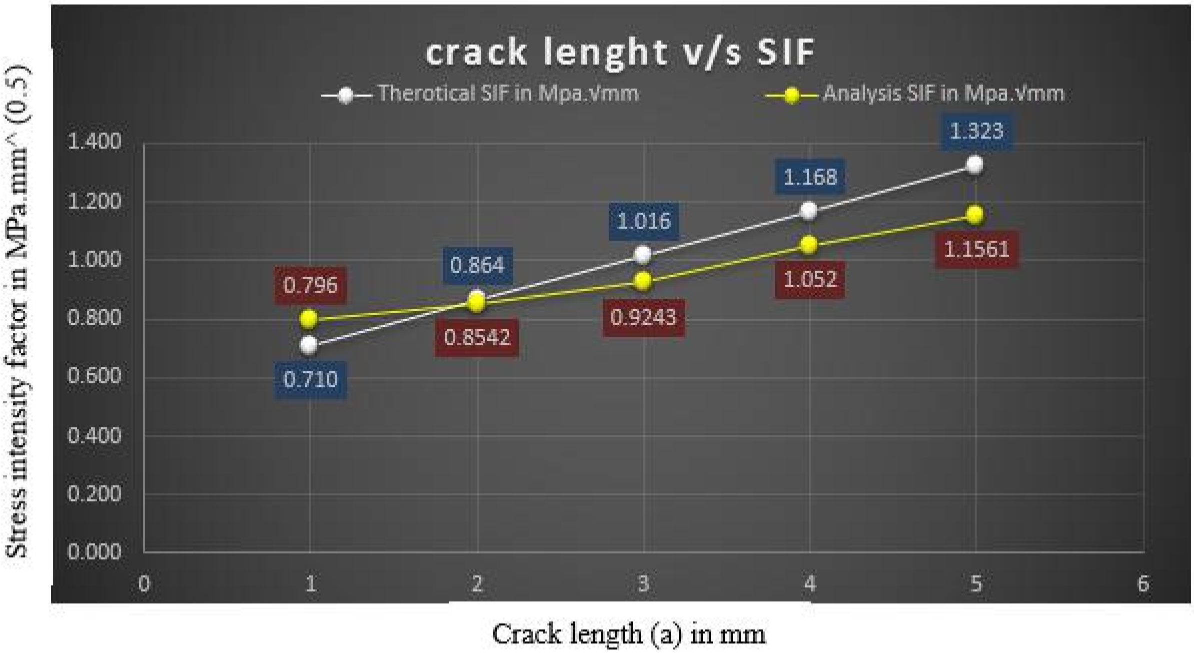


Figure 13: Graph Plotted by taking Crack Length (a) v/s Stress Intensity Factor

4.3 Comparison of stress intensity factor results of analysis for structural steel and 304 grade stainless steel.

According to the values of stress intensity factors from finite element analysis for structural steel and 304 grade stainless steel for same load and geometry, SIF values for 304 stainless steel is less than SIF values of structural steel as show in below table 4. Therefore from this we can say 304 grade stainless steel as less driving force to undergo fracture. Hence 304 stainless steel is preferred material for cryogenic pressure vessel.

a in mm	K in MPa √mm for structural steel	K in MPa √mm for 304 stainless steel	Difference
1	0.799	0.796	0.003
2	0.857	0.8542	0.003
3	0.928	0.9243	0.003
4	1.055	1.052	0.003
5	1.160	1.1561	0.004

Table 4: Comparison of SIF Results for Structural Steel and 304 grade Stainless Steel.

5. CONCLUSIONS

In present work it is aimed to calculate the stress intensity factor and characterizing the SIF of the structural steel and 304 stainless steel.

1. Stress intensity factor is calculated for the structural steel specimen using the empirical formula according to the ASTM E399 standard and analysis is shown in below table 2. It is observed from the result that the theoretical and analysis results are well within the limits and shows good argument for the present work.

By analysis of the structural steel specimen of crack length of 1mm the results for the von-mises stress (equivalent stress) is 1.7766MPa, The maximum principal stress is 2.3522 MPa total deformation is 9.00*10^-5 mm, directional deformation 5.3228*10^-5 mm, and stress intensity for the mode I is 0.799 MPa √mm. The maximum SIF obtained at the thickness of 3.2743mm.

2. Stress intensity factor is calculated for the stainless steel specimen using the empirical formula according to the ASTM E399 standard and analysis is shown in below table 3. It is observed from the result that the theoretical and analysis results are well within the limits and shows good argument for the present work

By analysis of the structural steel specimen of crack length of 1mm the results for the von-mises stress (equivalent stress) is 1.7723MPa, The maximum principal stress is 2.3415 MPa total deformation 9.3515*10^-5mm, directional deformation 5.5346*10^-5 mm, and stress intensity for the mode I is 0.796 MPa √mm .The maximum SIF obtained at the thickness of 3.2743mm.

3. By comparing results obtained for structural steel and 304 grade stainless steel done using empirical formula and analysis. As the values of von-mises stress, the maximum principal stress, total deformation, directional deformation, and stress intensity for the mode I for 304 grade stainless steel is less than structural steel. Therefore 304 stainless steel is preferred for cryogenic pressure vessel.

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