Modeling and Analysis of Fatigue Crack Growth in a Metallic pipe subjected to Internal Pressure

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Abstract : Fracture Mechanics is mechanics of solids containing planes of displacement discontinuities (crack) with special attention to their growth. It includes methods in which linear elastic fracture mechanics (LEFM) is a widely studied domain dealing with fracture growth sharp cracks in elastic bodies. This is made by assuming a small scale plastic zone region at the crack tip. This study is made to study the fatigue crack growth behavior of metallic components of ASTM standard and also analyze crack growth parameters like stress intensity factor and T-stress. Test specimens such as compact test specimen and semi elliptical crack specimen are used for predicting the fatigue crack growth with numerical approach and simulation results of these specimens are validated using analytical method. A metallic pipe with axial semi elliptical crack to simulate and predict the fatigue crack growth in a section metallic pressure vessel using ANSYS. The correlation and parametric studies are presented accordingly.

***IndexTerms* – Stress Intensity Factor, Fatigue Crack Growth, Linear Elastic Fracture Mechanics.**

I. INTRODUCTION

Fracture mechanics is the field of mechanics concerned with the study of the propagation of cracks in materials. It uses methods of analytical solid mechanics to calculate the driving force on a crack and those of experimental solid mechanics to characterize the material's resistance to fracture. In material science, fracture mechanics plays a vital role and it is an important tool used to improve the performance of mechanical components. There are three different approaches for a fracture mechanics and they are Linear Elastic Fracture Mechanics (LEFM), Elastic plastic fracture mechanics and Dynamic time dependent fracture mechanics. Concepts of Linear Elastic Fracture Mechanics is the main pillar to the present work. Linear Elastic Fracture Mechanics (LEFM) is the basic theory of fracture, is a highly simplified, yet sophisticated, theory that deals with sharp cracks in elastic bodies.

There are three ways to apply a force for crack to propagate, Mode I fracture – Opening mode (a tensile stress normal to the plane of the crack), Mode II fracture – Sliding mode (a shear stress acting parallel to the plane of the crack and perpendicular to the crack front) and Mode III fracture – Tearing mode (a shear stress acting parallel to the plane of the crack and parallel to the crack front).

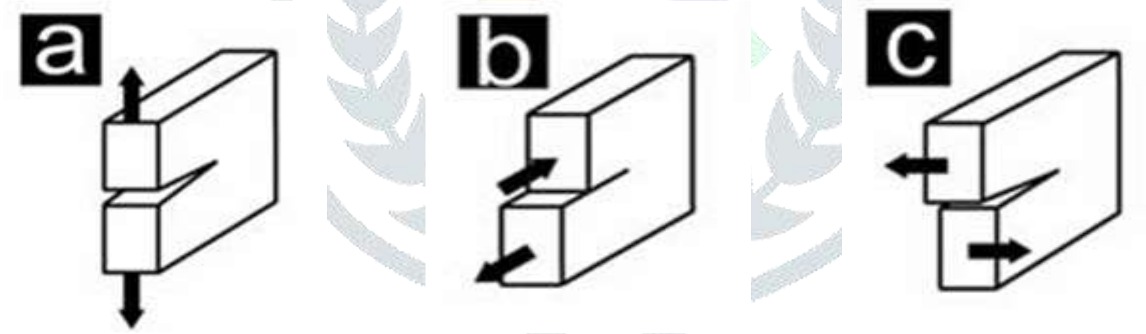

Figure. 1(a) Opening Mode Figure. 1(b) Sliding Mode Figure. 1(c) Tearing Mode

II. METHOD AND METHODOLOGY

Method:

Finite Element method: The Finite Element method is one of the numerical techniques used for obtaining approximate solution to variety of engineering problem. Some of the numerical methods are Finite Difference Method, Finite Element Method, Finite Volume Method, Mesh less Method and Boundary Element Method. Some of the typical problem areas of interest include structural analysis, heat transfer, fluid flow, mass transport and electromagnetic potential are solved using FEA (Finite Element Analysis). Steps involved in FEM are Division of Structure, Choosing of approximating function, Development of element stiffness matrix, Development of overall stiffness matrix, Development of element loading matrix, Development of overall loading matrix, Development of equilibrium equation, Inclusion of boundary condition, Calculation of nodal displacement and strain and stress. ANSYS workbench 17 is used in this present work.

Methodology:

Fatigue Crack Growth: Fatigue implies to a reducing strength of a material that is caused by repeated application of loads, which in turn results in progressive and localized damage in the material when subjected to cyclic loading. If the loads applied are above the threshold, than microscopic cracks will begin to form at grain interfaces in case of metals and with further increase of load or cycles, the crack will propagate to a larger extent and results in the failure of the structure. Micro structure, size effects, surface finish, frequency, residual stresses and environment condition are some of the factors which influence fatigue life of the components.

III. AIM AND OBJECTIVES

Aim

Modeling and Prediction of Fatigue Crack Growth in Metallic Standard test specimens and Metallic piping components subjected to cyclic loading.

Objectives:

1. Identification of ASTM standard Fracture study specimens with Experimental results through Literature Review.

2. Finite Element Modeling of the ASTM standard specimens using ANSYS Work Bench.

3. Simulation of ASTM standard specimens with prescribed loading and Boundary conditions

4. Determination of SIF's and Fracture Toughness for FE Models.

5. Validation of the simulation results with benchmarks.

IV. BENCHMARK AND VALIDATION

Problem 1: Compact Test Specimen

The specimen was modeled according to the ASTM E647 method as shown in figure 2 Initial crack length (a_n) was 3.54 mm and thickness of 4.85 mm and also edge radius (r_0) of 0.80 mm. The material used for analysis is 7075-T651 aluminum alloy. Young`s modulus is 71 GPa, Tensile ultimate strength is 552 MPa, Density is 2.78e3 kg/m3 and Poisson ratio is 0.33.

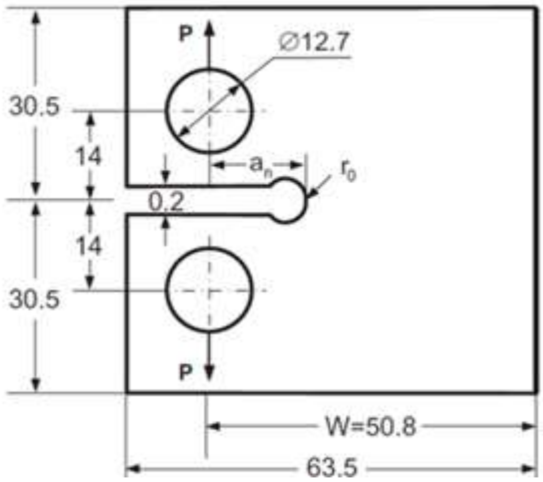

Figure. 2 Geometry of the model[1]

The specimen is modeled using CATIA V5R20 according to the dimensions given in journal paper [1] and FE analysis done using ANSYS workbench as shown in figure 2.

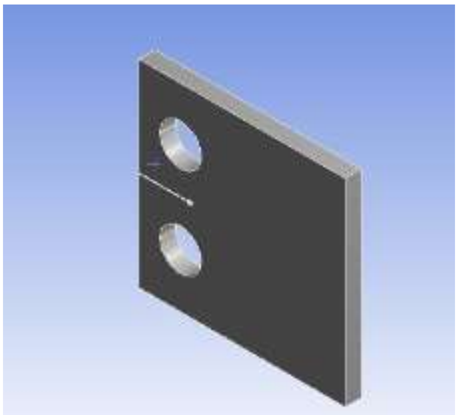

Figure. 3 FE model

The model is meshed by using quad element with a element size of 5mm as shown in figure 4. Hex20 (hexahedra) element is used near the crack tip. In order increase accuracy of the result at the crack tip, the elements are increased at the crack tip by decreasing the element size to 0.1mm at crack tip as shown in figure 5

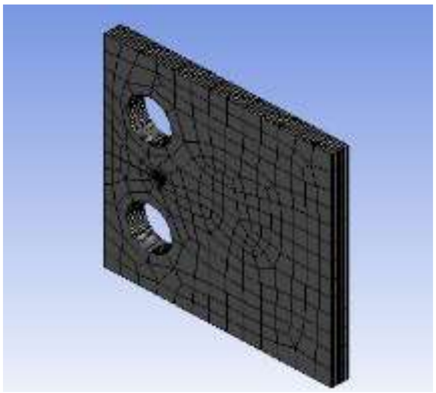

Figure. 4 Meshed model

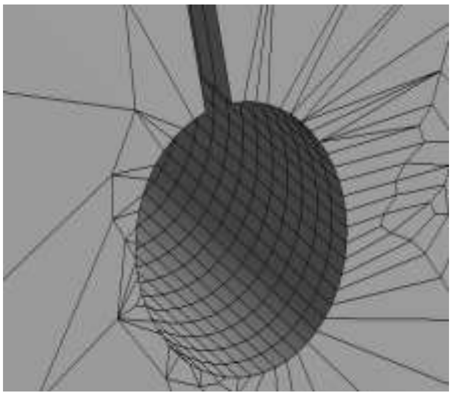

Figure. 5 Element size is reduced to 0.1 mm at crack tip

Crack inclusion is done near the tip of the crack as shown in figure 6. Boundary condition applied for compact tension specimen by applying fixed support at bottom of the hole and force of 2700 N is applied at upper hole of the specimen as shown in figure 7.

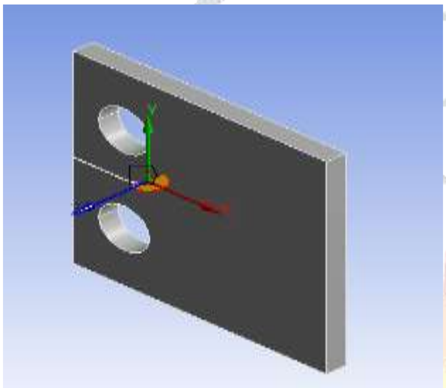

Figure. 7 crack inclusion at crack tip

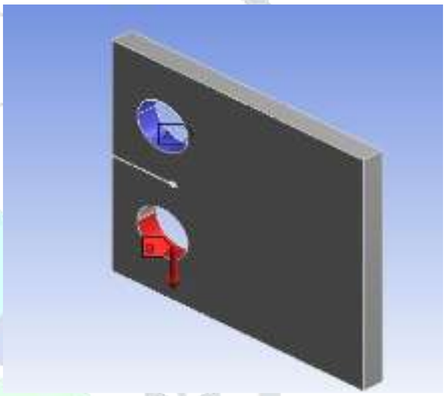

Figure. 8 Boundary conditions

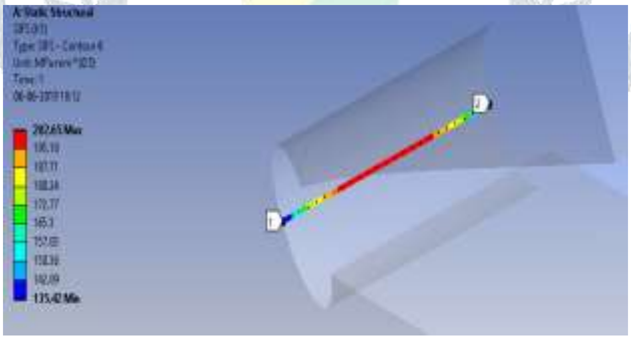

Figure. 9 Stress Intensity Factor for Compact Test Specimen

Figure 9: shows the maximun stress intensity factor for compact test specimen is 202.65 MPa$\sqrt{mm}$ through FE analysis.

Theoretical validation of compact tension specimen is made by taking the expressions from the journal paper of reference section[1]. Stress intensity factor is given by,

$$K= \frac{P(2+\xi)}{B\sqrt{W}(1-\xi)^{\frac{3}{2}}}(0.886 + 4.64\xi - 13.32\xi^2 + 14.72\xi^3 - 5.6\xi^4 \qquad (1)$$

Where, $\xi = \frac{a}{w}$

Crack length (a) = 3.54 mm
Thickness (B) = 4.85 mm
Width (W) = 50.80 mm
Force (P) = 2.7 KN

By substituting and simplification to main equation we get K= 206.96 MPa$\sqrt{mm}$.

Table 1 validatio of compact test specimen

Theoretical value of SIF	FEA value of SIF	Error
206.96 MPa$\sqrt{mm}$	202.65 MPa$\sqrt{mm}$	2%

Table 1: shows that, 2% of error is obtained after comparing theoretical and FEA value of stress intensity factor.

Problem 02 : Semi eliptical Crack Specimen

The specimen is modeled according to the geometry as shown in figure 10 from the journal paper which is mentioned in refernce section [2]. The length (L), width(W) and thickness of the specimen is 100mm, 50mm and 10mm respectively. The initial crack length along thickness and width is 3mm. The material used is 2219T851 aluminium alloy. Young`s modulus is 71 GPa and Poisson ratio is 0.33.

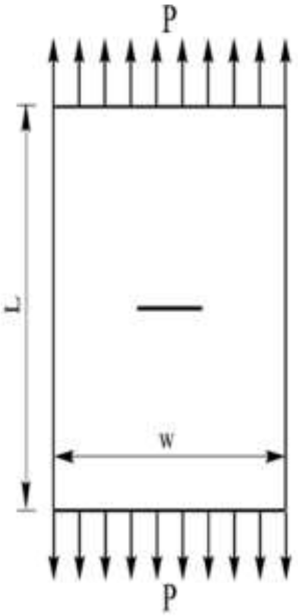

Figure. 10 Geometry of the model[2]

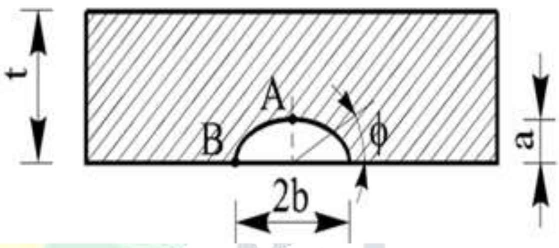

Figure. 11 Cross section of semi elliptical crack[2]

The specimen is modeled using CATIA V5R20 according to the dimensions given in journal paper [2] and FE analysis done using ANSYS workbench as shown in figure 12. Initially specimen is modeled without any crack in CATIA, later semi elliptical crack is inserted in ANSYS work bench.

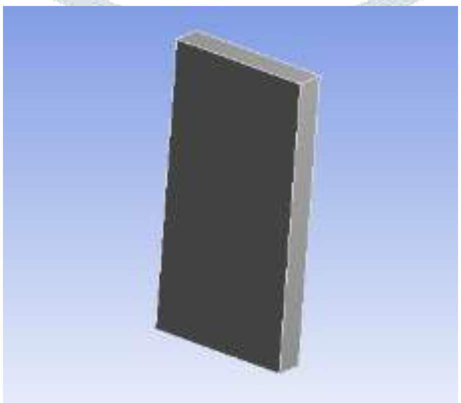

Figure. 12 FE model

The model is meshed using tetrahedron elements as shown in figure 13 and and the crack inclusion is given at the centre of the specimen along the thickness in x direction as shown in figure 14.

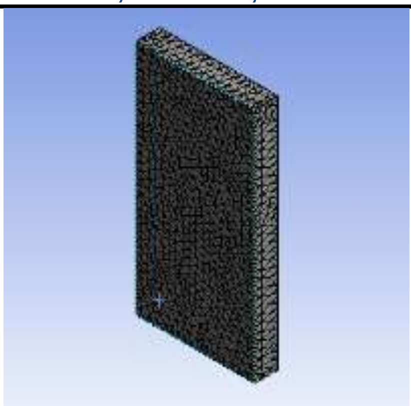

Figure. 13 Meshed model

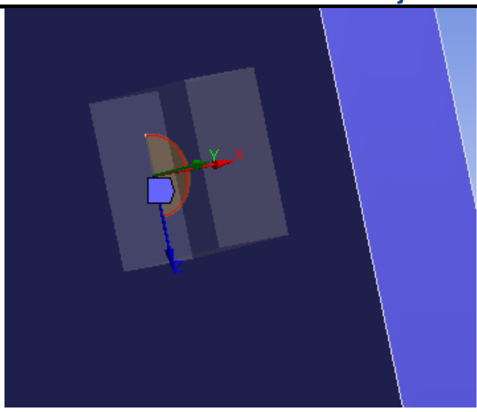

Figure. 14 Crack Inclusion

Boundary condition applied for semi eliptical crack specimen by applying a pressure of -100MPa at the upper face and lower face is fixed as shownmin figure 15.

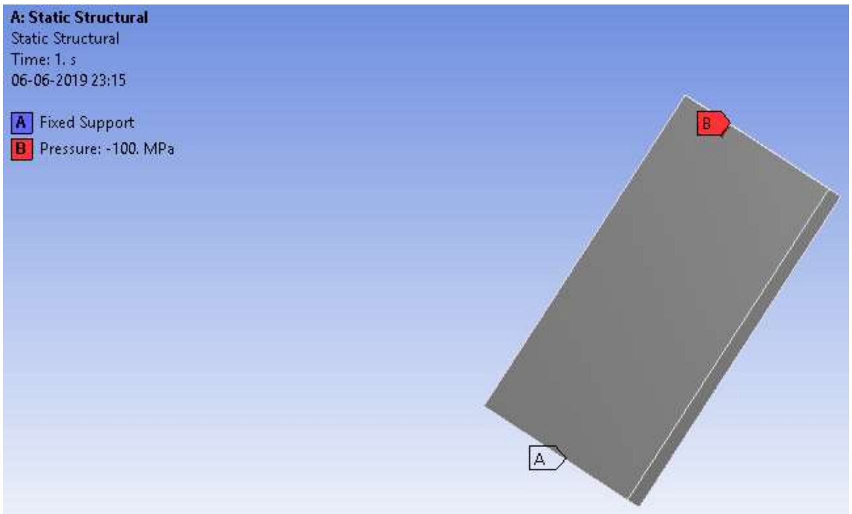

Figure. 15 Boundary Conditions

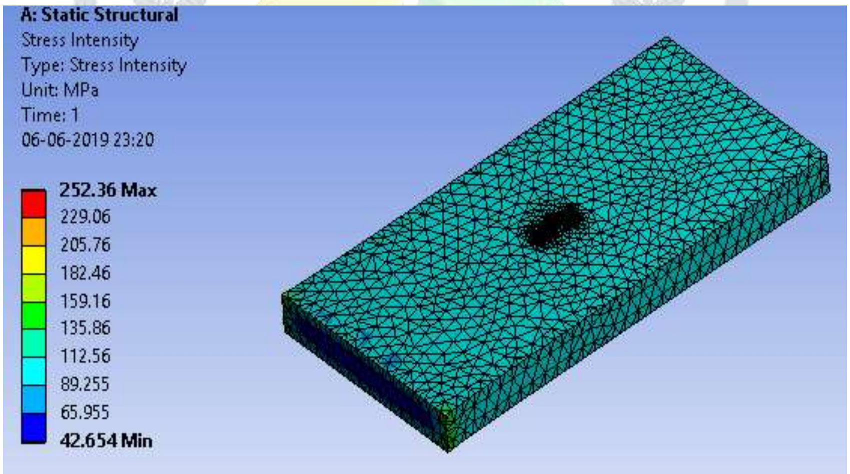

Figure. 16 Stress Intensity Factor for semi eliptical crack specimen

Figure 16 shows the maximun stress intensity factor for semi eliptical crack specimen is 252.36 MPa$\sqrt{mm}$ through FE analysis.

Theoretical validation of compact tension specimen is made by taking the expressions from the journal paper of reference section [2].

$$\Delta K = \Delta S\sqrt{\frac{\Pi a}{Q}} \times Me \qquad (2)$$

Where, ΔS = applied Stress range
Q = elastic shape factor
ΔK = Stress intensity factor range
a = crack length in the depth direction
Me = correction factor

$$Q = 1 + 1.47 \times \left(\frac{a}{b}\right)^{1.64} \qquad \left(\frac{a}{b} \le 1.0\right) \qquad (3)$$

b = crack length in the surface direction.

$$M_e = [M1 + (\sqrt{Q\frac{b}{a}} - M1)\times(\frac{a}{t})^p]f_w g \quad (4)$$

$$P=2+8(\frac{a}{b})^3 \quad (5)$$

$$M_1 = 1.13-0.1\frac{a}{b}, (0.02\leq \frac{a}{b} \leq 1.0) \quad (6)$$

f_w=finite width correction factor.

$$f_w = \sqrt{\frac{1}{\cos(\frac{\Pi b}{W})\sqrt{\frac{a}{t}}}} \quad (7)$$

$$g=1+(0.1+0.35(\frac{a}{t})^2)(1-\sin\phi) \quad (8)$$

Where g = geometrical correction and $\Phi = 90^0$

By substituting and simplification to main equation we get K=228.316 MPa$\sqrt{mm}$

Table 2 validation of semi eliptical crack specimen

Theoretical value of SIF	FEA value of SIF	Error
228.316MPa$\sqrt{mm}$	252.36MPa$\sqrt{mm}$	9.5%

Table 2 shows that, 9.5% of error is obtained after comparing theoretical and FEA value of stress intensity factor.

V. case study

For study purpose, pressurized hallow pipe, which is subjected to Fatigue Crack Growth (semi-elliptical crack) is taken. The study is made to find the stress intensity factor for two different materials i.e structural steel [3] and aluminum 7075-T6 [4]. The specimen is under the load of internal pressure, which is set to 3.5MPa [3] for a specific applications.

The figure 17 shows the geometry of both the materials having a length L=3000mm, internal radius Ri=1139.75mm and thickness t=19mm. The specimen is subjected to an internal pressure P_{int}=3.5MPa. Crack length is taken as c=10mm and crack depth is taken as a=5mm. The pipe length is reduced to 800mm in order to reduce the computational time. [3]

Properties of structural steel is Young's modulus (E) = 204.5 GPa, Poisson's ratio (ν) = 0.3. Properties of aluminum 7075-T6 is Young's modulus (E) = 71.7 GPa, Poisson's ratio (ν) = 0.33, Yield strength = 508 MPa, Density = 2810$\frac{kg}{m^3}$.[4]

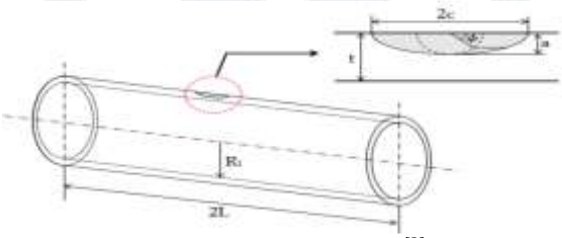

Figure. 17 Geometry of the model[3]

The specimen is modeled in CATIA V5R20 and FE analysis is done using ANSYS workbench. Figure 18 shows the length of the specimen as per the given parameters. Figure 19 shows the reduced length of the specimen in order to reduce the computational time.

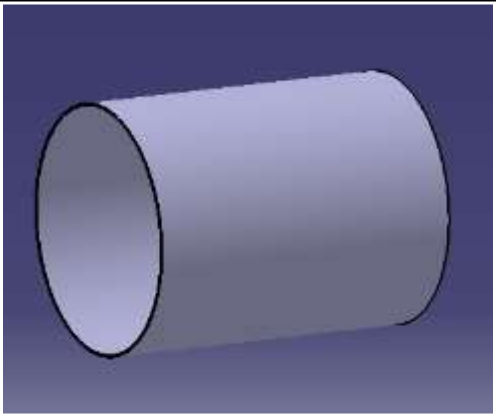

Figure. 18 FE model with L=3000mm

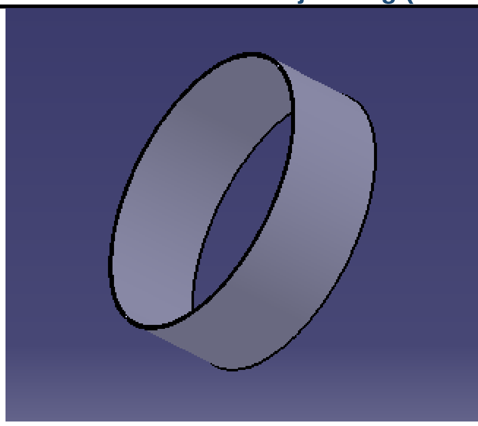

Figure. 19 FE model with L=800mm

The whole body is meshed with tetrahedrons elements as shown in figure 20 and the cracked portion is meshed with hexa-dominant elements as shown in figure 21 for accuracy in results.

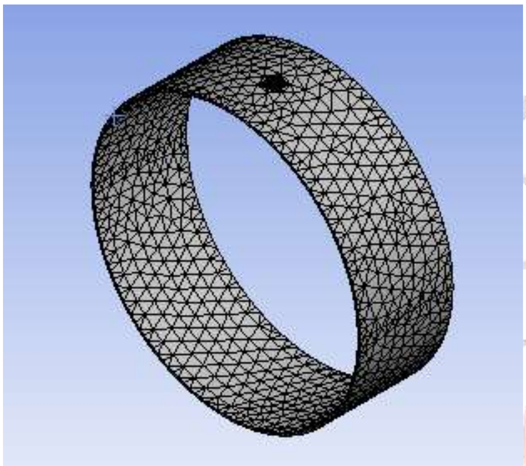

Figure. 20 Meshed model

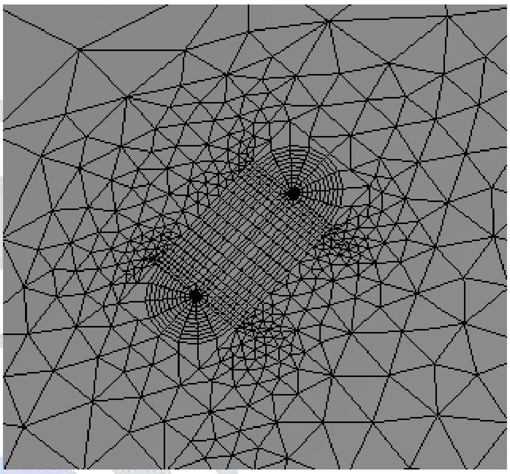

Figure. 21 Mesh at crack portion

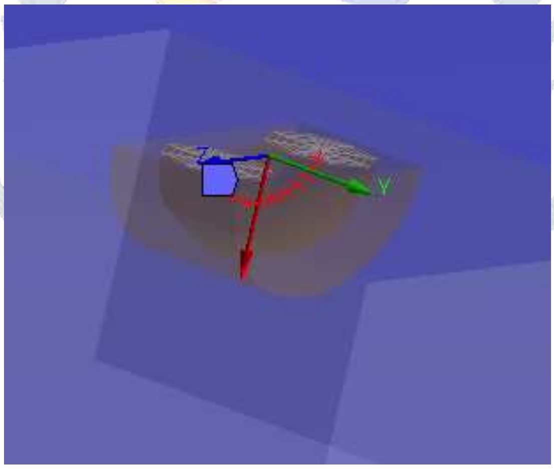

Figure. 22 Crack Inclusion

Boundary conditions applied internally by applying internal pressure of 3.5 MPa as shown in figure 23.

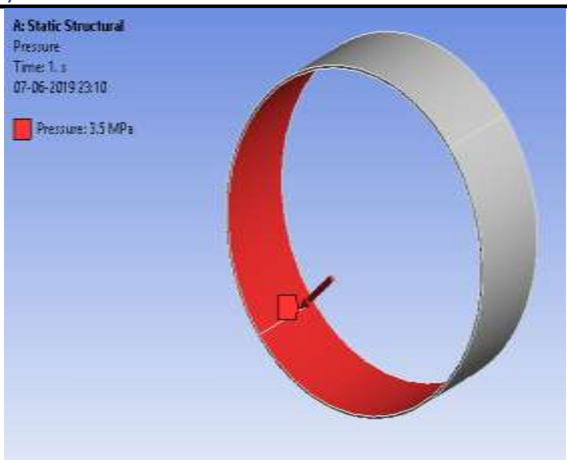

Figure. 23 Boundary Conditions

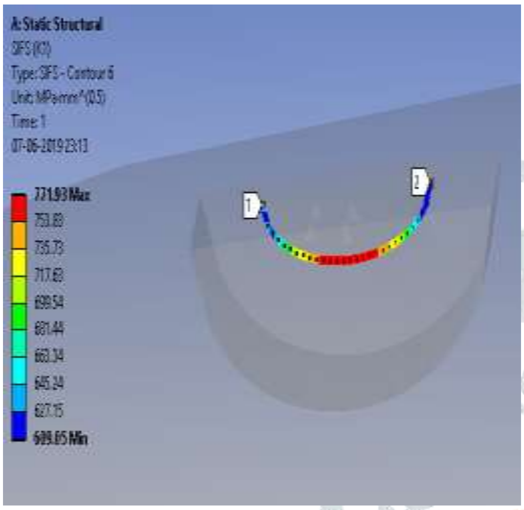

Figure. 24 Stress Intensity Factor for Strutural Steel

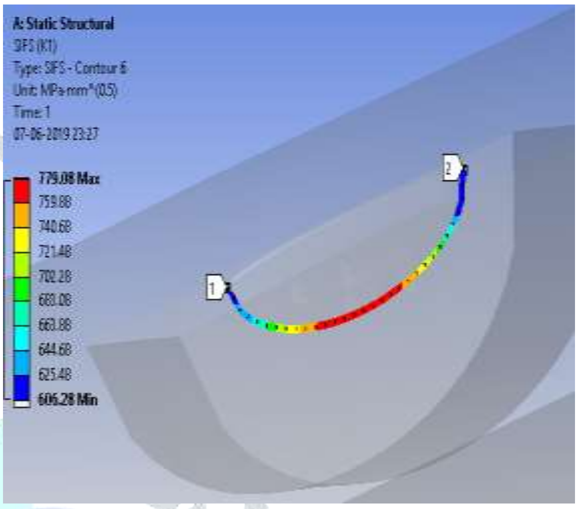

Figure. 25 Stress Intensity Factor for Aluminum 7075-T6

Figure 23 and figure 24 shows the maximum stress intensity factor structural steel and aluminum 7075-T6 respectively. Maximum stress intensity factor for structural steel is 771.93 MPa$\sqrt{mm}$, which gives good results when compared with the results obtained from a journal paper [3]. Later parametric study is made by varying crack length, crack depth and pressure to find stress intensity factor for both materials.

VI. Parametric study

1) The study made on structural steel, crack length of specimen kept constant c=10mm and crack depth 'a' is varied from 5mm to 11mm. Corresponding stress intensity factor is obtained for internal pressure of 3.5MPa through FE analysis. Figure 19 and figure 20 shows the geometric and FE model respectively.

Table 3 crack depth and SIF for structural steel

Crack Depth (a) in mm	**SIF in MPa$\sqrt{mm}$**
5	771.93
6	803.48
7	818.36
8	829.75
9	888.21
10	917.04
11	968.19

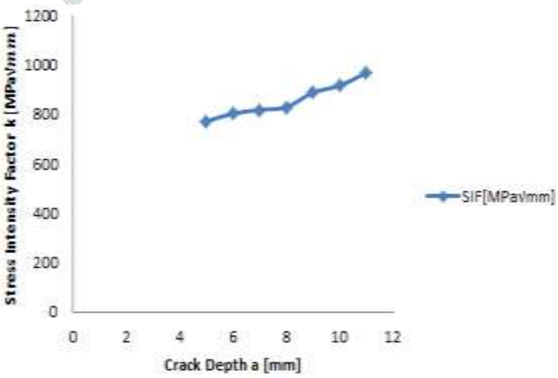

Figure. 26 Plot between crack depth and SIF

Table 3 shows the list of values of crack depth and corresponding stress intensity factors. Figure 26 shows a graph is drawn between crack depth and stress intensity factor. Graph clearly says that, as long as crack depth increases stress intensity factor also increases.

2) The study made on structural steel, crack depth of specimen kept constant a=5mm and crack length 'c' is varied from 10mm to 20mm. Corresponding stress intensity factor is obtained for internal pressure of 3.5MPa through FE analysis. Figure 19 and figure 20 shows the geometric and FE model respectively.

Table 4 crack length and SIF for structural steel

Crack Length (c) in mm	**SIF in MPa$\sqrt{mm}$**
10	771.93
11	797.65
12	815.16
13	825.73
14	833.8
15	850.08
16	858.56
17	869.28
18	873.57
19	892.25
20	901.17

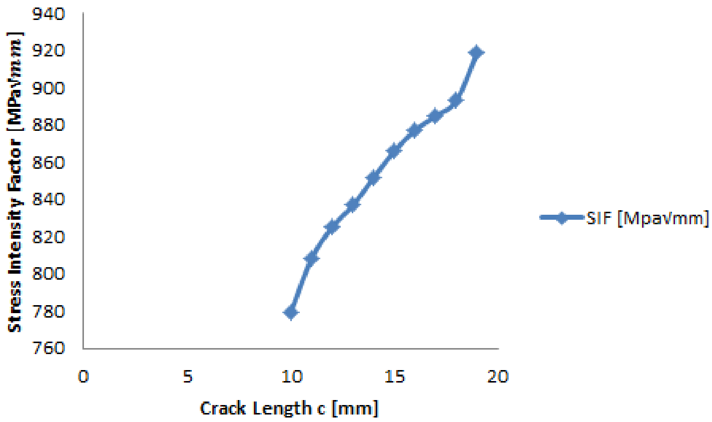

Figure. 27 Plot between crack length and SIF

Table 4 shows the list of values of crack length and corresponding stress intensity factors. Figure 27 shows a graph is drawn between crack length and stress intensity factor. Graph clearly says that, as long as crack length increases stress intensity factor also increases.

3) The study made on aluminum 7075-T6, crack length of specimen kept constant c=10mm and crack depth 'a' is varied from 5mm to 11mm. Corresponding stress intensity factor is obtained for internal pressure of 3.5MPa through FE analysis. Figure 19 and figure 20 shows the geometric and FE model respectively.

Table 5 crack depth and SIF for aluminum 7075-T6

Crack Depth (a) in mm	**SIF in MPa$\sqrt{mm}$**
5	779.08
6	809.17
7	823.55
8	828.60
9	887.88
10	920.01
11	966.13

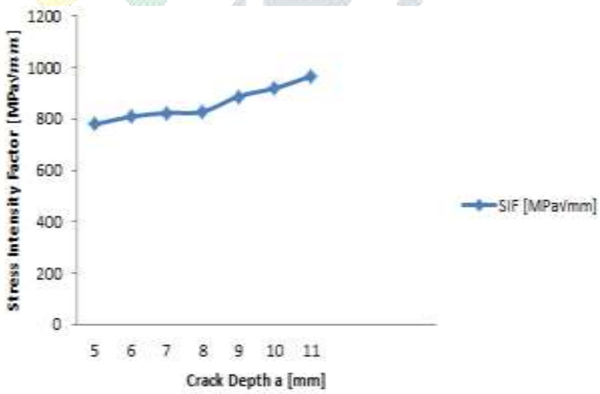

Figure. 28 Plot between crack depth and SIF

Table 5 shows the list of values of crack depth and corresponding stress intensity factors. Figure 28 shows a graph is drawn between crack depth and stress intensity factor. Graph clearly says that, as long as crack depth increases stress intensity factor also increases.

4) The study made on aluminum 7075-T6, crack depth of specimen kept constant a=5mm and crack length 'c' is varied from 10mm to 19mm. Corresponding stress intensity factor is obtained for internal pressure of 3.5MPa through FE analysis.

Table 6 crack length and SIF for aluminum 7075-T6

Crack Length (c) in mm	SIF in MPa$\sqrt{mm}$
10	779.08
11	808.21
12	825.12
13	836.88
14	851.76
15	865.98
16	877.29
17	884.89
18	893.29
19	919.02

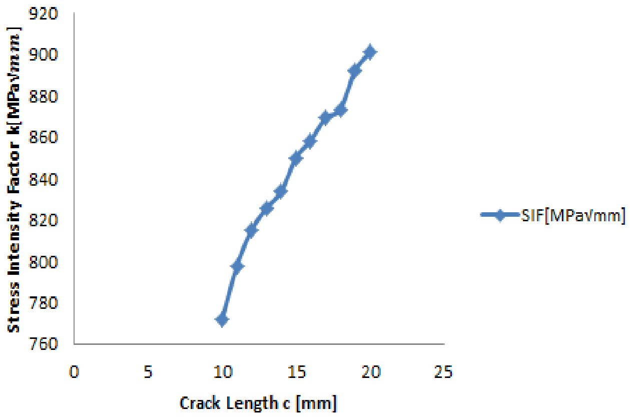

Figure. 29 Plot between crack length and SIF

Table 6 shows the list of values of crack length and corresponding stress intensity factors. Figure 29 shows a graph is drawn between crack length and stress intensity factor. Graph clearly says that, as long as crack length increases stress intensity factor also increases.

5) The study is made on structural steel, crack depth and crack length are made constant where internal pressure varied from 3.5MPa to 13MPa. Corresponding stress intensity factor is obtained through FE analysis. Figure 19 and figure 20 shows the geometric and FE model respectively.

Table 7 internal pressure and SIF for structural steel

Internal Pressure in MPa	SIF in MPa$\sqrt{mm}$
3.5	771.93
4	875.30
5	1094.10
6	1312.90
7	1531.80
8	1750.60
9	1969.40
10	2188.20
11	2407.10
12	2626.90
13	2844.70

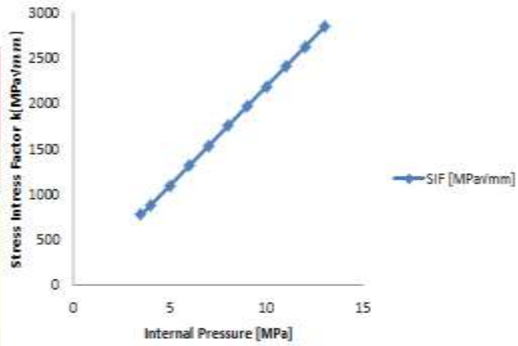

Figure. 30 Plot between internal pressure and SIF

Table 7 shows the list of values of internal pressure and corresponding stress intensity factors. Figure 30 shows a graph is drawn between internal pressure and stress intensity factor. Graph clearly says that, as long as internal pressure increases stress intensity factor also increases.

6) The study is made on aluminum 7075-T6, crack depth and crack length are made constant where internal pressure varied from 3.5MPa to 13MPa. Corresponding stress intensity factor is obtained through FE analysis. Figure 19 and figure 20 shows the geometric and FE model respectively.

Table 8 internal pressure and SIF for aluminum 7075-T6

Internal Pressure in MPa	SIF in MPa$\sqrt{mm}$
3.5	779.08
4	889.50
5	1111.90
6	1334.20
7	1556.60
8	1779
9	2001.40
10	2223.70
11	2446.10
12	2668.50
13	2890.90

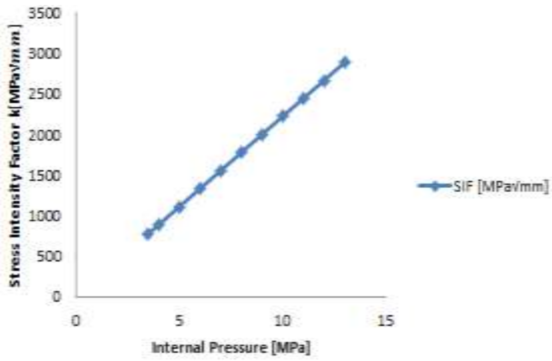

Figure. 31 Plot between internal pressure and SIF

Table 8 shows the list of values of internal pressure and corresponding stress intensity factors. Figure 30 shows a graph is drawn between internal pressure and stress intensity factor. Graph clearly says that, as long as internal pressure increases stress intensity factor also increases.

VII. RESULTS AND DISCUSSION

For benchmark and validation two specimens were taken, compact test specimen and semielliptical crack specimen. Finite element analysis was done for compact test specimen to find stress intensity factor, where the specimen is under fatigue crack growth. Analytical calculation is done to find the stress intensity factor by taking the equations from journal paper [1]. For the same geometry and boundary conditions FE analysis is done for compact test specimen. The SIF value by analytical calculation is 206.96MPa$\sqrt{mm}$ and the SIF value by FE analysis is 202.65MPa$\sqrt{mm}$. On comparison percentage error between analytical and FE analysis is 2%. Finite element analysis was done for semi elliptical crack specimen to find stress intensity factor, where the specimen is under fatigue crack growth. Analytical calculation is done to find the stress intensity factor by taking the equations from journal paper [2]. For the same geometry and boundary conditions FE analysis is done for compact test specimen. The SIF value by analytical calculation is 228.316MPa$\sqrt{mm}$ and the SIF value by FE analysis is 252.36MPa$\sqrt{mm}$. On comparison percentage error between analytical and FE analysis is 9.5%.

The study is made on pressure pipe which is subjected to semielliptical crack on the surface in axial direction. Geometry of the model, boundary conditions and results are taken from the journal paper [3] . Stress intensity factor is obtained through FE analysis. Comparison is made between the values given in the referred journal paper [3] and the values obtained through FE analysis. According to the paper stress intensity factor is 780MPa$\sqrt{mm}$ and according to FE analysis stress intensity factor is 771.93MPa$\sqrt{mm}$. Comparison gives the good results.

Parametric study is made on two materials, structural steel and aluminum 7075-T6 by varying crack length, crack depth and internal pressure to obtain stress intensity factor. For structural steel, by keeping crack length c=10mm and internal pressure P_{int}=3.5MPa and by varying crack depth 'a' from 5mm to 11mm stress intensity factor is obtained. Minimum SIF is found at crack depth 5mm is 771.93MPa$\sqrt{mm}$ and maximum SIF is found at crack depth 11mm is 968.19MPa$\sqrt{mm}$. By keeping crack depth a=5mm and internal pressure P_{int}=3.5MPa and by varying crack length 'c' from 10mm to 20mm stress intensity factor is obtained. Minimum SIF is found at crack length 10mm is 771.93MPa$\sqrt{mm}$ and maximum SIF is found at crack length 20mm is 901.17MPa$\sqrt{mm}$. Stress intensity factor increases with increase in crack length and crack depth.

For aluminum 7075-T6, by keeping crack length c=10mm and internal pressure P_{int}=3.5MPa and by varying crack depth 'a' from 5mm to 11mm stress intensity factor is obtained. Minimum SIF is found at crack depth 5mm is 779.08MPa$\sqrt{mm}$ and maximum SIF is found at crack depth 11mm is 966.13MPa$\sqrt{mm}$. By keeping crack depth a=5mm and internal pressure P_{int}=3.5MPa and by varying crack length 'c' from 10mm to 19mm stress intensity factor is obtained. Minimum SIF is found at crack length 10mm is 779.08MPa$\sqrt{mm}$ and maximum SIF is found at crack length 20mm is 919.02MPa$\sqrt{mm}$. Stress intensity factor increases with increase in crack length and crack depth.

For structural steel, by keeping crack length c=10mm and crack depth a=5mm and by varying internal pressure 'P_{int}' from 3.5MPa to 13MPa stress intensity factor is obtained. Minium SIF is found at internal pressure 3.5MPa is 771.93MPa$\sqrt{mm}$ and maximum SIF is found at internal pressure 13MPa is 2844.70MPa$\sqrt{mm}$. For aluminum 7075-T6, by keeping crack length c=10mm and crack depth a=5mm and by varying internal pressure 'P_{int}' from 3.5MPa to 13MPa stress intensity factor is obtained. Minium SIF is found at internal pressure 3.5MPa is 779.08MPa$\sqrt{mm}$ and maximum SIF is found at internal pressure 13MPa is 2890.9MPa$\sqrt{mm}$. Stress intensity factor increases with increase in internal pressure.

VIII. CONCLUSION AND FUTURE WORK

Conclusion

Predication of stress intensity factor and fatigue crack growth for standard test specimens has been carried out. Finite Element Analysis results are good argument with theoretical values. Case study has been made on pressure vessel, Finite Element Analysis result is in good argument with the values taken from referred journal papers. Parametric study is done on pressure vessel using ANSYS workbench software, which gives knowledge how stress intensity factor varies with crack depth, crack length and internal pressure.

Future Work

Numerical analysis on Elliptical crack, arbitrary crack and angle crack by using ANSYS workbench and AFROW software. Analysis on circumferential crack on pressure vessel. Multiple crack growth analysis on pipe and pressure component. Cyclic fracture studies on welded straight pipes and elbow pipes.

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