Journal of Engineering Research and Application www.ijera.com
ISSN : 2248-9622, PP 36-46

RESEARCH ARTICLE OPEN ACCESS

Fatigue Crack Growth Prediction of a Semi-Elliptical Surface Crack in Pressure Vessel using AFGROW

Vinay K*, Manjunath S. B**
**(Post Graduate Student, Department of Mechanical Engineering,Dayananda Sagar College of Engineering, Bangalore, Karnataka-560078, India.*
*** (Assistant Professor, Department of Mechanical Engineering,Dayananda Sagar College of Engineering, Bangalore, Karnataka-560078, India.*

ABSTRACT : *Fracture mechanics is the field of mechanics concerned with the study of the propagation of cracks in materials. The analysis of crack growth is one of the key problems in safety evaluation of industrial components subjected to cyclic loading. Different approach for fracture mechanics are Linear Elastic Fracture Mechanics, Elastic Plastic Fracture Mechanics and Dynamic time dependent fracture Mechanics. Linear Elastic Fracture Mechanics (LEFM) method is used in present study mainly based on the assumption of small scale yielding condition. This is expressed by means of two parameters, the stress intensity factor and the T stress. If the loads are above a certain threshold, microscopic cracks will begin to form at the surface. Eventually a crack will reach a critical size, and the structure will suddenly fracture. To predict the fatigue crack growth with numerical approach, ASTM standard fracture test specimens viz., compact tension specimen, semi-elliptical crack specimen and single edge notch specimen are simulated and its fatigue crack growth is predicted and validated using analytical method. Further, the approach is applied to simulate and predict the fatigue crack growth on an axial semi-elliptical surface crack in a section metallic pressure vessel using AFGROW.*

Keywords– *Crack length,Fatigue crack growth, Pressure vessel,Stress intensity factor, Semi-elliptical crack.*

I. INTRODUCTION

Many investigations have shown that sudden failures of aircraft components, pressure vessels or pipeline systems might occur due to presence of surface cracks. Potential sources of these cracks are material defects or geometric discontinuities i.e. zones where stress increase happens. These zones, known as local stress concentrations, are regions where the points with an extremely high magnitude of stresses could appear. These points are areas where cracks are most often initiated and later propagate under cyclic loadings. Fatigue process consists of three stages, initiation and early crack propagation, subsequent crack growth, and final fracture Due to previous reasons the ability to assess the effects of thesedefects on structural integrity under fatigue and fracture loadings is of much practical significance.

The basic parameter that should be defined when formulating computational models is a shape of the flaw i.e. initial crack. One of the most common flaws found in structural components is a part-through surface flaw. These flaws could most often be approximated and analyzed as a semi-elliptical crack. For the assessment of fracture strength and residual fatigue life for defects contained in structures, or for damage tolerance analysis recommended to be performed at the stage of structure design, the important aspect is the calculation of the stress intensity factor.

Yanyao Jiang et al. [1] presented an investigation on both standard and non-standard compact specimen to determine the fatigue crack growth behavior of 7075-T651 aluminum alloy experimentally in normal environment condition. The effect of the stress ratio on the crack growth was studied with overloading and under loading. From the experiment they observed relationship between da/dN and ΔK are practically independent of the geometry and also the size of the specimen.

SlobodankaBoljanovie [2] made an investigation on estimating the fatigue crack growth behavior on the finite plate having semi-elliptical crack which is subjected to cyclic tensile loading. The Stress intensity factor was obtained by applying analytical and numerical methods. The analytical results were compared with experimental results and it has shown good results.

K. Ray et al. [3] presented a methodology to determine the fatigue crack growth rate curves without integration of it. Exponential model has been used to predict the crack growth. The model provided a good agreement with experimental data. \

P. Kannana et al [4] has carried out the work on determining the leak pressure prior to failure, having axial semi elliptical crack with crack length four times to that of thickness value which represent a typical crack length of tested cylinder specimen. Theoretical results of fracture pressure were validated with experimental results. With the maximum plane strain fracture toughness, leak pressure is obtained.

II. BENCHMARK

For benchmark or validation, three test specimens are taken from journals paper of references section of [1], [2] and [3] which are compact tension, semi elliptical crack specimen and single edge notch specimen. As it is necessary to find stress intensity factor which represents the stress state at crack tip which is very important factor in fracture mechanics ANSYS workbench 17 is used for it.For better feasibility of modeling standard test specimens CATIA V5 is used. The standard test specimens were modeled in CATIA and then imported to ANSYS workbench. A stress intensity factor result which is obtained from ANSYS workbench is validated with the theoretical results. The theoretical formulas used for validation are again taken from same journals paper of stated above reference section. Air Force Crack Growth(AFGROW) software is used for finding the fatigue crack growth of standard test specimens by using geometrical similarity model which are inbuilt in the AFGROW software.

1.1 Compact tension specimen

The specimen was modeled according to the ASTM E647 method as shown in figure 1. Initial crack length (a_n) was 3.54mm and thickness of 4.85mm and also edge radius (r_0) of 0.80mm. The material used for analysis is 7075-T651 aluminum alloy. Young`s modulus is 71GPa and Poisson ratio is 0.33.

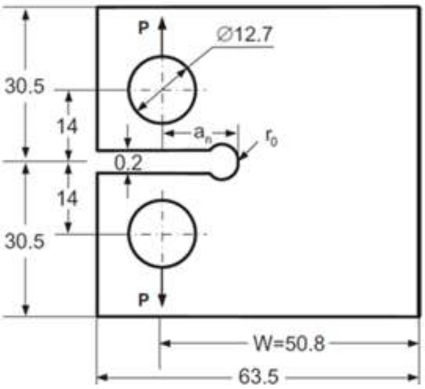


Fig.1 Dimension of compact tension specimen.

Meshed model of compact tension specimen shown in figure 2 having element size 5mm as global mesh. 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.

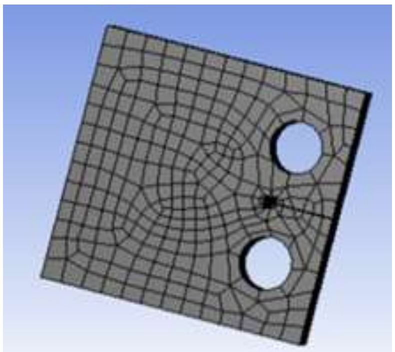


Fig.2 Meshed model of compact tension specimen.

Boundary condition applied for compact tension specimen by applying fixed support at bottom of the hole and force applied at upper hole of the specimen, force applied is of 2700N as shown in figure 3

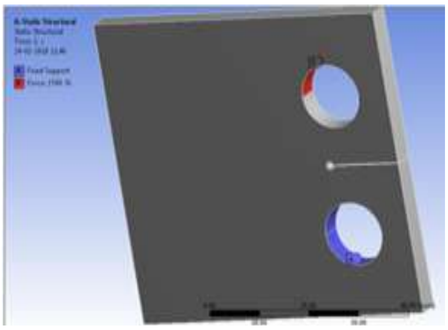


Fig.3 Boundary condition.

Figure 4 shows the value of stress intensity factor of compact tension specimen, maximum value is of 204.66MP$\sqrt{mm}$ and minimum value is of 133.25MPa$\sqrt{mm}$.

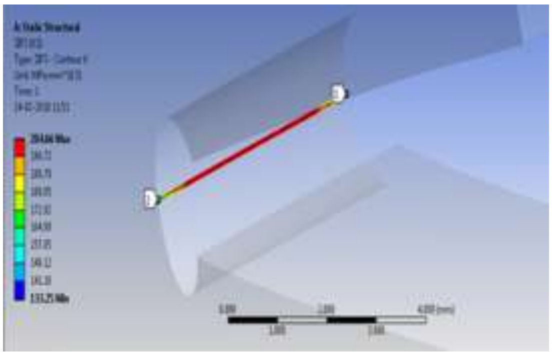


Fig.4 Stress intensity factor of compact tension specimen.

Theoretical validation of compact tension specimen is made by taking the expressions from the journalpaper of reference section [1].

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

K= Stress intensity factor
P= applied load
Crack length to width ratio (ξ) = a/w
a= Crack length
w =Width
B= thickness

By substituting and simplification to main equation we get K= 206.96MPa$\sqrt{mm}$ and the difference (error) between theoretical value and ANSYS result is of 1.11%.

Fatigue crack growth is determined using Air Force Crack Growth (AFGROW) software which is subjected to load ratio of 0.1. Figure 5 shows the graph of crack length v/s number of cycle up to failure and finial crack length along width direction is of 0.0494m.Where da/dN is crack growth rate and ΔK is stress intensity factor range.

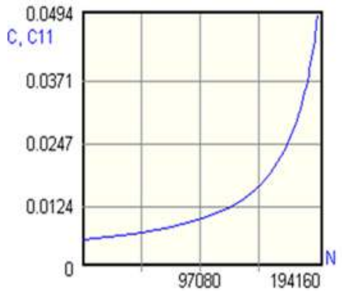


Fig. 5 Crack length verses number of cycles.

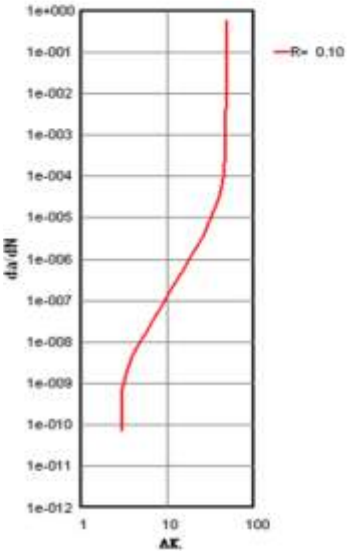


Fig. 6 Crack growth rate.

Figure 6shows the crack growth of compact tension specimen and graph is plotted log da/dN verses logΔK for a load ratio of 0.1.

1.2 Semi-elliptical crack

The figure 7 shows geometry of semi elliptical crack having length (L) 100mm, width (W) of the specimen is 50mm and thickness (t) is of 10mm. The initial crack length along thickness and width direction is 3mm. The material used for analysis is 2219T851 aluminum alloy. Young`s modulus is 71GPa and Poisson ratio is 0.33.The semi-elliptical crack specimen was modeled using CATIA without any crack inserted to the model, the crack is inserted in ANSYS workbench with the selection of semi-elliptical (not a pre-meshed crack). a/2b ratio is equal to 1, that is crack length in thickness direction (a) to the width direction(2b) ratio is equal to 1.

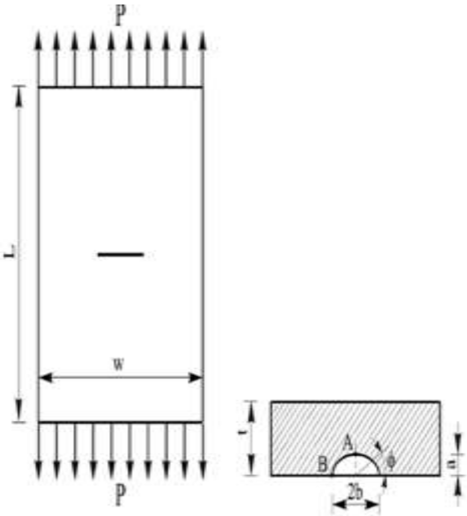


Fig. 7 Geometry of semi elliptical crack.

Tet 10(Tetrahedron element) is used to mesh the specimen having element size 1mm. Figure 8 shows the boundary condition applied to specimen by applying upper face of the specimen with the pressure of -100MPa and lower face is fixed.

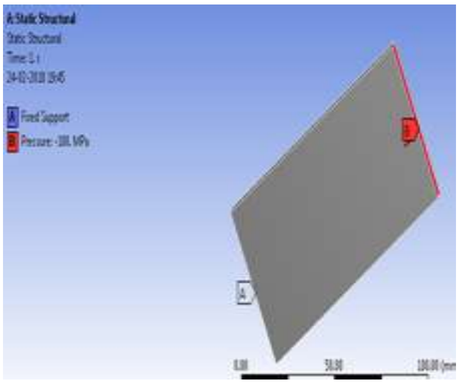


Fig. 8 Boundary condition.

Figure 9 shows the value of stress intensity factor for semi elliptical crack specimen having maximum value of $226.6\text{MPa}\sqrt{\text{mm}}$ and minimum value of $203.89\text{MPa}\sqrt{\text{mm}}$

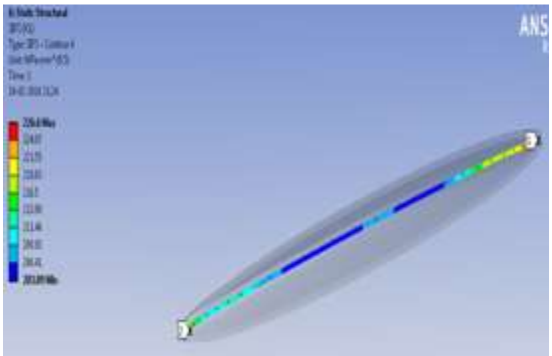


Fig. 9 Stress intensity factor of semi elliptical specimen.

Theoretical validation of semi elliptical crack specimen is made by taking the expressions from the journal paper of reference section [2].

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

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

$$Q = 1 + 1.47 \times (\tfrac{a}{b})^{1.64} \quad (\tfrac{a}{b} \leq 1.0) \qquad (3)$$

b = crack length in the surface direction

$$M_e = [\,M_1 + (\sqrt{Q\tfrac{b}{a}} - M_1) \times (\tfrac{a}{t})^{P}]f_w g \qquad (4)$$

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

$$M_1 = 1.13 - 0.1\tfrac{a}{b}, \left(0.02 \leq \tfrac{a}{b} \leq 1.0\right) \qquad (6)$$

The term f_w is the finite width correction factor

$$f_w = \sqrt{\frac{1}{\cos\left(\frac{\pi b}{w}\sqrt{\frac{a}{t}}\right)}} \qquad (7)$$

The expression for g is given by

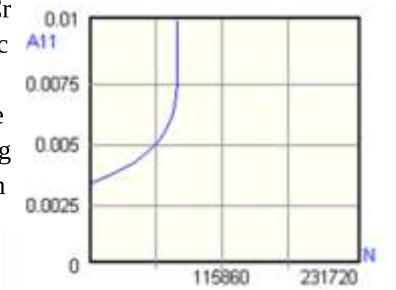
$$g = 1 + (0.1 + 0.35(\tfrac{a}{t})^2)(1 - \sin\phi) \qquad (8)$$

$\phi = 90^0$
Where g = geometrical correction

By substituting and simplification to main equation we get K= $228.316\text{MPa}\sqrt{\text{mm}}$ and the difference (error) between theoretical value and ANSYS result is of 0.7515%.From the ANSYS result stress intensity factor is higher at crack end. So that crack propagation is higher along width direction than along thickness direction for the above loading condition and geometrical dimension of the semi elliptical crack specimen.

Fatigue crack growth of semi elliptical specimen is determined with the load ratio of 0. The crack growth was seen in both the thickness and width direction. Figure 10 and 11 shows crack length for both thickness (A) and also for width direction(C). Finial crack length along thickness was 0.01m and crack length along width direction was 0.0169m. Fatigue crack growth is determined by using NASGRO equation.

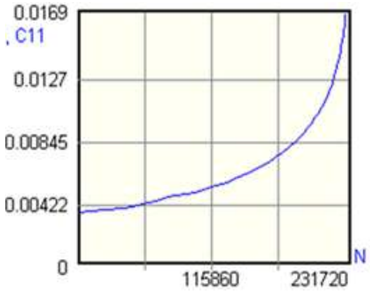
Crack length



Number of cycle

Fig.10 Crack length along thickness verses number of cycles.

Crack length in m

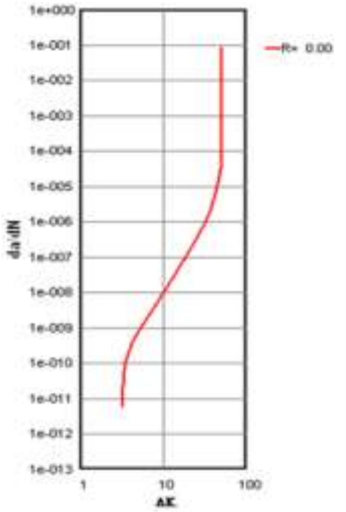


Number of cycle

Fig.11 Crack length along width verses number of cycles.

The figure 12 shows the fatigue crack growth of semi elliptical specimen having crack length of 3mm in width direction and 3mm along thickness direction.

da/dN in m/cycle



ΔK in $\text{MPa}\sqrt{\text{m}}$

Fig.12 Crack growth rate.

1.3 Single edge notch specimen

The figure 13 shows single edge notch specimen geometry having thickness of 6.5mm and initial crack length of 17.75mm. The material used for analysis is 2024T3 aluminum alloy. Young`s modulus is 73100MPa and Poisson ratio is 0.33. The Model of single edge notch specimen was modeled using CATIA with crack inserted in the model. Crack is defined in ANSYS workbench with the pre-meshed option.

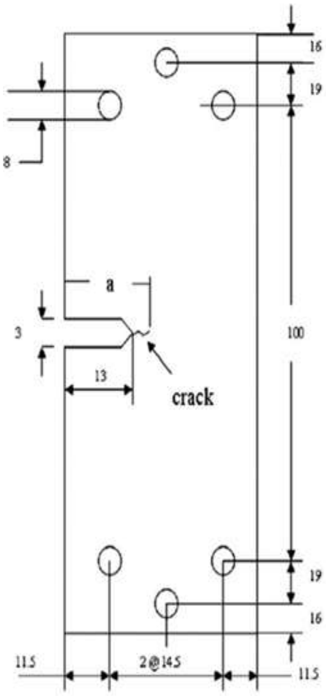


Fig.13 Geometry of single edge notch crack.

Tet 10(Tetrahedron element) is used to mesh the specimen having element size 1mm. The upper face of the specimen is applied with the pressure of -21.3MPa (tensile loading) and lower face is fixed. In order to increase the accuracy of stress intensity factor result element size near crack tip is reduced to 0.1mm so that element are more at the crack tip.

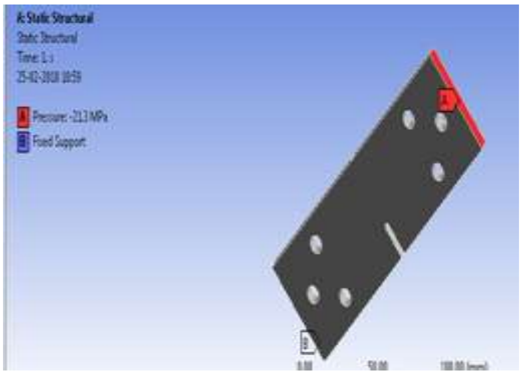


Fig.14 Boundary condition.

Figure 15 shows the value of stress intensity factor for single edge notch, having maximum value of 288.44MPa$\sqrt{\text{mm}}$and minimum value is 204.94MPa$\sqrt{\text{mm}}$.

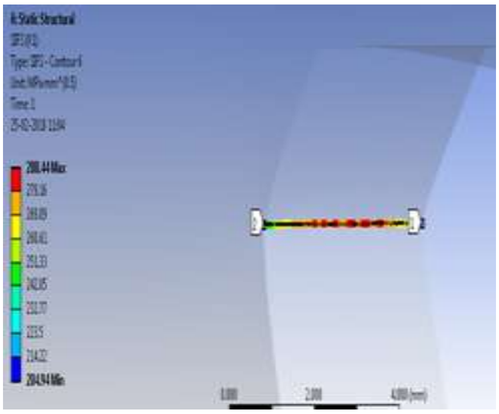


Fig.15 Stress intensity factor of single edge notch crack specimen.

From the reference section [3] journal paper, theoretical validation of single edge notched specimen is made.

$$K = f(g)\times\frac{F\sqrt{\pi a}}{WB} \qquad (9)$$

$$f(g) = 1.12 - 0.231\times\left(\frac{a}{w}\right) + 10.55\times\left(\frac{a}{w}\right)^2 - 21.72\times\left(\frac{a}{w}\right)^3 + 30.39\times\left(\frac{a}{w}\right)^4 \qquad (10)$$

Where F = applied force
a = crack length
w = width
B = thickness

By substituting and simplification to main equation we get K= 289.136MPa$\sqrt{\text{mm}}$ and the difference (error) between thetheoretical value and ANSYS result is of 0.2407%.

Fatigue crack growth of single edge notch specimen is determined with load ratio of 0.1. The crack length verses number of cycles up to failure is shown along width direction and having finial crack length of 0.039m.

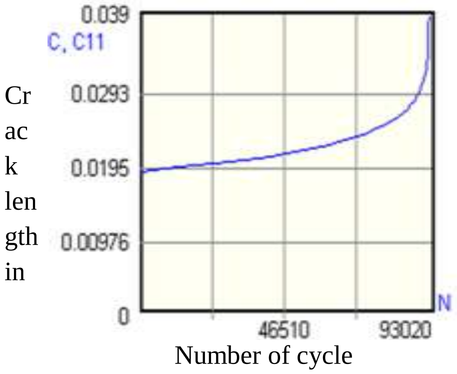
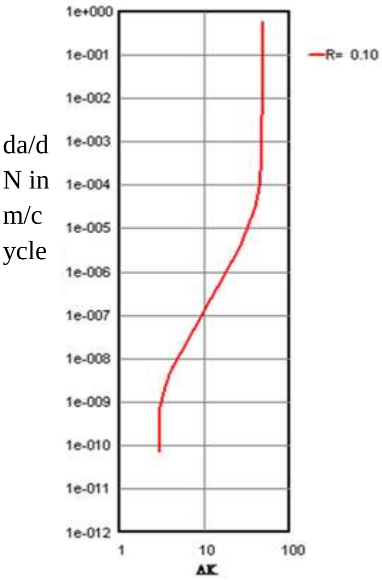


Fig.16 Crack length verses number of cycle.

The figure 17 shows the crack growth rate of single edge notched specimen having crack length of 17.75. NASGRO equation was used to determine the fatigue crack growth.



ΔK in MPa$\sqrt{m}$

Fig.17 Crack growth rate.

III. CASE STUDY on PRESSURE VESSEL

For the safe design of pressure vessel, Leak Before-Break (LBB) is important phenomenon required to prevent catastrophic failure of pressure vessel. The catastrophic failure can happen without the formation of through crack. So it is essentially need to find the leak pressure for safe design of pressure vessel. In present work semi-elliptical crack length was taken as four times of thickness length, since it represents a typical fatigue crack geometry observed at failure location in fatigue tested cylinders. In the present study, initially finding out the fracture pressure through theoretical means and thenfinding out stress intensity factor with theoretical way than with ANSYS workbench also.

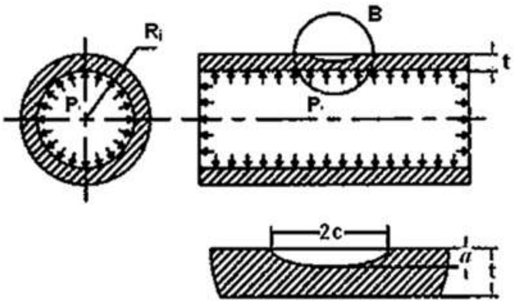


Fig.18 Geometry of the model.

The figure 18 show diagram of axial semi elliptical crack, having outer diameter 228.6mm and thickness of 7.2mm and minor radius of crack is 5.4mm and major radius is 25.4mm. Length of specimen is of 1400mm. The material used for analysis is AISI 4130 steel. Young`s modulus is 205GPa and Poisson ratio is 0.32.

Since large dimension of geometry involved in pressure vessel mainly in case of length, taking in the mind of computational time involved in meshing, computer configuration and also computational time involved in result extraction. It is essential to use symmetry of model. The figure below shows symmetry of pressure vessel model.

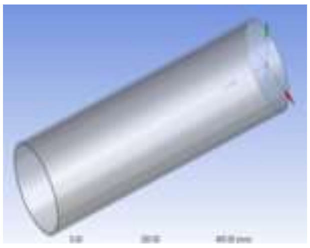


Fig.19 Symmetry region 1.

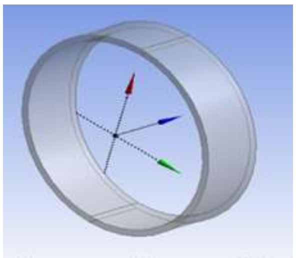


Fig.20 Symmetry region 2.

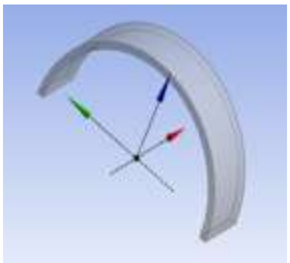


Fig. 21 Symmetry region 3.

Tet 10(Tetrahedron element) is used to mesh the specimen having element size 1mm. Since of symmetry boundary condition, we are applying or restricting Z=0 and X = 0 as shown below and applying pressure of 31.48N/mm^2 on the internal surface of pressure vessel.

Fig. 22 Restricting along Z direction.

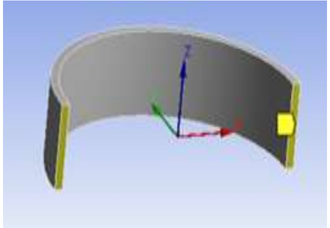


Fig. 23 Restricting along X direction.

Figure below shows the value of stress intensity factor for pressure vessel, having maximum value of 4048.7MPa$\sqrt{mm}$ and minimum value is 2412.8MPa$\sqrt{mm}$.

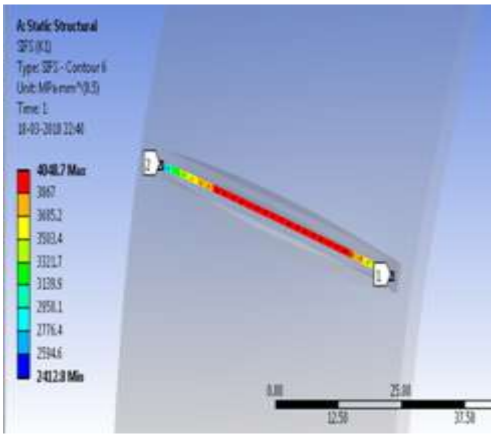


Fig. 24 Stress intensity factor of pressure vessel.

Theoretical validation of pressure vessel is made by taking the expressions from the journal paper of reference section [4].Than its value was applied to stress intensity factor equation.

$q = 2+8(\frac{a}{c})^3$ (11)
a = Depth of surface crack
c = Length of surface crack
$\lambda_s = \frac{c}{\sqrt{R_i \times t}} \times \frac{a}{t}$ (12)
Ri = inner radius of pressure vessel
t = thickness of pressure vessel
$f_s = (1 + 0.52 \times \lambda_s + 1.29 \times \lambda_s^2 - 0.074 \times \lambda s3)12$ for $0 \leq \lambda s \leq 10$ (13)
$M_1 = 1.13 - 0.1 \times \left(\frac{a}{c}\right)$ for $a \leq c$ (14)
$\phi^2 = 1 + 1.464 \times (\frac{a}{c})^{1.65}$ for $a \leq c$ (15)
Φ^2 = Crack shape factor
$M_e = M_1 + (\phi \times \sqrt{\frac{c}{a}} - M_1) \times (\frac{a}{t})^q$ (16)
$M = M_e \times F_s$ (17)
M = Magnification factor
Fracture strength equation is given as
$\sigma_u = \frac{P_b \times R_i}{t}$ (19)
σ_u= hoop stress of unflawed cylindrical vessel
P_b = bursting pressure of unflawed cylindrical vessel
R_i = inner radius of pressure vessel
t = thickness of pressure vessel
$P_b = \frac{2}{\sqrt{3}} \sigma_{ys} \left(2 - \frac{\sigma_{ys}}{\sigma_{ult}}\right) \ln(1 + \frac{t}{R_i})$ (20)
$(1-m) \times (\frac{\sigma_f}{\sigma_u})^P + \left(m + \frac{\sigma_u \times (\pi a)^{\frac{1}{2}} \times M}{\phi K_F}\right) \times \left(\frac{\sigma_f}{\sigma_u}\right) - 1 = 0$ (18)
K_F, m and p are fracture toughness parameters
σ_{ys} = yield strength of material (1097MPa)
σ_{ult} = ultimate tensile strength of material(1180MPa)
By substituting and simplification
σ_f=468.30MPa.
$\sigma_f = \frac{P_f \times R_i}{t}$ (21)
P_f = failure pressure
By substituting and simplification
P_f =31.48235 N/mm^2
$K_{max} = \sigma \times \sqrt{\frac{\pi a}{\phi^2}} M$ (22)
K=4496.21 MPa$\sqrt{mm}$

The difference (error) between theoretical value and ANSYS result is of 9%..

IV. PARAMETRIC STUDY on PRESSURE VESSEL

1.4 Parametric study using ANSYS workbench

Parametric study is made on pressure vessel by varying pressure with fixed thickness of 7.2mm till to the fracture pressure. The graph is plotted with stress intensity factor verses pressure as shown in figure 25. After the point A sudden increase in the stress intensity factor was seen mainly because pressure at a point A is nearer to the fracture pressure of the experimental results. With increase of pressure, stress intensity factor also increases.

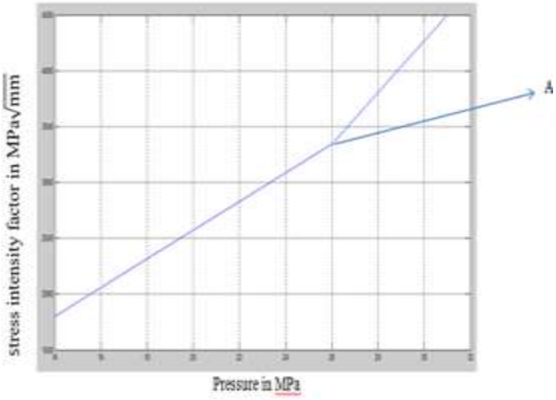


Fig. 25 Stress intensity factor verses pressure.

The figure 26 shows stress intensity factor verses thickness. The thickness variation is made with fixed pressure of 25MPa which is nearly below the fracture pressure. The stress intensity factor decreases with increase in the thickness and reaches to a minimum value, thereafter stress intensity factor does not decrease with increase in thickness which is known as plain strain fracture toughness. With the help of plain strain fracture toughness it is possible to calculate the leak pressure.

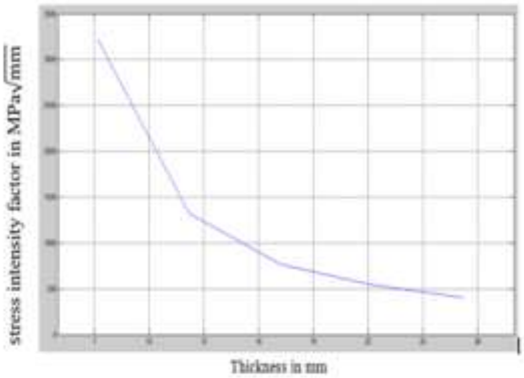


Fig. 26 Stress intensity factor verses thickness.

1.5 Parametric study using AFGROW

Parametric study is done on HY (higher yielding material) 130 steel pipe material using AFGROW. Same dimension are taken as earlier to that of pressure vessel. Same variation of pressure and thickness has been made as earlier to parametric study. Since due to insufficient material data of AISI 4130 steel material which is required for AFGROW software as input, so material chosen was HY 130 steel pipe which come under pressure vessel of NASGROW material data base file. Pressure variation has been made on pressure vessel having thickness of 12.2mm. For pressure of 22MPa there is no crack length because of crack growth is less than $2.54e^{-15}$m.The below figures shows crack length verses number of cycle up to failure along the thickness and length direction. Crack growths for the pressure of 14MPa, 18MPa and 22MPa with the fixed thickness of 12.2mm. Load ratio taken parametric study is of zero.

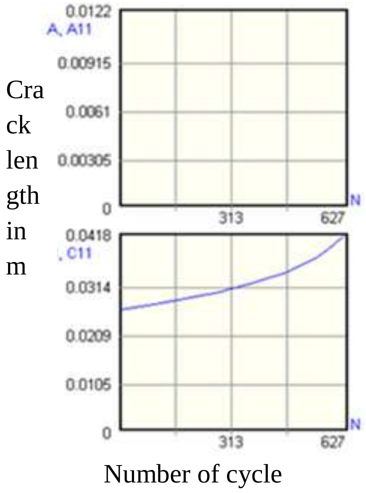


Fig. 27 Crack length verses number of cycle for pressure of 14MPa.

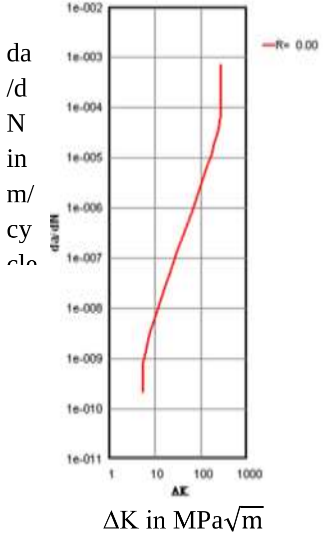


Fig. 28 Crack growth rate for pressure 14MPa.

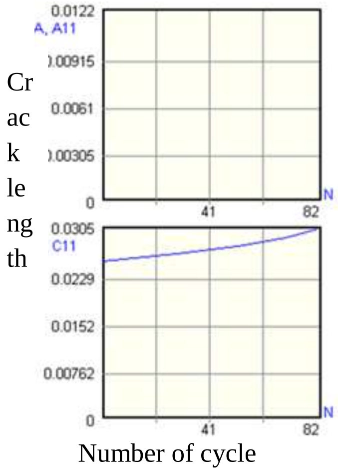
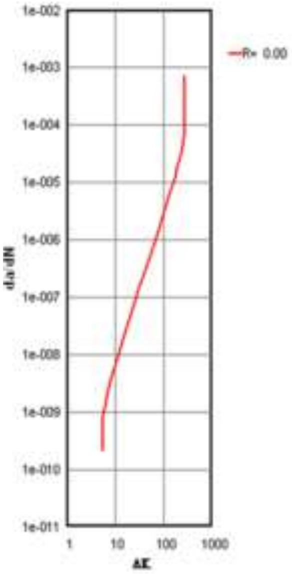


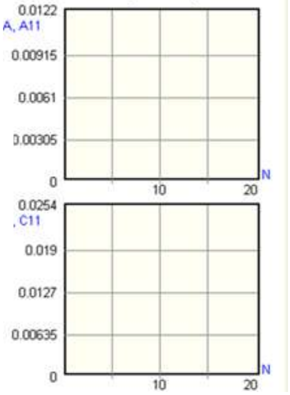
Fig. 29 Crack length verses number of cycle for pressure of 18MPa.



da/dN in m/cycle

ΔK in MPa$\sqrt{m}$

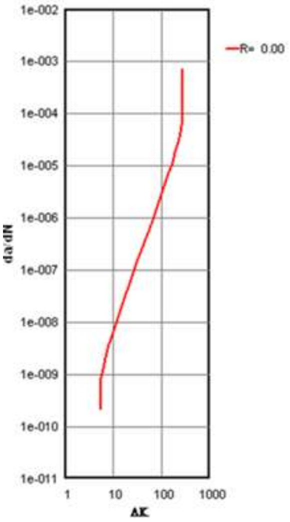
Fig. 30 Crack growth rate for pressure 18MPa.



Crack length

Number of cycle

Fig. 31 Crack length verses number of cycle for pressure of 22MPa.

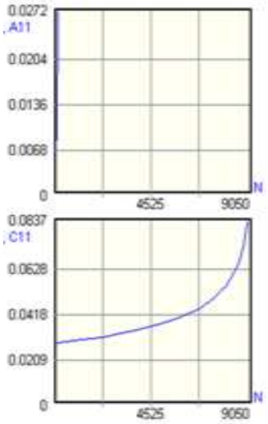


da/dN in m/cycle

ΔK in MPa$\sqrt{m}$

Fig. 32 Crack growth rate for pressure 22MPa.

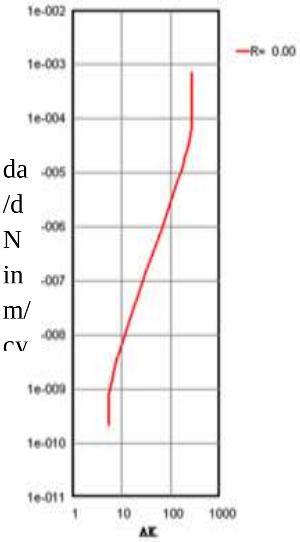
Thickness variation has been made on pressure vessel having fixed pressure of 25MPa. For thickness of 12.2mm there is no crack length because of crack growth is less than 2.54e^{-15}m.



Crack length in m

Number of cycle

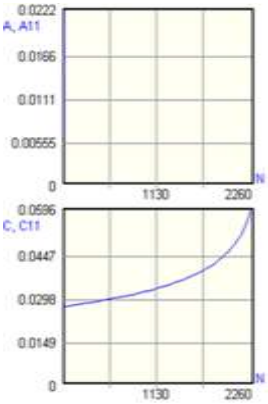
Fig. 33 Crack length verses number of cycle for thickness of 27.2mm.



da/dN in m/cy

ΔK in MPa$\sqrt{m}$

Fig. 34 Crack growth rate for thickness 27.2mm.

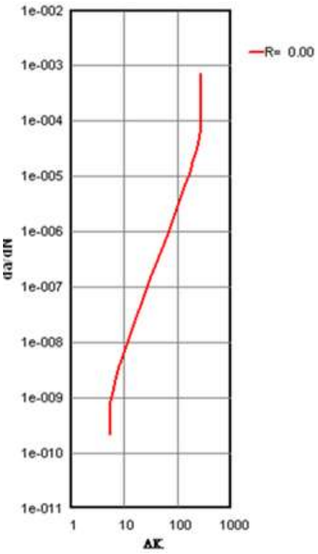


Crack length in

Number of cycle

Fig. 35 Crack length verses number of cycle for thickness of 22.2mm

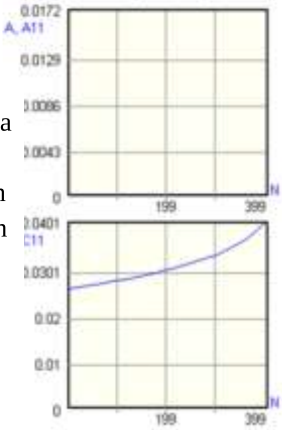
da/dN in m/cycle



ΔK in MPa$\sqrt{m}$

Fig. 36 Crack growth rate for thickness 22.2mm.

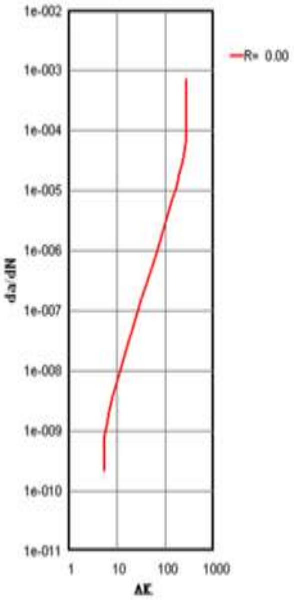
Crack length in m



Number of cycle

Fig. 37 Crack length verses number of cycle for thickness of 17.2mm.

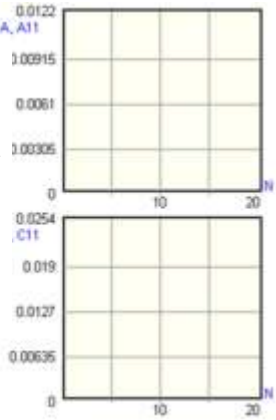
da/dN in m/cyc



ΔK in MPa$\sqrt{m}$

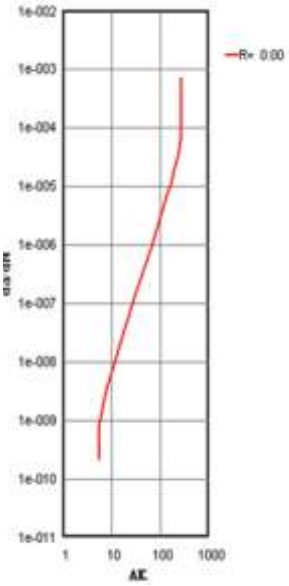
Fig. 38 Crack growth rate for thickness 17.2mm.

Crack length in m



Number of cycle

Fig. 39 Crack length verses number of cycle for thickness of 12.2mm.



da/dN in m/cycle

ΔK in MPa$\sqrt{m}$

Fig. 40 Crack growth rate for thickness 12.2mm.

V. 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 theoretical value. Parametric study is done on pressure vessel on both using ANSYS workbench and AFGROW software, which gives knowledge how stress intensity factor varies with thickness and pressure and also how crack length varies with the pressure and thickness value.

REFERENCES

[1] Tianwen Zhao, Jixi Zhang, Yanyao Jiang, "A study of fatigue crack growth of 7075-T651 aluminiumalloy",International Journal of Fatigue, 30, 2008, 1169–1180.

[2] SlobodankaBoljanovic, "Fatigue Strength Analysis of a Semi-Elliptical Surface Crack", Scientific Technical Review, 62(1), 2012, 10-16.

[3] J.R. Mohanty , B.B. Verma , P.K. Ray, " Prediction of fatigue crack growth and residual life using an exponential model", International Journal of Fatigue,31, 2009, 418-424.

[4] P. Kannana, K.S. Amirthagadeswaranb, T. Christopherc, B. Nageswara Raod, "A simplified approach for assessing the leak-before-break for theFlawed pressure vessels", Nuclear Engineering and Design, 302, 2016, 20–26.

[5] J.C. Newman, I S Raju, "Stress Intensity Factor Equations for Cracks in Three Dimensional Finite Bodies Subjected to Tension and Bending Loads", Computational Methods in the Mechanics of fracture, 1986.

[6] Zhenyu Ding, Zengliang Gao, Chenchen Ma, Xiaogui Wan, "Modeling of I + II mixed mode crack initiation and growth from the notch", Theoretical and Applied Fracture Mechanics, 84, 2016, 129–139.

[7] Ashok Saxena , Federico Bassi , Kevin Nibur , James C. Newman , "One single-edge-crack tensionspecimensfortension-compression fatigue crack growth testing", Engineering Fracture Mechanics, 176, 2017, 343–350.

[8] Behzad V, Farahani, Paulo J, Tavares, J Tavares, Jorge Belinha, P.M.G.P. Moreira, "A Fracture Mechanics Study of a Compact Tension Specimen: Digital Image Correlation, Finite Element and Meshless Methods", 2nd International Conference on Structural Integrity,5, 2017, 920-927.

[9] M. Benachoura, A. Hadjouia, M. Benguediabb, N. Benachoura, "Effect of the amplitude loading on fatigue crack growth", Procedia Engineering, 2, 2010,121–127.

[10] Gao Yi , Tiantang Yu , Tinh Quoc Bui , Chunping Ma, Sohichi Hirose, "SIFs evaluation of sharp V-notched fracture by XFEM and strain energy approach", Theoretical and Applied Fracture Mechanics ,89, 2017, 35–44.

[11] Punit Aroraa, P.K. Singh, V Bhasin, K.K. Vaze ,D.M. Pukazhendhi, P Gandhib, G. Raghava, "Fatigue crack growth behaviour in pipes and elbows of carbon steel and stainless steel materials", 6th International Conference on Creep, Fatigue and Creep-Fatigue Interaction, 55, 2013, 703-709.