Design and Analysis of a Spherical Pressure Vessel in Presence of Crack

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Abstract

A gas bottle is a spherical pressure vessel used in aerospace application. A typical gas bottle used in the liquid propulsion system of launch vehicle is considered for the present study. The design is carried out considering two materials namely- Ti - 6Al -4V alloy and Inconel 718. Design is validated through analytical and finite element analysis for specified load. Design is also validated for the different size of crack through fracture mechanics module in ANSYS workbench 18.0. Stress Intensity Factor was determined using analytical method and finite element method for various crack size. Three dimensional analysis of gas bottle in presence of crack is carried out. Stress Intensity factors are compared with the fracture toughness value of the respective materials.
Keywords- Stress Intensity Factor, Fracture toughness, Ti - 6Al -4V, Inconel 718, Surface Crack, ANSYS

I. INTRODUCTION

A pressure vessel is a closed container designed to hold gases or liquids at a pressure substantially different from the ambient pressure. The failure of pressure vessel may result in loss of life, health hazards and damage of property. Propulsion system of spacecraft and liquid propellant upper stage of launch vehicles require liquid tanks and gas bottles to store liquid propellant and highly compressed gases. It functions as a regulator of fuel and highly pressurized fluid such as helium is stored. The gas bottles are installed mainly over propellant tank. Gas bottles are used to provide enough pressure to regulate the flow of fuel. The design of a typical gas bottle used in launch vehicle is carried out and the design is validated through finite element analysis [1]. The presence of cracks in the wall of a pressure vessel, such as a cryogenic liquid rocket propellant tank, can severely reduce the strength of the structure and can cause sudden failure at nominal tensile stresses less than the material yield strength. The application of fracture mechanics in pressure vessel design along with the help of non-destructive inspection is found to be very effective way of dealing with the problem [2]. The evaluation of fracture parameter stress intensity factor (SIF) decides the criticality of crack shape. In the present study the SIF is determined for the crack in the weld region and results are compared with analytical solutions.

II. DESIGN SPECIFICATION

Inner diameter of the bottle is considered as 402 mm. The operating medium is Helium. Maximum temperature is 50˚C. 100% weld efficiency is considered in design. Material properties of Ti - 6Al -4V and of Inconel 718 are shown in table 1[3][4]. True Stress- strain graphs of Ti - 6Al -4V and of Inconel 718 are shown in figure 1(a) and 1(b) respectively [5][6].The maximum expected operating pressure (MEOP) considered for the design is 33 MPa. Burst pressure for the gas bottle can be obtained from Svensson's formula [7][8] , however in the present study, the burst pressure was taken as twice the maximum operating pressure. The proof pressure was considered 1.5 times MEOP and is found to be 49.5 MPa.

Table 1: Material Properties of Ti - 6Al -4V and of Inconel 718

Material properties	Ti - 6Al -4V	Inconel 718
Modulus of elasticity	110107.907 N/mm^2	204900 N/mm^2
Poisson's ratio	0.31	0.294
Fracture toughness	1609.1 $N/mm^{3/2}$	1517.893 $N/mm^{3/2}$
Ultimate Tensile Strength	920 N/mm^2	1240 N/mm^2
0.2% PS	840 N/mm^2	1050 N/mm^2

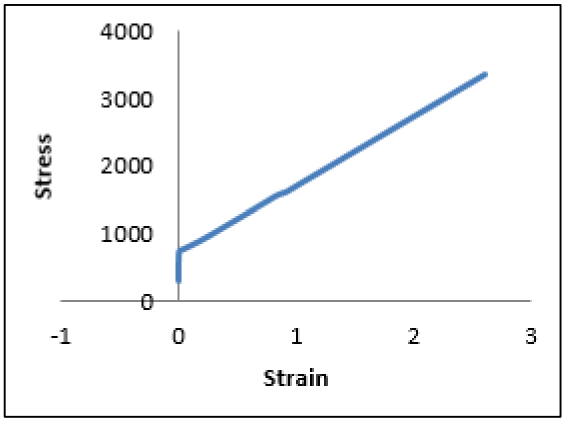

Fig. 1 (a):Stress strain graph of Ti - 6Al -4V

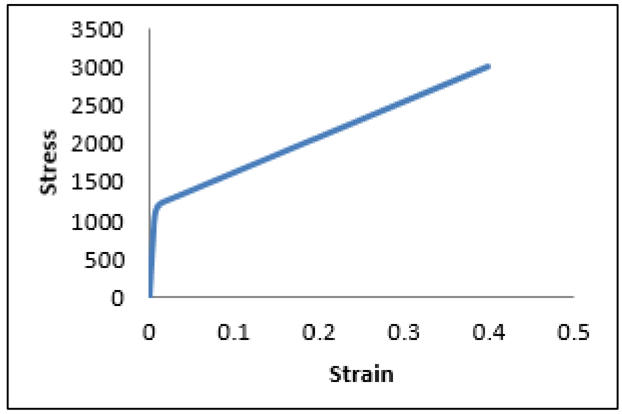

Fig. 1 (b): Stress strain graph of Inconel 718

III. Design and Analysis of Pressure Vessel

A. Design thickness calculation

IS code 2825. 1969Code for unfired pressure vessels is used to calculate the deign thickness [5]. Design thickness for Inconel 718 and Ti - 6Al -4V was found to be 5.42 mm and 8.05 mm respectively. Hoop stress, axial stress, hoop strain and radial displacement were found using theoretical equations. Thickness in weld region is higher than that of parent material [6].

B. Axisymmetric Analysis

The structural non-linear analysis of Inconel 718 and Ti - 6Al -4V gas bottle is carried out for the specified load and design is validated through analysis. Since the pressure vessels are symmetry in geometries, load and material, the axi-symmetric analysis is carried out. In ANSYS axi-symmetry is used about Y-axis. Y axis is used as axis of symmetry in Finite Element model [9]. Finite element model is shown in figure 2. The axi-symmetric element PLANE 182 is used for carrying out material and geometric nonlinear analysis. Mapped face meshing is done. There are 258 nodes and 110 elements in the Finite Element model.

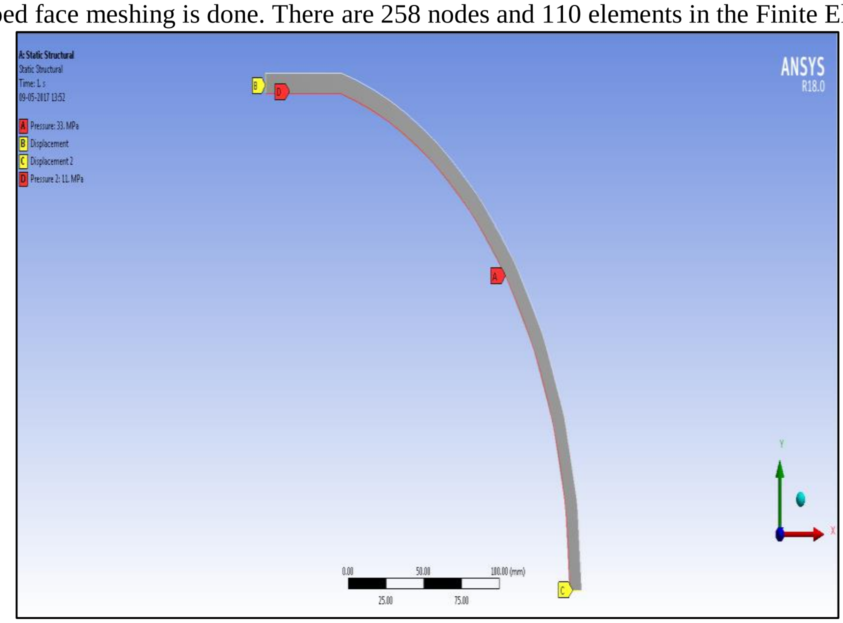

Fig. 2: Finite Element Model of pressure vessels

A non-linear analysis is carried out for maximum operating pressure of 33 MPa. The finite element stress compares well with analytical solution. It is seen that all stress are within the allowable limit. The results summary of Inconel 718 pressure vessel and of Ti - 6Al -4V pressure vessel are shown in Table 2 and 3 respectively.

Table 2: Results Summary of Geometric nonlinear Analysis of Inconel 718 pressure vessels

	Finite Element Analysis					*Theory*	
Loc.	*Thickness (mm)*	*Hoop Stress (MPa)*	*Meridional Stress(MPa)*	*von Mises stress(MPa)*	*Radial Deformation (mm)*	*Hoop Stress (MPa)*	*Radial Deformation (mm)*
In the shell	*5.42*	*628*	*605*	*620*	*0.46*	*620*	*0.61*

Table 3: Results Summary of Geometric nonlinear Analysis of Ti - 6Al -4V pressure vessels

	Finite Element Analysis					Theory	
Loc.	*Thickness(mm)*	*Hoop Stress (MPa)*	*Meridional Stress(MPa)*	*von Mises stress(MPa)*	*Radial Deformation (mm)*	*Hoop Stress (MPa)*	*Radial Deformation (mm)*
In the shell	*8*	*422*	*422*	*453*	*0.58*	*422*	*0.78*

IV. ANALYSIS IN PRESENCE OF A CRACK

A. Fracture Toughness and Stress Intensity Factor

Fracture mechanics is the field of mechanics concerned with the study of the propagation of cracks in materials. Fracture toughness is a property which describes the ability of a material containing a crack to resist fracture, and is one of the most important properties of any material for design applications [10]. Fracture toughness is a quantitative way of expressing a material's resistance to brittle fracture when a crack is present The stress intensity factor, is used in fracture mechanics to predict the stress state ("stress intensity") near the tip of a crack caused by a remote load or residual stresses[11]. Fracture toughness of a material is determined from the stress intensity factor at which a thin crack in the material begins to grow. Stress intensity factors are a measure of the change in stress within the vicinity of the crack tip.

B. Three Dimensional Analysis

Three dimensional analysis can be done in two different ways as mentioned below:

1) Analysis on a quarter section using cyclic symmetry approach
2) Analysis of the complete model.

To analyse the gas bottle 1/12th part of the gas bottle is taken in order to reduce the computation time. Finite Element mesh was generated in model module of ANSYS workbench, tetrahedral element is used to idealise the geometry. Cylindrical coordinate is created which is used for applying the symmetry boundary conditions. A Cartesian coordinate is created to orient the crack with respect to the definition of problem. Fracture module was created under the model. A crack was inserted on the surface of the pressure vessel under fracture module. Load is applied as an internal pressure in the pressure vessel. An internal pressure of 33 MPa was applied on the inner surface of the bottle. Meridional pull is applied at the upper edge of the bottle. Symmetric boundary conditions are applied. Displacement is zero at the bottom section of the bottle.

The finite element model is shown in Figure 3.Combined material and geometric nonlinear analysis of the gas bottle has been carried out for the specified pressure loading. Patch conforming mesh is done. Element used is SOLID187. There are 7956 elements and 17075 nodes [9].

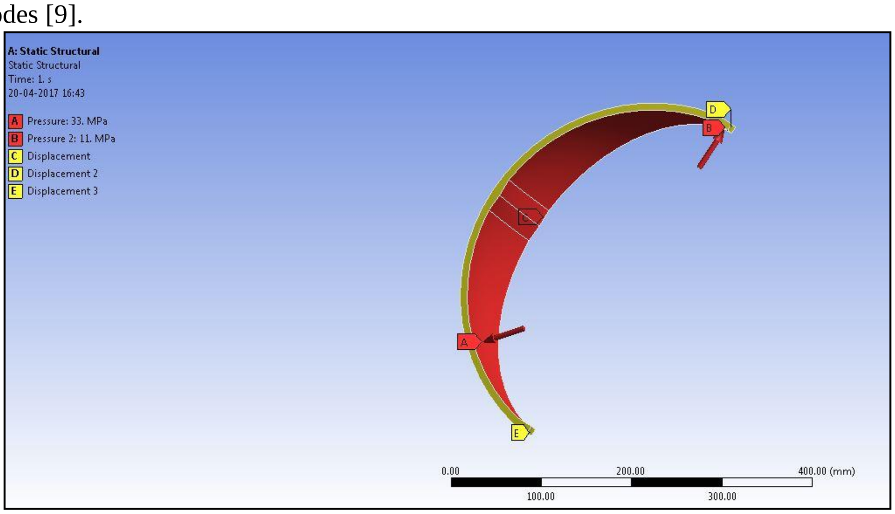

Fig. 3: Three dimensional Finite Element Model of Pressure Vessels

C. Stress Intensity Factor Calculations using Analytical Method

Stress Intensity factor was calculated analytically from NASA TN D 8325[12]

$$K_{Ic} = S_n\sqrt{\pi c}\, F \qquad (1)$$

$$S_n = \frac{PR}{2t} \qquad (2)$$

$$F = (1 + 0.52\,\lambda_s + 1.29\,\lambda_s{}^2 - 0.074\,\lambda_s{}^3)^{1/2} \qquad (3)$$

$$Q = 1 + 1.47\,(\tfrac{a}{c})^{1.64} \quad \frac{a}{c} < 1$$

$$Q = 1 + 1.47\,(\tfrac{c}{ac})^{1.64} \quad \frac{a}{c} > 1$$

$$M_e = M_1 + \left(\sqrt{(Q\frac{c}{a})} - M_1\right)(\frac{a}{t})^q \qquad (4)$$

where q was determined empirically as

$$q = 2 + 8(\frac{a}{c})^3 \qquad (5)$$

The term M_1 is the front- face correction, and the a/t term is the back-face correction. The expression for M_1 is given by

$$M_1 = 1.13 - 0.1(\frac{a}{c}) \qquad 0.02 < \frac{a}{c} < 1$$

$$M_1 = \sqrt{\frac{c}{a}}\,(1 + 0.03\,\frac{c}{a}) \qquad \frac{a}{c} > 1.0$$

The shell curvature correction factor for surface crack f_s is given by

$$f_s = (1 + 0.52\,\lambda_s + 1.29\,\lambda_s{}^2 - 0.074\,\lambda_s{}^3)^{1/2}$$

for $0<\lambda_s<10$

$$\text{where } \lambda_s = \frac{ca}{\sqrt{Rt}}\frac{a}{t} \qquad (6)$$

D. Stress Intensity factor using Finite element method

A crack was inserted on the surface of the pressure vessel. Figure 4(a) shows surface crack in the pressure vessel. Figure 4(b) and 4(c) show crack meshing of the pressure vessel. Crack was inserted by creating a coordinate system which was defined with respect to global coordinates and the crack was inserted there.

For fracture analysis internal surface crack is inserted at the middle portion of the bottle. Crack length is represented as 'c' and crack depth as 'a'. Crack size is varied. ANSYS workbench is used for calculating the value of first mode stress intensity factor. In ANSYS work bench, using fracture module semi-elliptical crack is inserted as per mentioned dimension. The comparison of stress intensity factor for Ti - 6Al -4V and Inconel 718 for FEM and analytical solution is shown in Table-4 and 5 respectively. It can be seen that the finite results matches well with analytical solution within 10 % error.

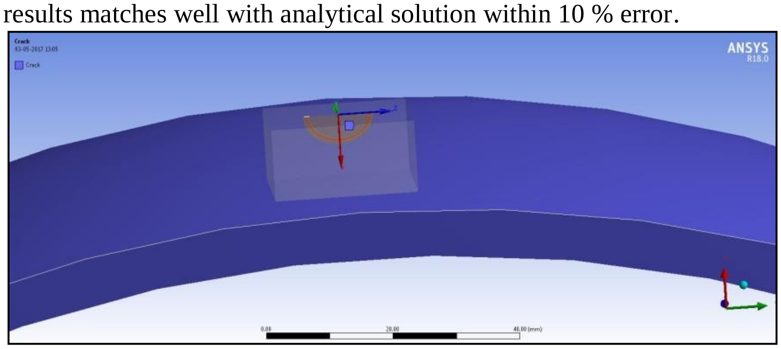

Fig. 4(a): Surface crack

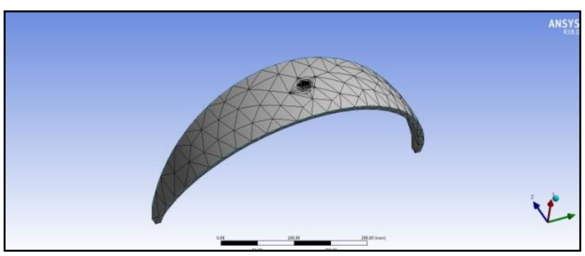

Fig. 4(b): Crack meshing

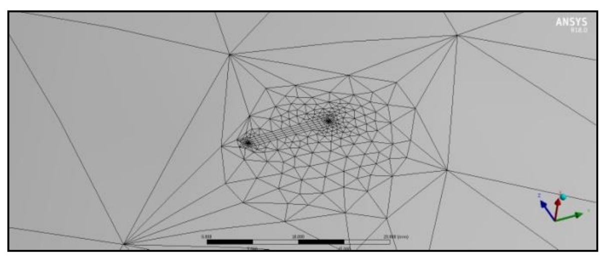

Fig. 4(c): Crack meshing

Table 4: Comparison of Stress Intensity factor (FEM VS ANALYTICAL) for Ti - 6Al -4V

Sl No	c	a	SIF (Ansys)	SIF (theoretical)	Percentage Error
1	2.5	2	739.69	771.215	4.08
2	2.8	2.8	892.13	811.249	9.97
3	3.3	3	819.43	888.1766	7.74
4	3	2.5	750.5	846.96	11.38
5	2.1	2	732.75	702.86	4.25

Table 5: Comparison of Stress Intensity factor (FEM VS ANALYTICAL) for Inconel 718

Sl No	c	a	SIF (Ansys)	SIF (theoretical)	Percentage Error
1	2.5	2	1069.3	1145.085	6.61
2	1.625	1.5	889.07	914.3831	2.76
3	2.53	2.2	1071	1151.123	6.96
4	3.3	3	1012.5	1122.722	9.81
5	3	2.5	1079.7	1206.216	10.48

E. Effect of Poisson's Ratio on Stress Intensity Factor

Analysis was carried out on the same spherical shell by varying the Poisson's ratio of the material for four different crack sizes. Variations in SIF values were found to be negligible.

F. Analysis for through crack

An analysis was also done for a through crack. Crack with depth = 8mm (equal to the thickness of the Ti - 6Al -4V pressure vessel) was analysed. Figure 5 shows a through crack in the Ti - 6Al -4V pressure vessel. Stress Intensity factor was calculated from the analysis and it was found to be equal to 996.45 N/mm$^{3/2}$. The through crack is shown in Figure 5. The stress intensity factor of 996 N/mm$^{3/2}$ which matches fairly well with analytical solution of 1053.92 N/mm$^{3/2}$.

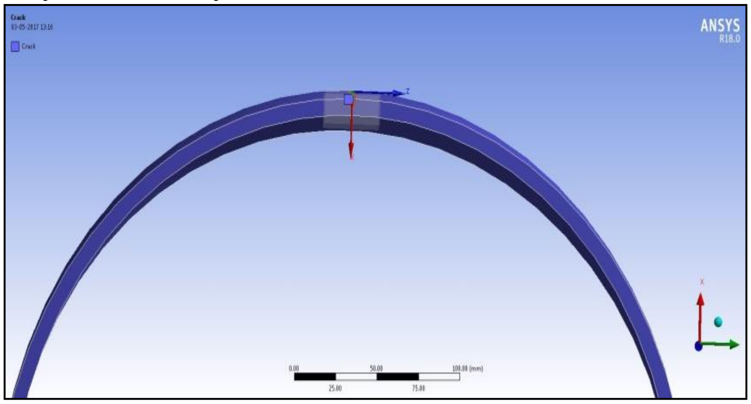

Fig. 5: Through crack in Ti - 6Al -4V pressure vessel

V. CONCLUSIONS

Design is carried out for Ti - 6Al -4V alloy and Inconel 718 pressure vessels using IS CODE. Design is validated through analytical solution and axi-symmetric finite element geometric non linear analysis. All stresses are within the allowable limits. Finite Element results match well with analytical solution. SIF (stress intensity factor) is calculated using finite element analysis and empirical equations. 3D stress analysis in presence of crack is carried out for calculating the stress intensity factor using finite element method. SIF values using finite element method for different crack size (for different aspect ratios) are compared with the analytical SIF and error is within 10%. SIF for through crack is calculated using finite element method and it was found to be comparable to the SIF obtained from the Empirical Equations. The effect of Poisson's ratio on the stress intensity factors is found to be negligible. SIF for different crack size are obtained using finite element method and are compared with the Fracture toughness value of the respective materials and are found to be less than the fracture toughness of the respective material. Ti - 6Al -4V gas bottle has lower mass as compared to Inconel gas bottle. The results are comparable with analytical solutions and hence finite element method can be used for design of pressure vessels through analysis.

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