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Finite Element Analysis of Toroidal Pressure Vessels Using FEAST^{SMT}/PreWin

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ABSTRACT

*The design of pressure vessels for operating at very high pressure is a complex problem. The pressure vessels used in wide applications such as in thermal and nuclear power plants, in chemical industries, in space and ocean depths, in hydraulic units of aircrafts and fluid supply systems in industries. The pressure vessels have different shape of opening like manholes, hand holes, and nozzles and have different size of opening such as small drain to full vessel size opening with body flange. The opening cannot be avoided in the pressure vessels because of various piping attachment. Due to openings in the vessels shell around the opening are weakened. This cause stress concentration because of geometrical discontinuity in the vessels. Such discontinuities are called as stress raiser and region in which they occur is called the area of stress concentration. Stress concentration factor is used to quantify how the stress is concentrated in a component. So the present study makes an attempt to find the effect of diameter and position of openings on toroidal pressure vessels. The pressure vessels shall be analyzed by using PreWin, a graphical pre and post processor for the structural analysis software FEAST (**F**inite **E**lement **A**nalysis of **St**ructures). The toroidal shell is idealized with various elements like 4 / 8 noded solid of revolution and shell/ solid elements using FEAST and results compared with those obtained using analytical values. This paper is an attempt to study of the effect of openings of 10 mm to 150 mm on toroidal pressure vessels. Also find out the variation of stress concentration factor for different diameter of hole. To find the effect of position of hole, the holes of different diameters are placed at two different locations of the shell.*

Key words: stress concentration, stress concentration factor, toroidal pressure vessels

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INTRODUCTION

Pressure vessel is defined as a container with a pressure differential between inside and outside. Pressure vessels often have a combination of high pressures together with high temperatures and in some cases flammable fluids or highly radioactive materials. The design is such that the pressure vessels should withstand design pressure without any leak. Pressure vessels are used in a number of industries like, power generation industry for fossil and nuclear power, the petrochemical industry for storing, in hydraulic units for aircraft and Solid Rocket motor cases, liquid pressure vessels as storage tanks for launch vehicles in space industry, and processing crude petroleum oil in tank farms as well as storing gasoline in service stations [1-2, 11].

Toroidal vessels are commonly used for the storage of pressurized fluids in automotive and aerospace applications due to their optimal use of space[3-4]. Here, the aim is to provide insight into the effect of openings on toroidal pressure vessels.

Openings in pressure vessels in the regions of shells or heads are required to serve the following purposes; i) Man ways (for maintenance and repair),ii)Holes for draining or cleaning the vessel, iii)Hand hole openings (for inspecting the vessel from outside, iv)Nozzles attached to pipes to convey the working fluid inside and outside of the vessel. The stress levels at the opening will be peak due the removal of the material and hence will lead to weak region of the total structure. So the stress concentration at these locations should be estimated for the safe design of pressure vessels. The amount of weakening is dependent on (i) Diameter of hole, (ii) The number of holes, (iii) Spacing of holes (iv) Location of hole [5-6].

OBJECTIVES

- Familiarization of software PreWin, the Graphical User Interface (GUI) based pre & post Processor of **FEAST**^{SMT}, structural analysis software developed by scientists of VSSC/ISRO based on Finite Element Method (FEM).
- To conduct structural analysis using PreWin for toroidal pressure vessel by varying the diameter of hole.
- Conduct a study on the effect of diameter of hole on stress concentration factor around the holes.
- To study the effect of position of openings on displacement and stress around the hole region.

METHODOLOGY

Toroidal shell, without hole and the loads (ie. internal pressure) is axisymmetric in nature was analyzed and the results were compared with theoretical values available in literature survey. The analysis was performed for both 4 noded and 8 noded shell element and the results were compared so that the suitable element can be selected for further analysis [7]. Then the analysis is done for toroidal shell with hole diameters varying from 10 mm to 150 mm at two locations were selected for placing these holes. Here the assumption is that the toroidal shell is planned to made of top/bottom half of the shell and then welded in the inner / outer curvature. These positions are called the Long Seam Inner (LSI) and Long Seam Outer (LSO) positions.

MODEL

In order to calculate the stresses in the region of hole, three finite element models have been used. i) Toroidal pressure vessel one quarter portion without holeas shown in Fig.1,ii) Toroid with circular holes of diameters 10 mm to 150 mm placed at outer (LSO) region as shown in Fig.2,iii) Toroid with circular holes of diameters varying from 10 mm to 150 mm placed at inner(LSI) region of the pressure vessel as shown in Fig.3. Toroid without hole is an example for axisymmetric shell of revolution. So it can also be modeled as axisymmetric shell of revolution [8].

Meshing

For uniform toroid hole, both 4 noded and 8 noded elements are used for meshing. For toroid without hole only 4 noded shell elements is used for meshing.The configuration of the toroidal shell considered for the analysis is given in Table 1.

Boundary Conditions

The pressure vessel is analyzed for an internal pressure of 0.575 MPa. In order to avoid rigid body motion, both the ends were symmetrically constrained.

Table -1 Inputs for Finite Element Analysis

Toroid Major Radius, mm	1500
Toroid Minor Radius, mm	250
Shell thickness, mm	2.4
Material	AA6061 Al. Alloy
Modulus of elasticity, GPa.	70
Poisson’s ratio	0.3
Internal pressure, MPa	0.575

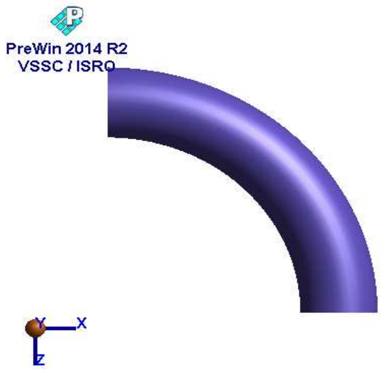

Fig.1: Toroid without hole (One quarter portion)

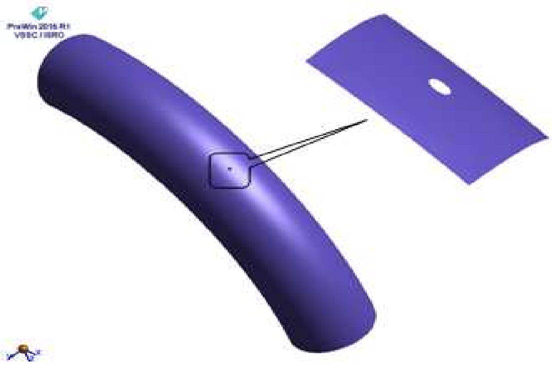

Fig.2: Toroid with opening at LSO

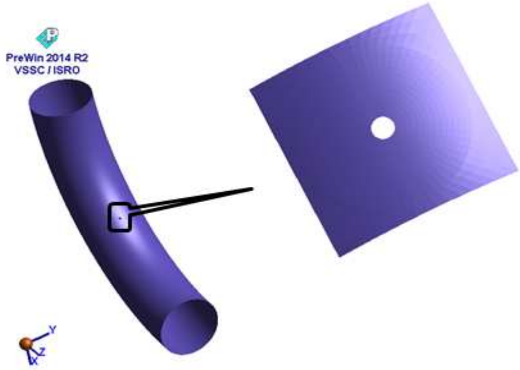

Fig.3: Toroid with opening at LSI

RESULTS & DISCUSSION

The maximum stress values and displacement values are obtained from the analysis as follows.

TOROID WITHOUT HOLE

As toroid without hole can be modeled as an axi-symmetric shell of revolution, it is modeled with axisymmetric element with as a chord of radius 250 mm, mean radius as 1500 mm and thickness 2.4 mm. FE idealization of toroid without opening with 4 node element is shown in Fig.4 below [9-10].

Toroidal Shell with Axisymmetric 4 Noded Shell Elements

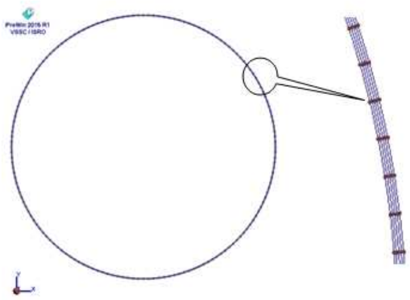

Fig.4: FE Idealisation with 4 noded axisymmetric element

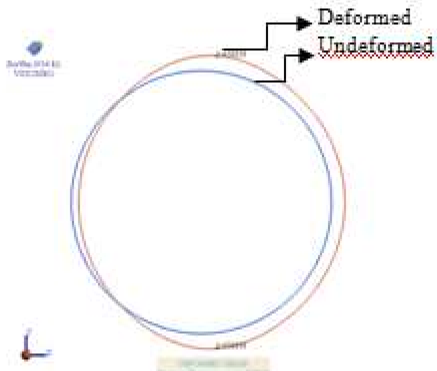

Fig.5: Deformed shape (4 noded axisymmetric element)

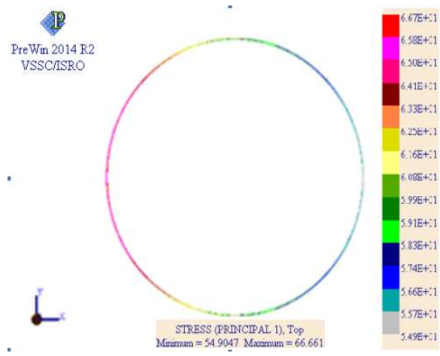

Fig.6: First Principal stress (4 noded axisymmetric element)

The analysis results for 4 noded axisymmetric shell elements are shown in figs.5 & 6. Fig.5 shows the maximum displacement as 0.4588 mm at two locations as shown in figure.Fig.6 shows the principal stress contour, which shows the maximum value of 66.66 MPa at LSI.

Toroidal Shell with Axisymmetric 8 Noded Shell Element

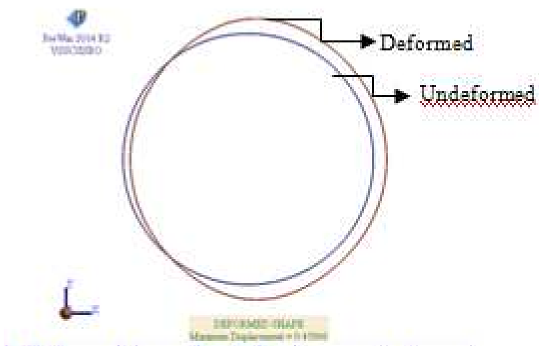

Fig.7: Deformed shape (8 noded axisymmetric element)

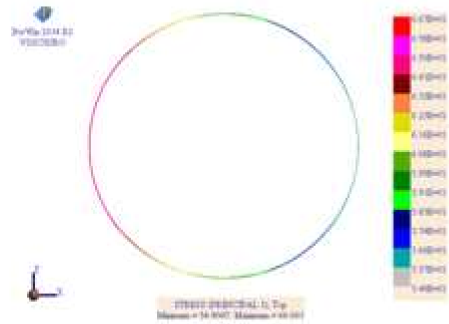

Fig.8: First Principal stress (8 noded axisymmetric element)

Fig.7 shows the maximum displacement as 0.4591 mm at two locations of the shell. Fig.8 shows the principal stress contour, which shows the maximum value of 66.66 MPa at LSI. The displacement and principal stress values obtained using 4 noded and 8 noded axisymmmetric shell elements are almost the same.

Toroid (Without Hole) Quarter Model- 4 Noded Shell Element

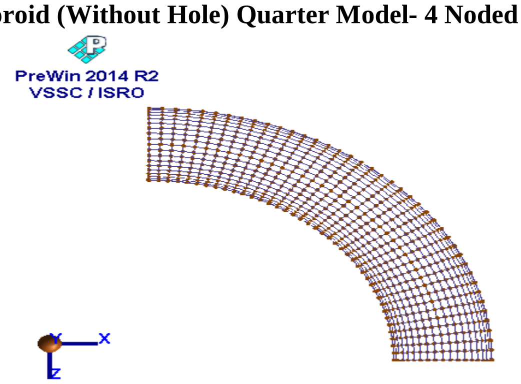

Fig.9: FE Idealisation for toroid without opening (4 noded shell element)

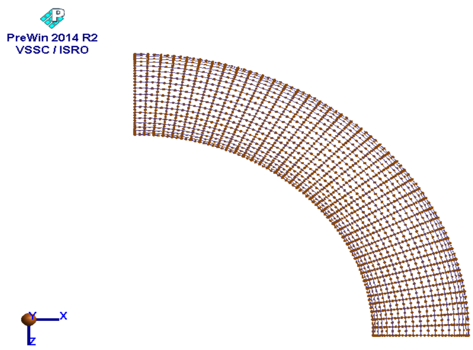

Fig.12: FE Idealisation for toroid without opening (8 noded shell element)

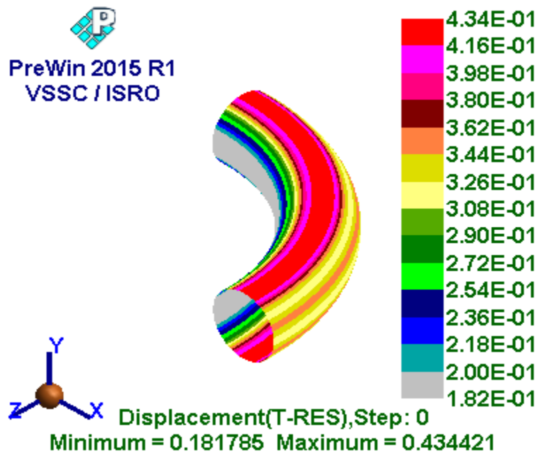

Fig.10: Deformation contour (4 noded shell element)

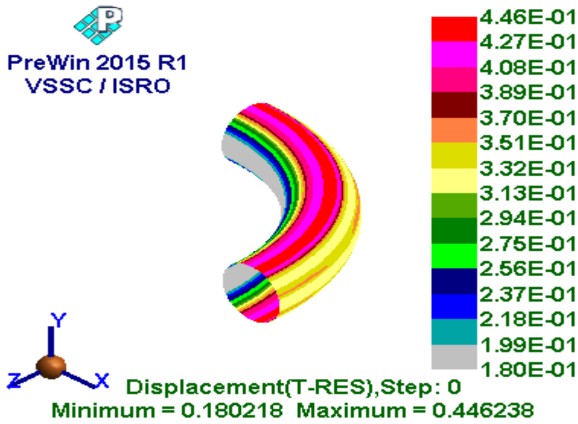

Fig.13:Deformation contour (8 noded shell element)

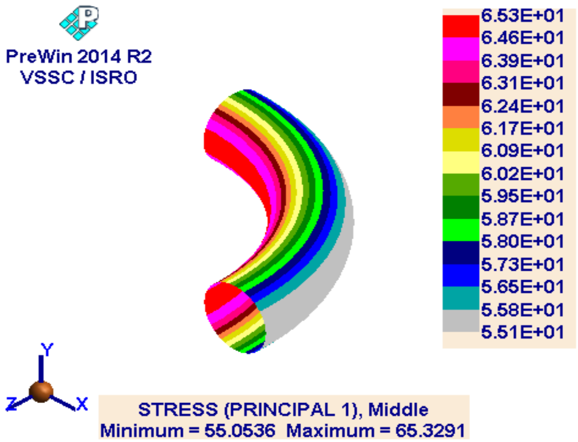

Fig.11: Principal stress (4 noded shell element)

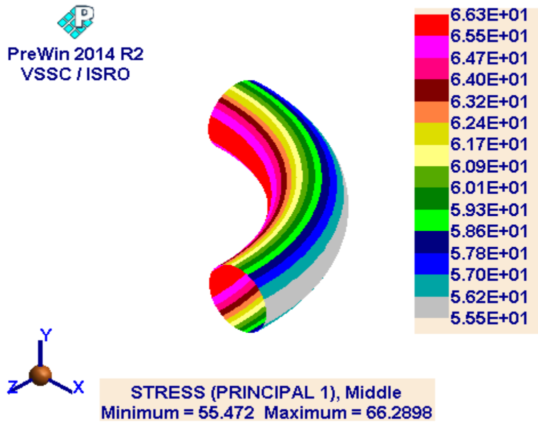

Fig.14:Principal stress(8 noded shell element)

Fig.9 shows FE idealization for quarter portion model of toroid without opening using 4 noded shell element. The maximum deformation is observed as 0.4344 mm as shown in Fig.10. From Fig.11 the maximum stress occur at the LSI of toroidal shell, and the maximum value of principal stress obtaines as 65.33 MPa.

Toroid (without hole) Quarter Model- 8 Noded Shell Element

Fig.12 shows FE idealization for quarter portion model of toroid without opening. The maximum deformation is observed as 0.4624 mm in Fig.13. From Fig.14 the maximum stress occur at the LSI of toroidal shell,the maximum value of principal stress obtaines as 65.33 MPa.

Table -2 Displacement and stress with various elements

Element type	Maximum displacement (mm)	Principalstress(MPa)
4 noded axisymmetric element	0.4588	66.66
8 noded axisymmetric element	0.4591	66.66
4 noded shell element	0.4344	65.33
8 noded shell element	0.4462	66.29

Table 2 shows the displacement and the MaximumPrincipal stress by idealizing with four different element types. It can be seen that the displacement and stresses are comparable.

TOROID WITH HOLE

Hole at Outer Region of Shell

Finite element idealization for toroidal shell with 20 mm opening at LSO is shown in Fig.15, which shows a continous uniform mesh at the region of opening.

Fig.16 shows that the maximum displacement i.e. 0.4529 mm which occur at the region of opening. The maximum principal stress of 145.26MPa also occurs near the vicinity of the hole, as shown in Fig.17; it is due to weakening of toroidal shell at the location of opening.

For toroid with hole, stress concentration factor is calculated to quantify how the stress is concentrated in the region of opening. Stress concentration factor (K), is a dimensionless factor. It is defined as the ratio of the highest stress in the element to the reference stress [1].

$$SCF,K = \sigma_{max}/\sigma_{ref}$$

Reference stress is the total stress within an element under the same loading conditions without the stress concentrators, meaning the total stress on the material where the material is free from holes, cuts, shoulders or narrow passes. The analysis carried out by considering various sizes of the openings at LSO and LSI. The maximum displacement and the maximum stress around the opening and the computed SCF values are shown in Tables -3and 4 for LSO and LSI respectively.

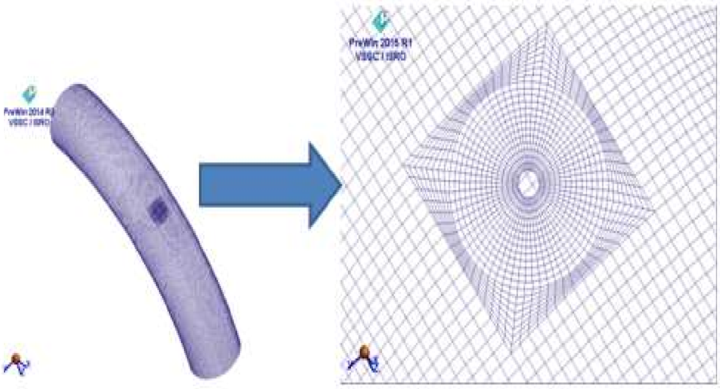

Fig.15: FE Idealisation for 20 mm dia. opening at LSO

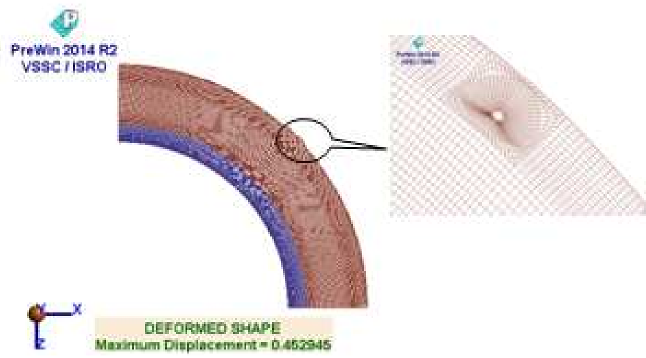

Fig.16: Deformed shape for opening of 20mm dia. at LSO

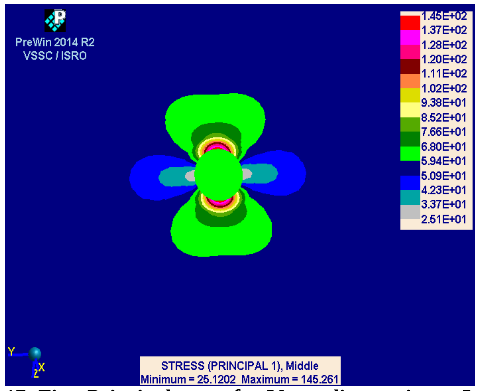

Fig.17: First Principal stress for 20mm dia opening at LSO

Table.3: SCF for various openings at LSO

Hole diameter (mm)	Displacement (mm)	Principal stress (MPa)	SCF
Without hole	0.4588	55.62	
10	0.4514	125.35	2.25
20	0.4529	145.26	2.61
30	0.5304	159.76	2.87
40	0.4618	174.38	3.14
50	0.5411	188.47	3.39
60	0.6597	201.59	3.62
70	1.1187	216.96	3.90
80	1.6632	224.98	4.04
90	2.3977	235.51	4.23
100	3.3091	249.20	4.48
110	4.4204	267.59	4.81
120	5.7530	289.14	5.20
130	7.3329	313.57	5.64
140	9.1829	338.74	6.09
150	11.3372	360.56	6.48

Table.4: SCF for various openings at LSI

Hole diameter (mm)	Displacement (mm)	Principal stress (MPa)	SCF
Without hole	0.4588	65.89	
10	0.4575	149.86	2.27
20	0.5340	170.61	2.59
30	0.9586	178.77	2.71
40	1.5579	181.24	2.75
50	2.3149	179.00	2.72
60	3.2156	181.29	2.75
70	4.2529	195.20	2.96
80	5.3939	212.62	3.23
90	6.6293	234.21	3.55
100	7.9561	255.83	3.88
110	9.3551	278.61	4.23
120	10.8150	301.63	4.58
130	12.3259	323.49	4.91
140	13.8810	342.75	5.20
150	15.4777	352.13	5.34

Finite element idealization for toroidal shell with 20 mm opening at LSO is shown in Fig.18.From Fig.19 the maximum displacement is obtained as 0.5340 mm at opening region. Here the maximum stress is larger than that obtained for 20 mm diameter opening at LSO region. In Fig.20, it is clear that, at opening region the maximum stress reaches 170.61 MPa.

The maximum displacement and the computed SCF values are plotted against diameter of opening in Fig.21 & 22respectively. So from Fig.21, For toroid with hole at inner region have higher displacement than toroid with hole at inner region for every diameters of the hole. But in Fig.22 for all diameters of opening at LSO region, the SCF is higher than that at LSI region.

Hole at LSI of Shell

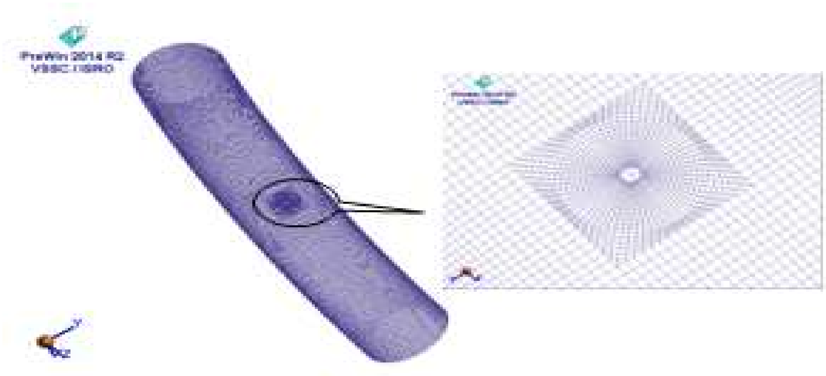

Fig.18 FE Idealisation for 20 mm dia. opening at LSI

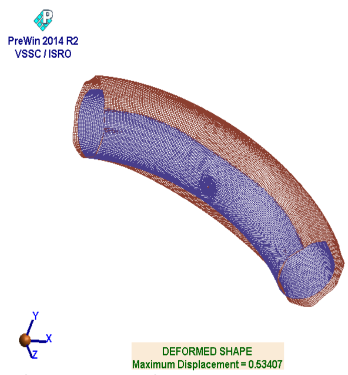

Fig.19 Deformed shape for 20 mm dia. opening at LSI

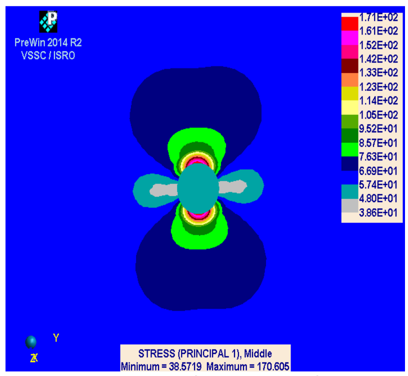

Fig.20 Principal stress for opening of dia.20 mm

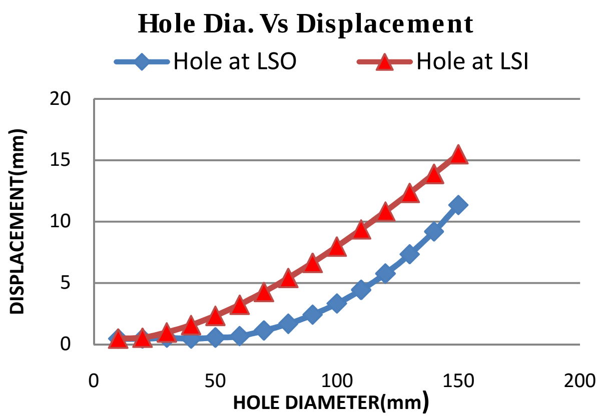

Fig.21: Hole dia. Vs Displacement

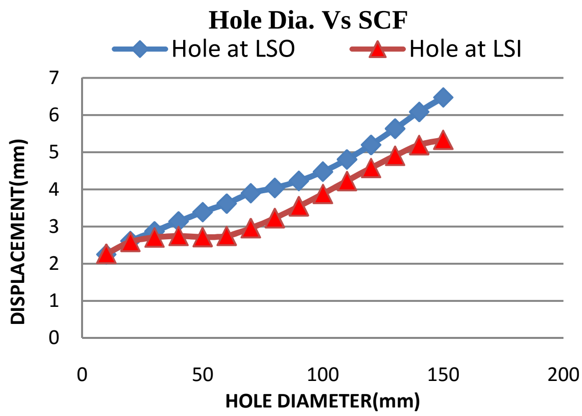

Fig.22: Hole dia. Vs SCF

CONCLUSIONS

- From the results obtained through the analysis of toroid without hole it can be observed that the maximum stress occurs at the inner region of the torus and the minimum stress occurs at outer region of torus.
- The stress concentration factor increases with increase in diameter of the hole.

- For toroid with hole at inner region have higher displacement than toroid with hole at outer region for every diameters of the hole.
- For toroid with hole at outer region have higher stress concentration factor than toroid with hole at inner region for all hole diameters.

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