ISSN No: 2348-4845
International Journal & Magazine of Engineering, Technology, Management and Research
A Peer Reviewed Open Access International Journal

Finite Element Analysis of Composite Toroidal Pressure Vessels

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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 ANSYS for composite materials.. This paper is an attempt to study of the effect of openings of 50 mm to 100 mm on toroidal pressure vessels. Also find out the variation of stress concentration factor for different diameter of hole for composite materials. To find the effect of position of hole, the holes of different diameters are placed at two different locations of the shell.

I. 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.

Toroidal vessels are commonly used for the storage of pressurized fluids in automotive and aerospace applications due to their optimal use of space. Here, the aim is to provide insight into the effect of openings on toroidal pressure vessels. The use of liquid petroleum gas (LPG) as a fuel source in motor vehicles is steadily increasing. LPG tanks are pressure vessels, which can normally be considered as thin shells. The shapes of pressure vessels that have been studied extensively over the years are mostly cylindrical, spherical and conical. Toroidal vessels have received lesser attention, largely due to their greater geometric complexity. The mechanical properties which are of interest for toroidal LPG containers are the static behaviour under internal pressure and collapse loads.

II. LITERATURE REVIEW:

Finite Element Analysis of Toroidal Pressure Vessel Using FEASTSMT/PreWin by Rakendu R, MK Sundaresan and Pinky Merin Philip. 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 (Finite Element Analysis of Structures). 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.

III. PROBLEM DEFINITION AND METHODOLOGY

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. So, to check stress concentration, analysis is done on Toroidal pressure vessel with different hole diameters at different locations.

III.I The methodology followed in this project

- 3D model of Toroidal pressure vessel is generated by using NX-CAD software.
- 3d model is converted into parasolid file.
- The parasolid file is imported to ANSYS software to perform analysis on Toroidal pressure vessel.
- Static analysis is performed on Toroidal pressure vessel for Eglass/Epoxy material.
- Analysis is done on Toroidal pressure vessel with hole on outer shell and inner shell for different hole diameters.
- Results and graphs are plotted for Eglass/Epoxy material.
- Static analysis is performed on Toroidal pressure vessel for Carbon/Epoxy material.
- Analysis is done on Toroidal pressure vessel with hole on outer shell and inner shell for different hole diameters.
- Results and graphs are plotted for Carbon/Epoxy material.

III.II.3D MODELLING OF TOROIDAL PRESSURE VESSEL

The 3D model of the toroidal pressure vessel is created using NX-CAD software. NX-CAD is the world's leading 3D product development solution. This software enables designers and engineers to bring better products to the market faster.

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International Journal & Magazine of Engineering, Technology, Management and Research
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It takes care of the entire product definition to serviceability. NX delivers measurable value to manufacturing companies of all sizes and in all industries.

IV. MATERIAL PROPERTIES

Eglass/Epoxy Mechanical Properties:

Table.1: Properties of E-Glass/Epoxy

Sl.No	Property	Units	E-Glass/Epoxy
1.	E_{11}	GPa	50.0
2.	E_{22}	GPa	12.0
3.	G_{12}	GPa	5.6
4.	ν_{12}	-	0.3
5.	$S^t_1 = S^c_1$	MPa	800.0
6.	$S^t_2 = S^C_2$	MPa	40.0
7.	S_{12}	MPa	72.0
8.	ρ	Kg/m^3	2000.0

SHELL63 Element Description

No of Nodes: 4 No. of dof: 6 (Ux, Uy, Uz, Rotx, Roty, Rotz) SHELL63 has both bending and membrane capabilities. Both in-plane and normal loads are permitted. The element has six degrees of freedom at each node: translations & rotations in the nodal x, y, and z directions. The geometry, node locations, and the coordinate system for this element are shown in the above Figure 1. The element is defined by four nodes, four thicknesses, elastic foundation stiffness, and the orthotropic material properties. The thickness is assumed to vary smoothly over the area of the element, with the thickness input at the four nodes. 3D model of the Toroidal pressure vessel was developed in UNIGRAPHICS. The model was converted into a Para solid to import in ANSYS.

V. STATIC ANALYSIS OF TOROIDAL PRESSURE VESSEL WITH HOLE ON OUTER SIDE OF SHELL

Static analysis is used to determine the displacements, stresses, strains and forces in structures or components caused by loads that do not induce significant inertia and damping effects.

V.I. Boundary conditions

- Both sides of pressure vessel is constrained in all dof
- Pressure load of 0.6 MPa is applied on areas of shell.

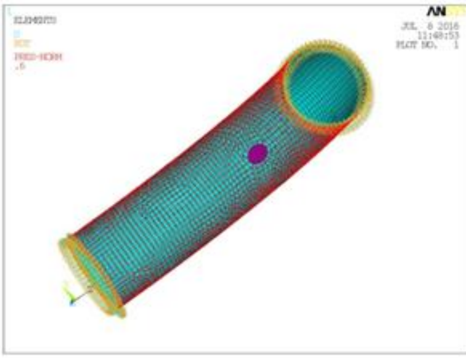


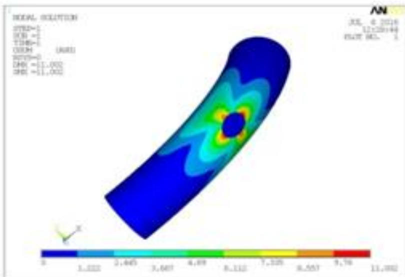
Fig.7 shows applied boundary conditions on Toroidal pressure vessel

Toroidal pressure vessel is subjected to pressure load for different hole diameters on outer shell. Static analysis is done for hole diameters from 50 to 100 mm. Results of Toroidal pressure vessel with different hole diameters are shown below.

VI. RESULTS

CASE-1: Toroidal pressure vessel with 90mm hole diameter:

Displacements



b

Fig.43 shows total displacement of Toroidal pressure vessel

- The maximum displacement on Toroidal pressure vessel for 90mm hole diameter is 11.002 mm.

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International Journal & Magazine of Engineering, Technology, Management and Research
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Stresses

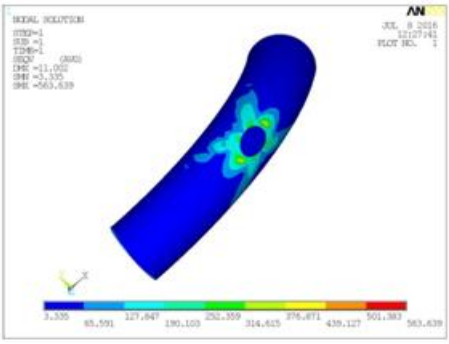

Fig.47 shows von misses stress of Toroidal pressure vessel

From results, the von misses stress of Toroidal pressure vessel is 563.6 MPa**.** The yield strength of Eglass/Epoxy material is 800 MPa. the von misses stress of Toroidal pressure vessel is less than the yield strength of material. Hence, the Toroidal pressure vessel with 90mm hole diameter is safe for pressure load.

CASE-2: Toroidal pressure vessel with 100mm hole diameter:

Displacements

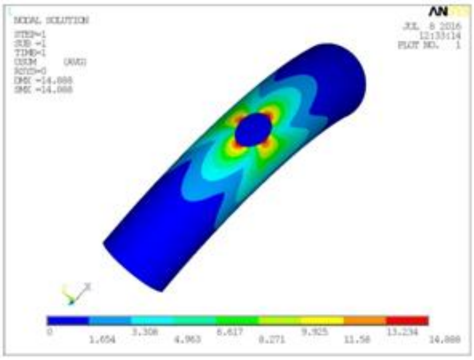

Fig.51 shows total displacement of Toroidal pressure vessel

- The maximum displacement on Toroidal pressure vessel for 100mm hole diameter is 14.8 mm.

Stresses

From results, the von misses stress of Toroidal pressure vessel is 530.8 MPa**.** The yield strength of Eglass/Epoxy material is 800 MPa. the von misses stress of Toroidal pressure vessel is less than the yield strength of material. Hence, the Toroidal pressure vessel with 100mm hole diameter is safe for pressure load.

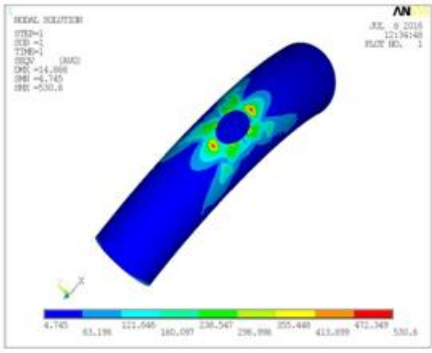

Fig 55 shows von misses stress of Toroidal pressure vessel

VI.I. STATIC ANALYSIS OF TOROIDAL PRESSURE VESSEL WITH HOLE ON INNER SIDE OF SHELL

VI.I.I. Boundary conditions

- Both sides of pressure vessel is constrained in all dof
- Pressure load of 0.6 MPa is applied on areas of shell.

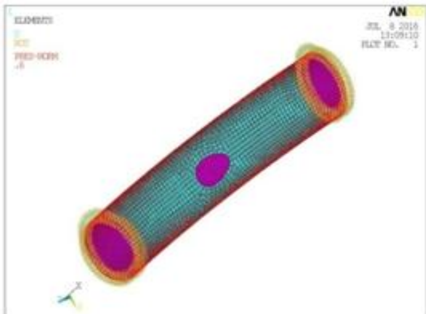

Fig.58 shows applied boundary conditions on Toroidal pressure vessel

VII. RESULTS

CASE-3: Toroidal pressure vessel with 90mm hole diameter:

Displacements

The maximum displacement on Toroidal pressure vessel for 90mm hole diameter is 7.31 mm.

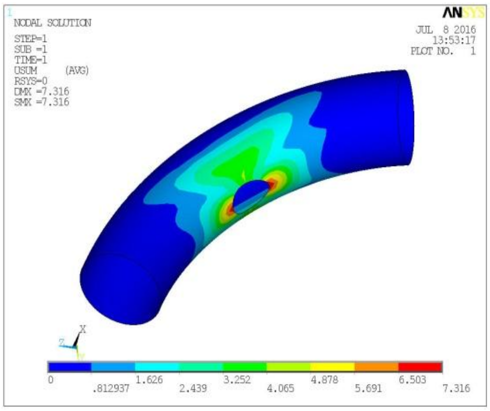

Fig.94 shows total displacement of Toroidal pressure vessel

Stresses

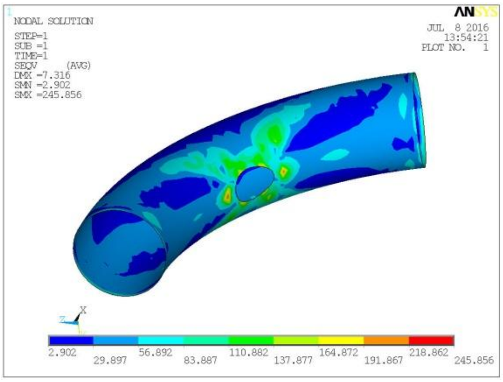

Fig.97 shows von misses stress of Toroidal pressure vessel

From results, the von misses stress of Toroidal pressure vessel is 245.8 MPa**.** The yield strength of Eglass/Epoxy material is 800 MPa. the von misses stress of Toroidal pressure vessel is less than the yield strength of material. Hence, the Toroidal pressure vessel with 90mm hole diameter is safe for pressure load.

CASE-4: Toroidal pressure vessel with 100mm hole diameter:

Displacements

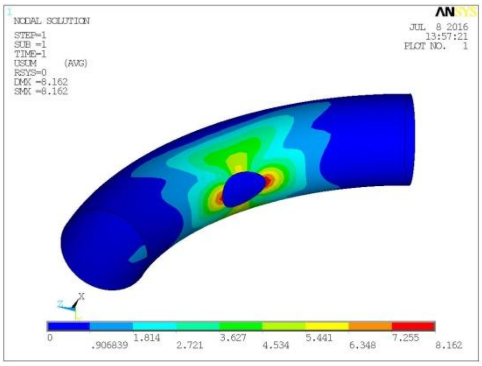

Fig.101 shows total displacement of Toroidal pressure vessel

- The maximum displacement on Toroidal pressure vessel for 100mm hole diameter is 8.16 mm.

Stresses

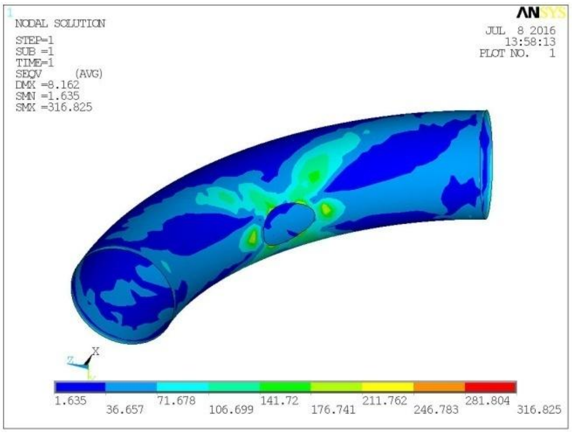

Fig.104 shows von misses stress of Toroidal pressure vessel

From results, the von misses stress of Toroidal pressure vessel is 316.8 MPa**.** The yield strength of Eglass/Epoxy material is 800 MPa. the von misses stress of Toroidal pressure vessel is less than the yield strength of material. Hence, the Toroidal pressure vessel with 100mm hole diameter is safe for pressure load.

VII.I.COMPARISON OF TOROIDAL PRESSURE VESSEL FOR DIFFERENT HOLE DIAMETERS AND DIFFERENT TYPE OF HOLE

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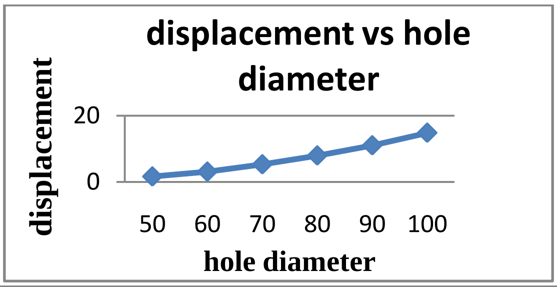
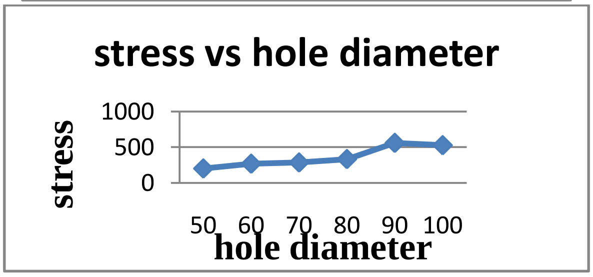
S. No	Hole diameter (mm)	Hole on outer shell		Hole on inner shell	
		Displacement (mm)	Von misses stress (MPa)	Displacement (mm)	Von misses stress (MPa)
1	90	11	563.6	7.31	245.8
2	100	14.8	530.8	8.16	316.8

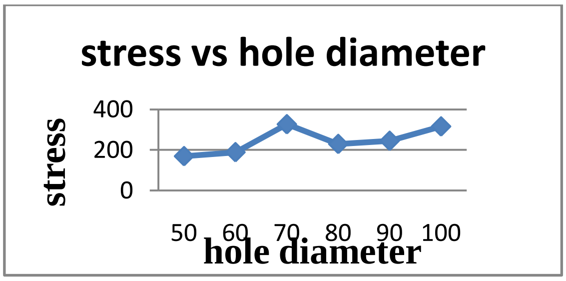
GRAPHS

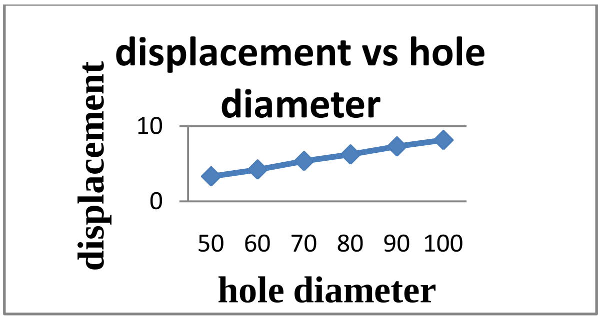
Toroidal pressure vessel with different hole diameter on outer shell:



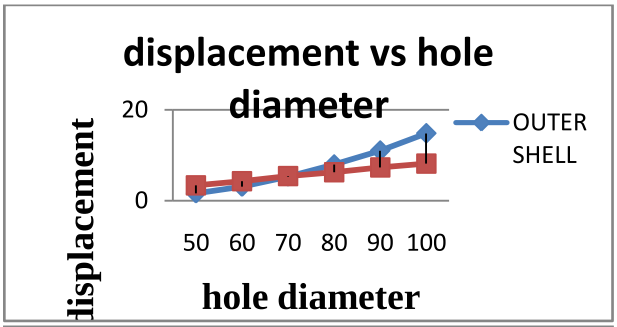


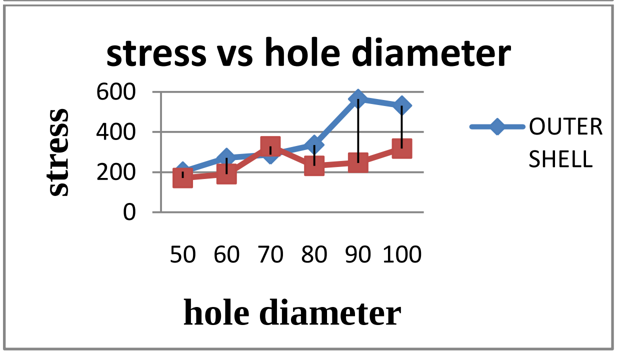
Toroidal pressure vessel with different hole diameter on inner shell:





Comparisons of displacement for outer shell and inner shell of toroidal pressure vessel





VII.II.FINITE ELEMENT ANALYSIS OF TOROIDAL PRESSURE VESSEL FOR CARBON/EPOXY MATERIAL

VII.II.I. MATERIAL PROPERTIES

Sl. No	Property	Units	Carbon/Epoxy
1.	E_{11}	GPa	134.0
2.	E_{22}	GPa	7.0
3.	G_{12}	GPa	5.8
4.	ν_{12}	-	0.3
5.	$S^t_1 = S^c_1$	MPa	880
6.	$S^t_2 = S^C_2$	MPa	60.0
7.	S_{12}	MPa	97.0
8.	ρ	Kg/m^3	1600.0

Table: Properties of HS Carbon/Epoxy

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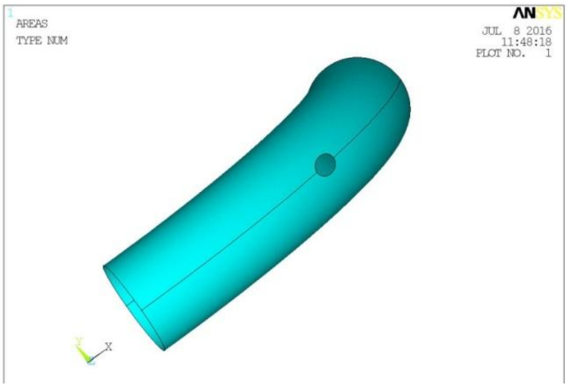

Fig.104 shows the geometric model of the Toroidal pressure vessel

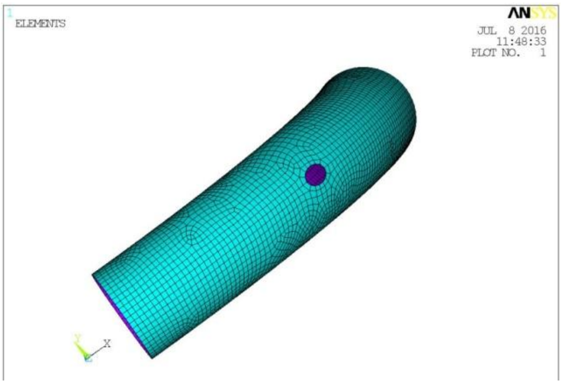

Fig.105 shows the finite model of the Toroidal pressure vessel

VII.III.STATIC ANALYSIS OF TOROIDAL PRESSURE VESSEL WITH HOLE ON OUTER SIDE OF SHELL

Boundary conditions

- Both sides of pressure vessel is constrained in all dof

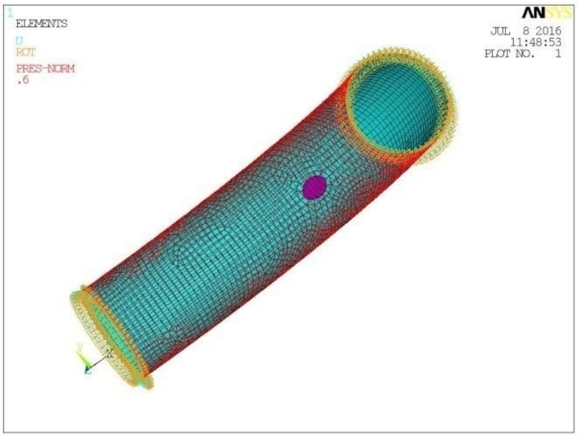

Fig 106 shows applied boundary conditions on Toroidal pressure vessel

Static analysis is done for hole diameters from 50 to 100 mm. Results of Toroidal pressure vessel with different hole diameters are shown below.

VIII. RESULTS

CASE-5: Toroidal pressure vessel with 90mm hole diameter:

Displacements

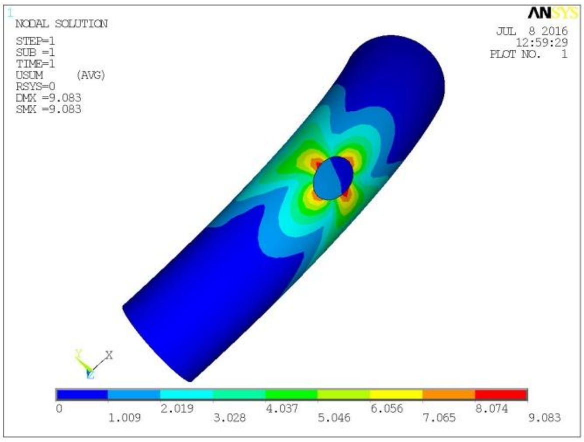

Fig.141 shows total displacement of Toroidal pressure vessel

- The maximum displacement on Toroidal pressure vessel for 90mm hole diameter is 9.08 mm.

Stresses

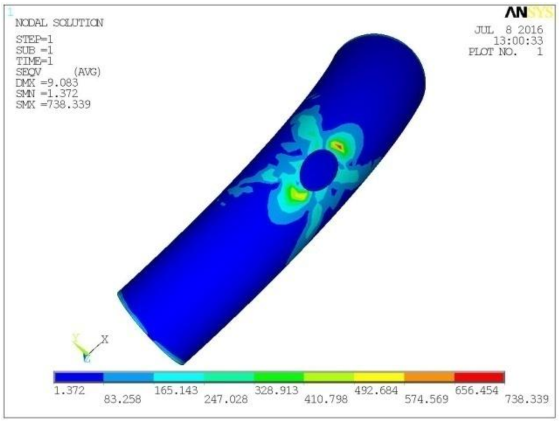

Fig.145 shows von misses stress of Toroidal pressure vessel

From results, the von misses stress of Toroidal pressure vessel is 738.3 MPa. The yield strength of Carbon/Epoxy material is 945 MPa. the von misses stress of Toroidal pressure vessel is less than the yield strength of material.

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Hence, the Toroidal pressure vessel with 90mm hole diameter is safe for pressure load.

CASE-6: Toroidal pressure vessel with 100mm hole diameter

Displacements

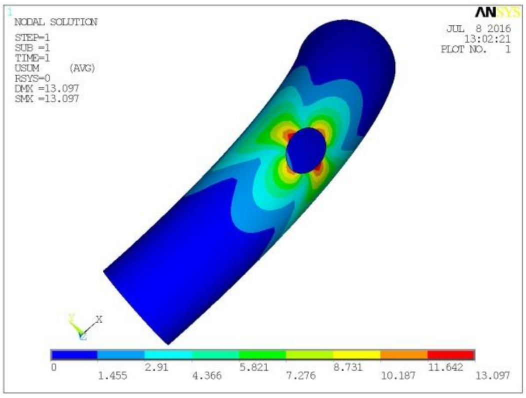

Fig.149 shows total displacement of Toroidal pressure vessel

- ➢ The maximum displacement on Toroidal pressure vessel for 100mm hole diameter is 13.09 mm.

Stresses

From results, the von misses stress of Toroidal pressure vessel is 939.06 MPa**.** The yield strength of Carbon/Epoxy material is 945 MPa. the von misses stress of Toroidal pressure vessel is less than the yield strength of material. Hence, the Toroidal pressure vessel with 100mm hole diameter is safe for pressure load.

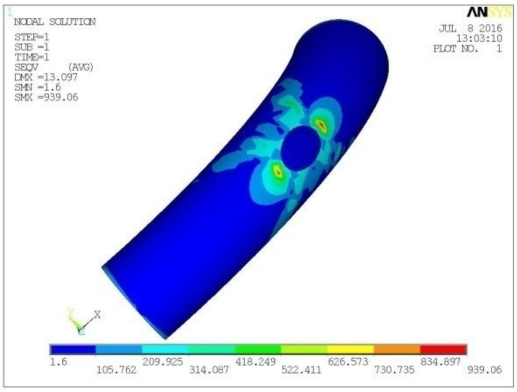

Fig.153 shows von misses stress of Toroidal pressure vessel

VIII.I. STATIC ANALYSIS OF TOROIDAL PRESSURE VESSEL WITH HOLE ON INNER SIDE OF SHELL

Boundary conditions

- ➢ Both sides of pressure vessel is constrained in all dof
- ➢ Pressure load of 0.6 MPa is applied on areas of shell.

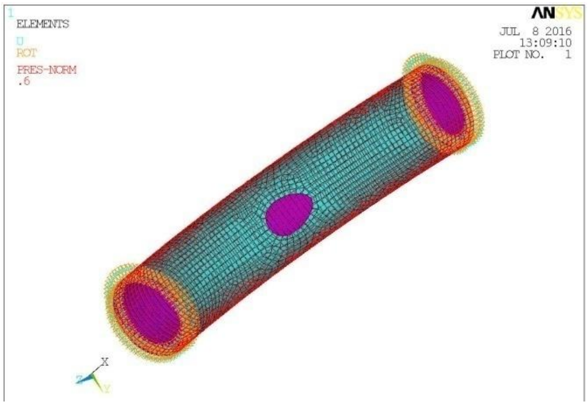

Fig..156 shows applied boundary conditions on Toroidal pressure vessel

CASE-7: Toroidal pressure vessel with 90mm hole diameter:

Displacements

The maximum displacement on Toroidal pressure vessel for 90mm hole diameter is 6.77 mm.

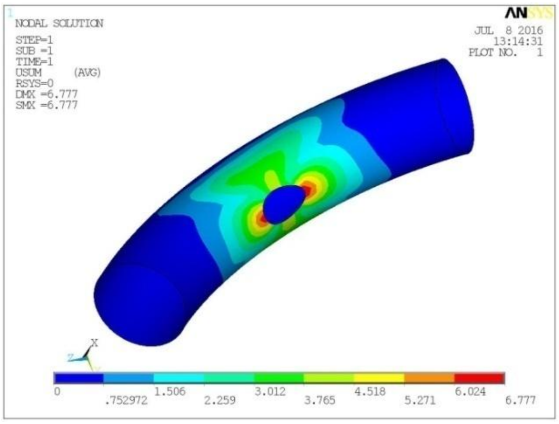

Fig.192 shows total displacement of Toroidal pressure vessel

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Stresses

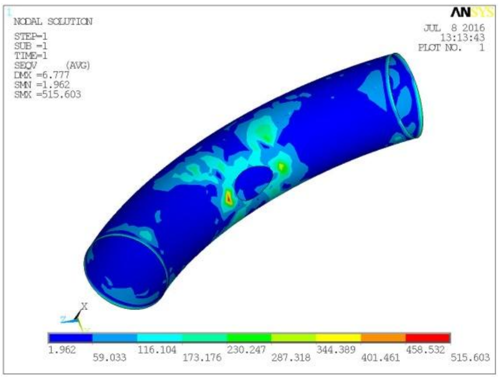

Fig.196 shows von misses stress of Toroidal pressure vessel

From results, the von misses stress of Toroidal pressure vessel is 515.60 MPa**.** The yield strength of Carbon/Epoxy material is 945 MPa. the von misses stress of Toroidal pressure vessel is less than the yield strength of material. Hence, the Toroidal pressure vessel with 90mm hole diameter is safe for pressure load.

CASE-8: Toroidal pressure vessel with 100mm hole diameter:

Displacements

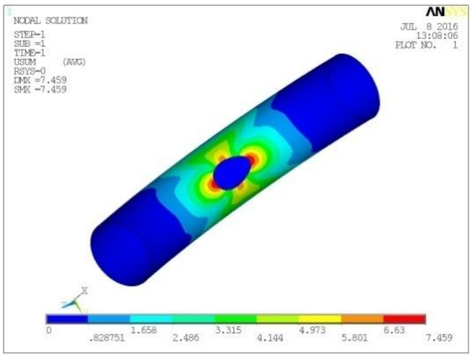

Fig.200 shows total displacement of Toroidal pressure vessel

- The maximum displacement on Toroidal pressure vessel for 100mm hole diameter is 7.45 mm.

Stresses

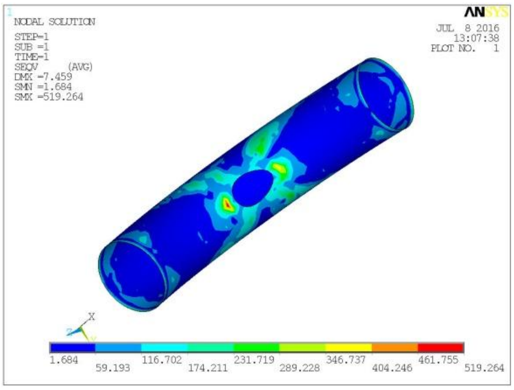

Fig.204 shows von misses stress of Toroidal pressure vessel

From results, the von misses stress of Toroidal pressure vessel is 519.26 MPa**.** The yield strength of Carbon/Epoxy material is 945 MPa. the von misses stress of Toroidal pressure vessel is less than the yield strength of material. Hence, the Toroidal pressure vessel with 100mm hole diameter is safe for pressure load

VIII.II. COMPARISON OF TOROIDAL PRESSURE VESSEL FOR DIFFERENT HOLE DIAMETERS AND DIFFERENT TYPE OF HOLE

S. No	Hole diameter (mm)	Hole on outer shell		Hole on inner shell	
		Displacement (mm)	Von misses stress (MPa)	Displacement (mm)	Von misses stress (MPa)
1	90	9.08	738.3	6.77	515.6
2	100	13.09	939.06	7.45	519.26

GRAPHS

Toroidal pressure vessel with different hole diameter on outer shell:

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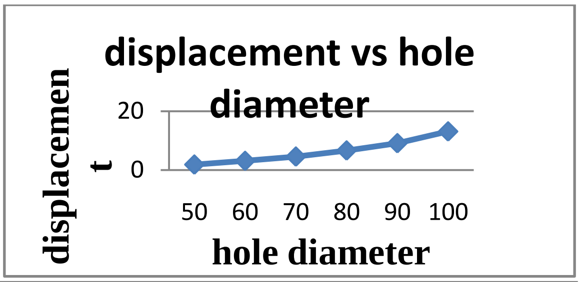
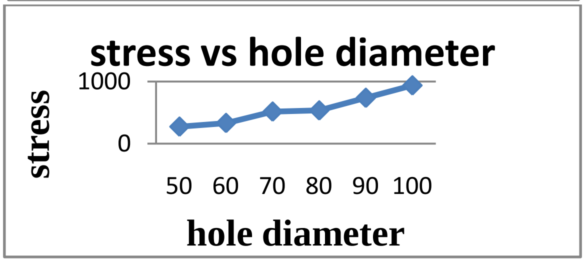
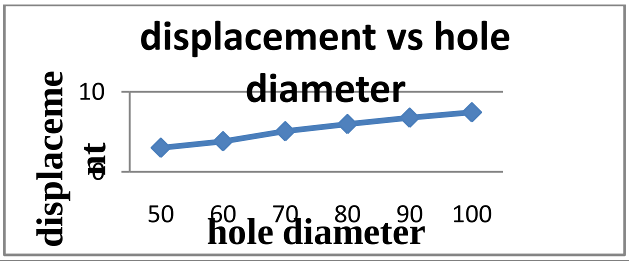
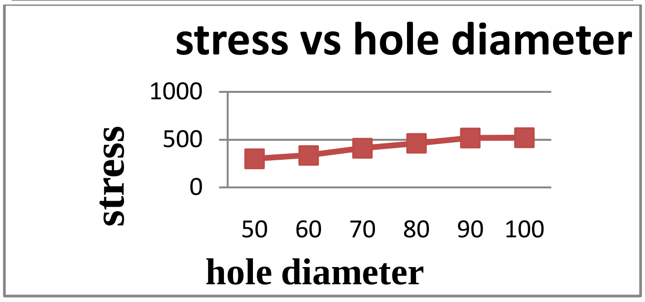


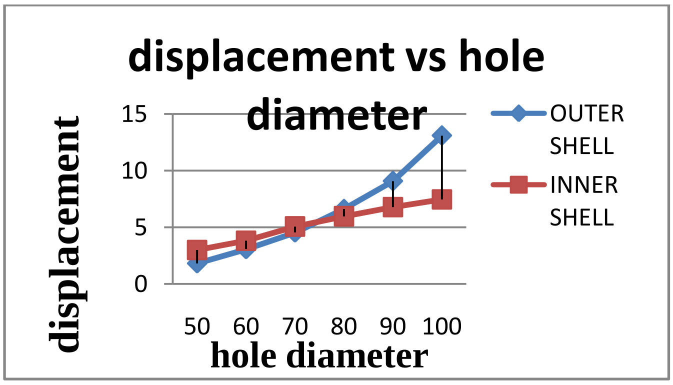


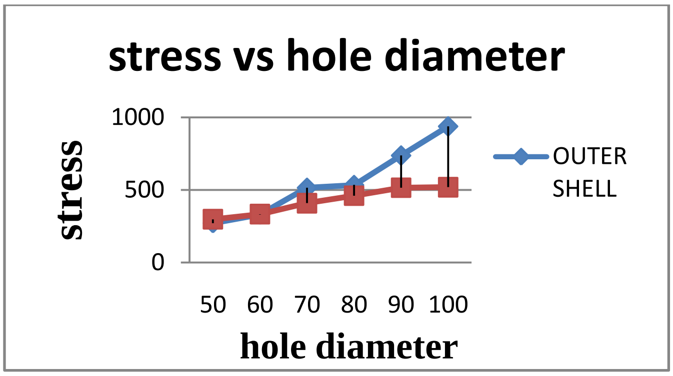
Toroidal pressure vessel with different hole diameter on inner shell:





Comparisons of displacement for outer shell and inner shell of toroidal pressure vessel:





IX. RESULTS AND CONCLUSION

Toroidal pressure vessel was subjected to structural analysis for two composite materials i.e. Eglass/Epoxy and Carbon/Epoxy materials. Toroidal pressure vessel with hole on surface was studied for different hole diameters.

IX.I. FOR EGLASS/EPOXY MATERIAL:

Static analysis of toroidal pressure vessel with hole on outer side of shell

CASE-1: Toroidal pressure vessel with 90mm hole diameter:

The maximum displacement on Toroidal pressure vessel for 90mm hole diameter is 11.002 mm. the von misses stress of Toroidal pressure vessel is 563.6 MPa**.** The yield strength of Eglass/Epoxy material is 800 MPa. the von misses stress of Toroidal pressure vessel is less than the yield strength of material. Hence, the Toroidal pressure vessel with 90mm hole diameter is safe for pressure load.

CASE-2: Toroidal pressure vessel with 100mm hole diameter:

The maximum displacement on Toroidal pressure vessel for 100mm hole diameter is 14.8 mm. the von misses stress of Toroidal pressure vessel is 530.8 MPa**.** The yield strength of Eglass/Epoxy material is 800 MPa. the von misses stress of Toroidal pressure vessel is less than the yield strength of material. Hence, the Toroidal pressure vessel with 100mm hole diameter is safe for pressure load.

ISSN No: 2348-4845
International Journal & Magazine of Engineering, Technology, Management and Research
A Peer Reviewed Open Access International Journal

Static analysis of toroidal pressure vessel with hole on inner side of shell:

CASE-3: Toroidal pressure vessel with 90mm hole diameter:

The maximum displacement on Toroidal pressure vessel for 90mm hole diameter is 7.31 mm. the von misses stress of Toroidal pressure vessel is 245.8 MPa**.** The yield strength of Eglass/Epoxy material is 800 MPa. the von misses stress of Toroidal pressure vessel is less than the yield strength of material. Hence, the Toroidal pressure vessel with 90mm hole diameter is safe for pressure load.

CASE-4: Toroidal pressure vessel with 100mm hole diameter:

The maximum displacement on Toroidal pressure vessel for 100mm hole diameter is 8.16 mm. the von misses stress of Toroidal pressure vessel is 316.8 MPa**.** The yield strength of Eglass/Epoxy material is 800 MPa. the von misses stress of Toroidal pressure vessel is less than the yield strength of material. Hence, the Toroidal pressure vessel with 100mm hole diameter is safe for pressure load.

FOR CARBON/EPOXY MATERIAL:

Static analysis of toroidal pressure vessel with hole on outer side of shell:

CASE-5: Toroidal pressure vessel with 90mm hole diameter:

The maximum displacement on Toroidal pressure vessel for 90mm hole diameter is 9.08 mm. the von misses stress of Toroidal pressure vessel is 738.7 MPa**.** The yield strength of Carbon/Epoxy material is 945 MPa. the von misses stress of Toroidal pressure vessel is less than the yield strength of material. Hence, the Toroidal pressure vessel with 90mm hole diameter is safe for pressure load.

CASE-6: Toroidal pressure vessel with 100mm hole diameter:

The maximum displacement on Toroidal pressure vessel for 100mm hole diameter is 13.9 mm. the von misses stress of Toroidal pressure vessel is 939.06 MPa**.** The yield strength of Carbon/Epoxy material is 945 MPa. the von misses stress of Toroidal pressure vessel is less than the yield strength of material. Hence, the Toroidal pressure vessel with 100mm hole diameter is safe for pressure load.

Static analysis of toroidal pressure vessel with hole on inner side of shell:

CASE-7: Toroidal pressure vessel with 90mm hole diameter:

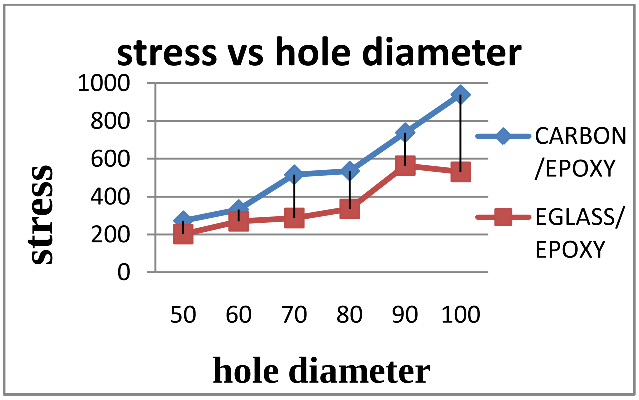
The maximum displacement on Toroidal pressure vessel for 90mm hole diameter is 6.77 mm. the von misses stress of Toroidal pressure vessel is 515.6 MPa**.** The yield strength of Carbon/Epoxy material is 945 MPa. the von misses stress of Toroidal pressure vessel is less than the yield strength of material. Hence, the Toroidal pressure vessel with 90mm hole diameter is safe for pressure load.

CASE-8: Toroidal pressure vessel with 100mm hole diameter:

The maximum displacement on Toroidal pressure vessel for 100mm hole diameter is 7.45 mm. the von misses stress of Toroidal pressure vessel is 519.26 MPa**.** The yield strength of Carbon/Epoxy material is 945 MPa. the von misses stress of Toroidal pressure vessel is less than the yield strength of material. Hence, the Toroidal pressure vessel with 100mm hole diameter is safe for pressure load.

GRAPHS

Comparison of stress values of toroidal pressure vessel with hole on outer shell for two materials:



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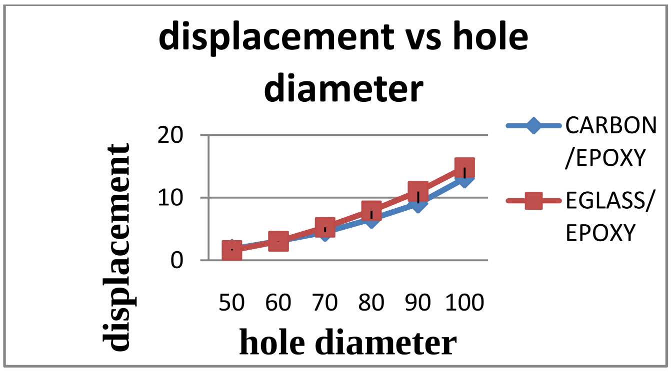
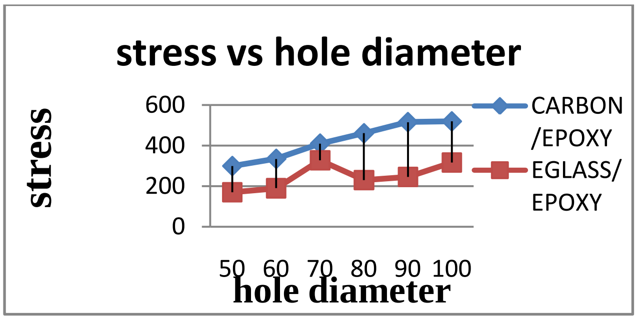
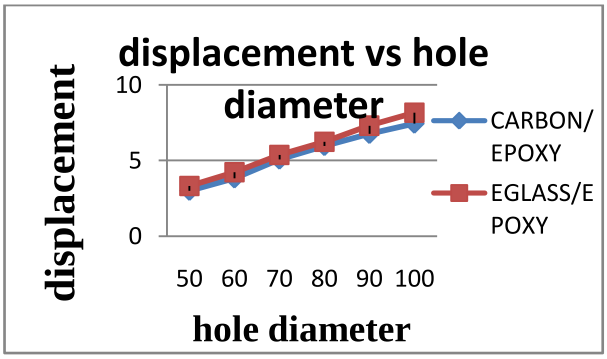


Comparison of stress values of toroidal pressure vessel with hole on inner shell for two materials:



Comparison of displacement values of toroidal pressure vessel with hole on inner shell for two materials:



CONCLUSION

Toroidal pressure vessel was developed in NX-CAD SOFTWARE. Static analysis was performed on toroidal pressure vessel for two different locations of hole on shell.

Toroidal pressure vessel was also studied for two composite materials (i.e. Eglass/Epoxy and Carbon/Epoxy materials). Based on results, Eglass/Epoxy material for different locations have less displacement values than Carbon/Epoxy material. The von misses stresses of Eglass/Epoxy material at different locations for different hole diameters were less comparative to Carbon/Epoxy material. hence, Eglass/Epoxy material was best suitable for Toroidal pressure vessel.

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