International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 10, October-2016

Design and Analysis of Filament Wound Toroidal Pressure Vessel

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***Abstract* - The main objective of this investigation is to study and compare experimentally the deformations, stresses, buckling load multipliers, frequency values for Conventional Toroidal Pressure vessel and Filament wound Pressure Vessel used to store CNG. The Toroidal Pressure vessel and Filament wound Pressure Vessel are modeled in 3D modeling software Creo 2.0. Theoretical calculations and analysis is also carried to determine stress and displacement values for toroidal pressure vessel. Static, Buckling and Modal analyses are performed on Toroidal Pressure vessel and Filament wound Pressure Vessel and the results were compared . The analysis is done in Ansys.**

Key words – Pressure Vessel, Toroid, Filament and Buckling

I. INTRODUCTION TO PRESSURE VESSEL

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.

Pressure vessels have been manufactured by filament winding for a long time. Although they appear to be simple structures, pressure vessels are difficult to design. Filament-wound composite pressure vessels have found widespread use not only for military but also for civilian applications. This technology originally developed for military use has been adapted to civilian purposes and was, in a later stage, extended to the commercial market. A potential widespread application for composite pressure vessels is the automotive industry. Emphasis on reducing emissions promotes the conversion to CNG or hydrogen fuelled tanks worldwide. Filament-wound composite pressure vessels utilizing high strength/modulus to density ratio offer significant weight savings over conventional all-metal pressure vessels for the containment of high pressure gases and fluids. Composite pressure vessels are expected to withstand a maximum burst pressure at a maximum internal volume and a minimum weight.

II. OBJECTIVE

The main of this thesis is to compare the analytical results for Conventional Toroidal Pressure vessel and Filament wound Pressure Vessel used to store CNG. The Toroidal Pressure vessel and Filament wound Pressure Vessel are modeled in 3D modeling software Creo 2.0.Theoretical calculations are done to determine stress and displacement values for toroidal pressure vessel. Static, Buckling and Modal analyses are performed on Toroidal Pressure vessel and Filament wound Pressure Vessel and compared for the deformations, stresses, buckling load multipliers, frequency values. The analysis is done in Ansys

III. LITERATURE SURVEY

The following works are done by some authors on toroidal pressure vessels: The work done by J Błachut[1], presents results of a numerical study into the buckling resistance of geometrically perfect and imperfect steel toroidal shells with closed cross-sections. Elastic and elastic-plastic buckling analyses of shells subjected to uniform external pressure were carried out for a range of geometries, boundary conditions and material properties. Toroids with circular and elliptical cross-sections were investigated. In the work done by Rakendu R[2], an attempt is made 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. In the paper by Lei ZU[3], presented an overview and comprehensive treatment for toroidal and domed pressure vessels. Since the geodesic winding has severe boundary conditions that confine the layup optimization, the non-geodesic trajectories are here extensively applied to enlarge the design space. The mathematical description of the geodesics and non-geodesics on a generic shell of revolution is briefly presented.

IV. PRESSURE VESSELS MODELS

3d Model Of Toroidal Pressure Vessel

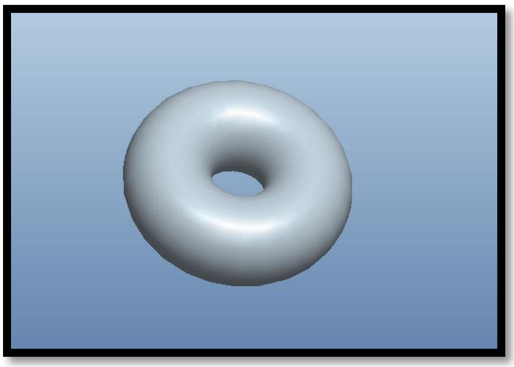

Fig - Final model

3D MODEL OF FILAMENT WOUND TOROIDAL PRESSURE VESSEL

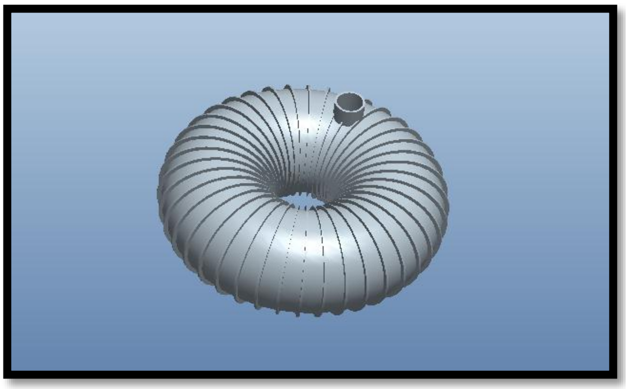

Fig – Final Model of Filament wound pressure vessel

V. THEORITICAL CALCULATIONS FOR STRESS AND DISPLACEMENT FOR TOROIDAL PRESSURE VESSEL

Introducing the aforementioned values the following expression for the shell point transversal displacements in the radial direction is obtained

$$\Delta r_0 = \frac{pa}{2E\delta} * (r_0 - \nu (r_0 + b))$$

The Meridoinal Stress σφ

⇨ $\sigma_\varphi = \sigma_\theta * \frac{r0+b}{r0}$

⇨ where Normal Stress $\sigma_\theta = \frac{pa}{2\delta}$

VI. ANALYSIS OF TOROIDAL AND FILAMENT WOUND TOROIDAL PRESSURE VESSEL

I. STRUCTURAL ANALYSIS OF FILAMENT WOUND TOROIDAL PRESSURE VESSEL

MATERIAL - STEEL

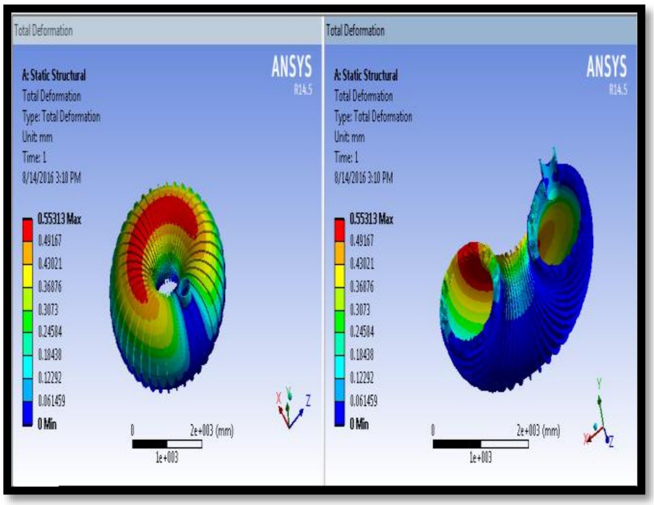

Fig – Total Deformation for Steel

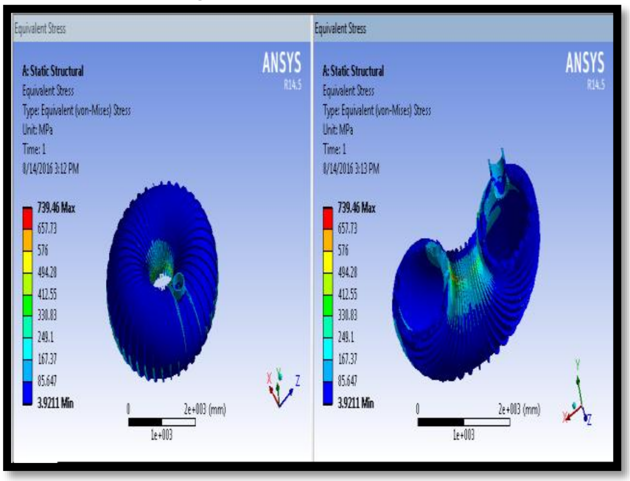

Fig – Equivalent Stress for Steel

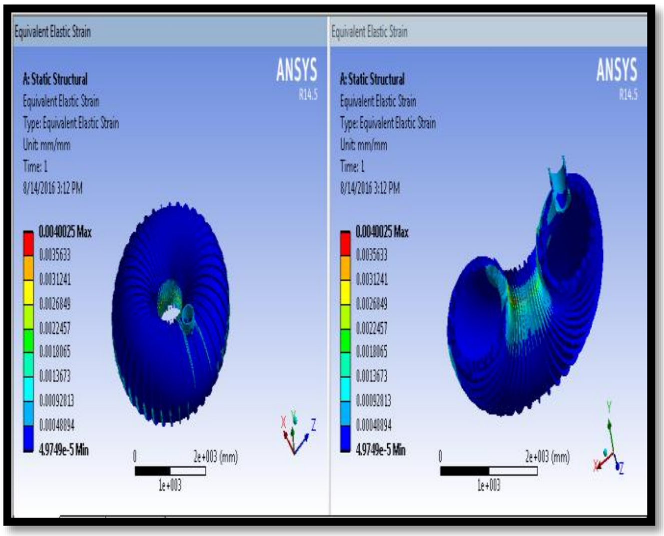

Fig – Equivalent Elastic Strain for Steel

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II. BUCKLING ANALYSIS OF FILAMENT WOUND TOROIDAL PRESSURE VESSEL

MATERIAL- KEVLAR

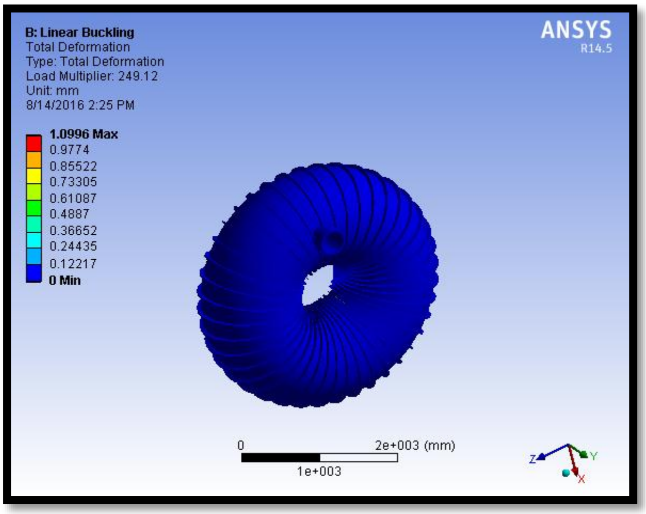


Fig – Total Deformation 1 for Kevlar

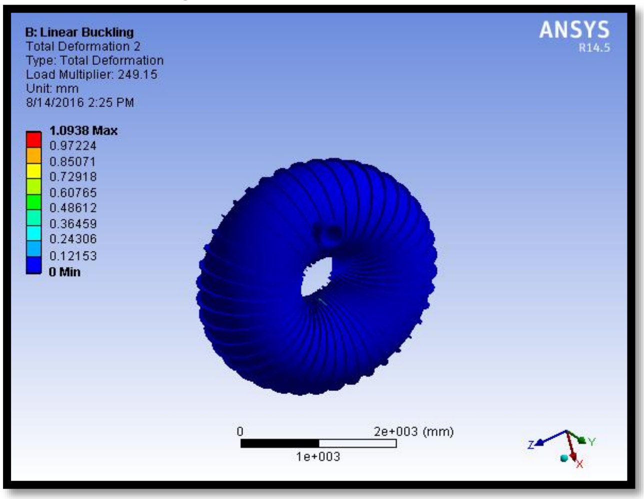


Fig – Total Deformation 2 for Kevlar

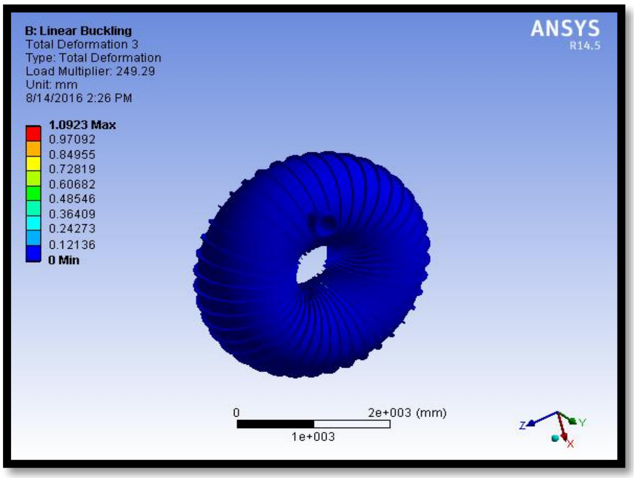


Fig – Total Deformation 3 for Kevlar

III. MODAL ANALYSIS OF WITH FILAMENT WOUND TOROIDAL PRESSURE VESSEL

MATERIAL - CARBON FIBER

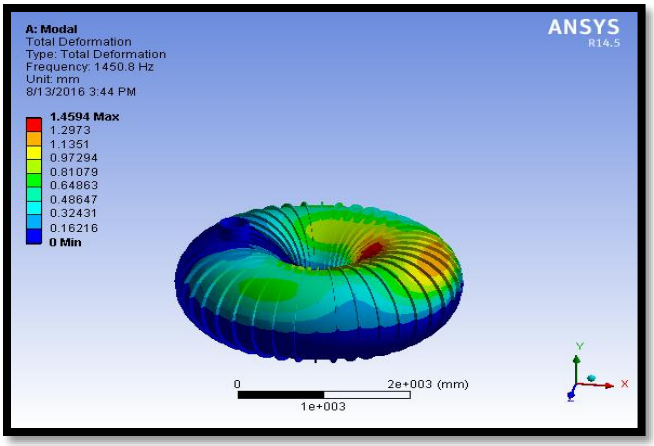


Fig – Total Deformation at Mode1 for Carbon Fiber

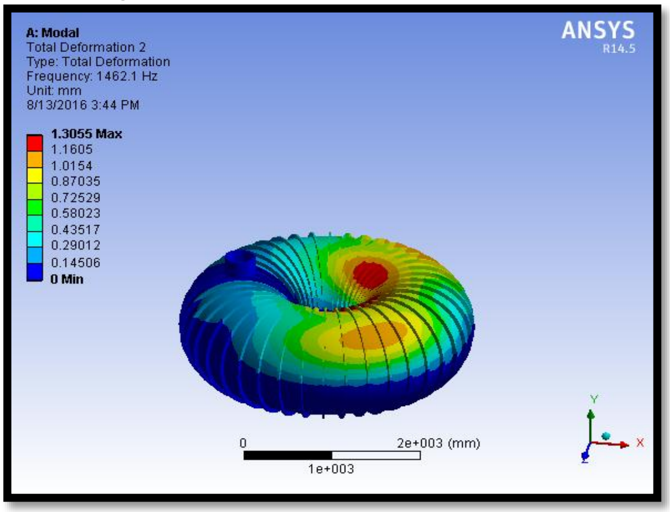


Fig – Total Deformation at Mode2 for Carbon Fiber

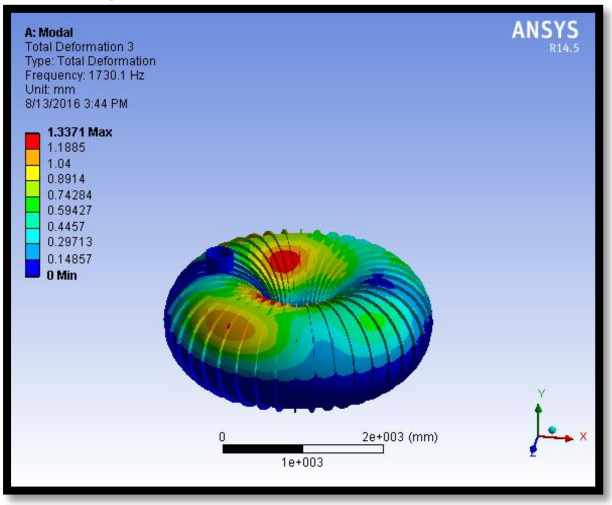


Fig – Total Deformation at Mode3 for Carbon Fiber

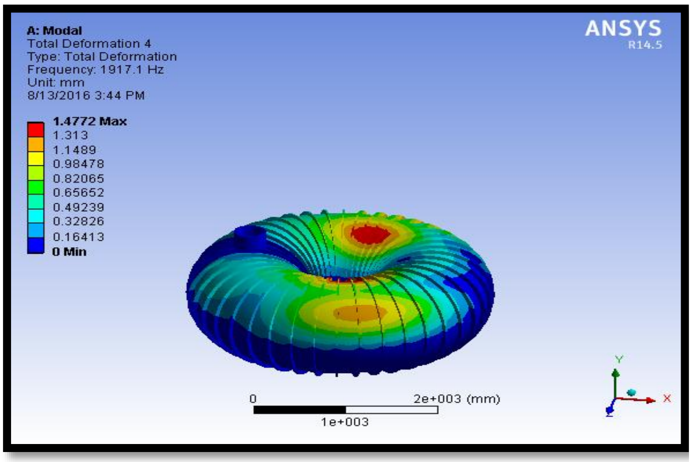


Fig – Total Deformation at Mode4 for Carbon Fiber

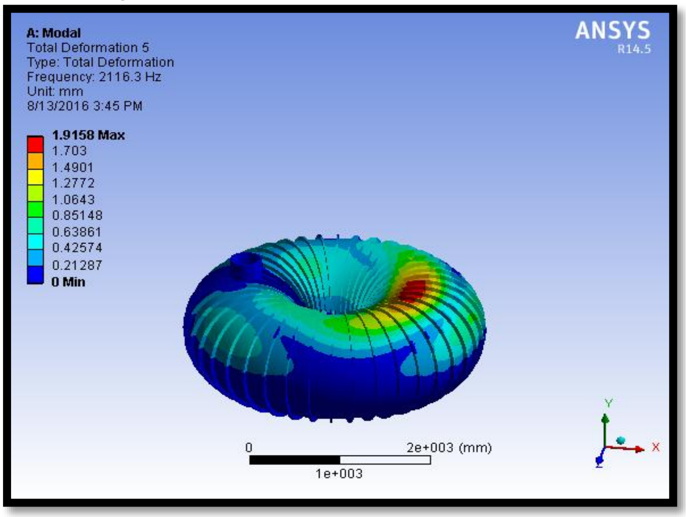


Fig – Total Deformation at Mode5 for Carbon Fiber

VII. RESULT & DISCUSSIONS

STATIC ANALYSIS

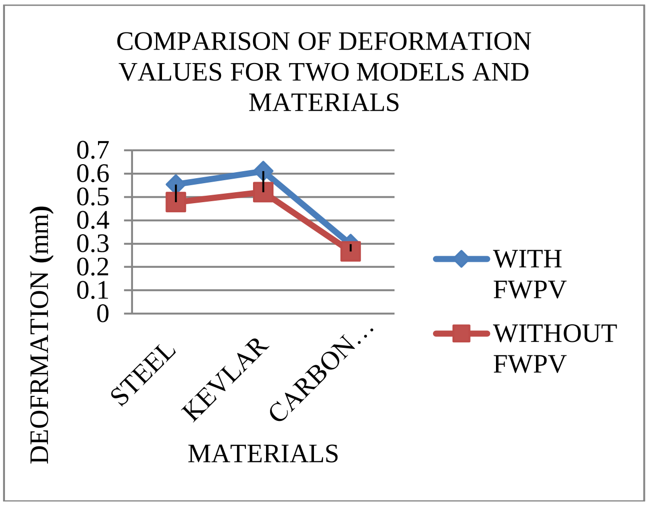
Table – Static analysis results of Filament wound toroidal pressure vessel

MATERIALS	DEFORMATION (mm)	STRESS (MPa)	STRAIN
STEEL	0.55313	739.46	0.0040025
KEVLAR	0.61059	707.49	0.004253
CARBON FIBER	0.29737	833.73	0.0023469

Table – Static analysis results of Toroidal pressure vessel

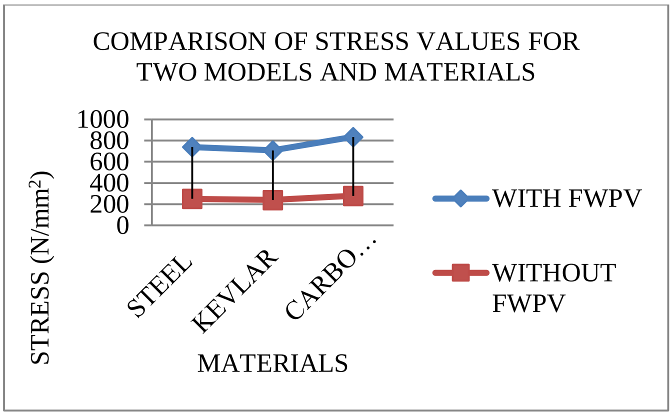
MATERIALS	DEFORMATION (mm)	STRESS (MPa)	STRAIN
STEEL	0.47742	250.38	0.0013985
KEVLAR	0.52034	240.4	0.0014948
CARBON FIBER	0.26662	280.29	0.00082847

Graph – Comparison of Deformation values for two models and different materials



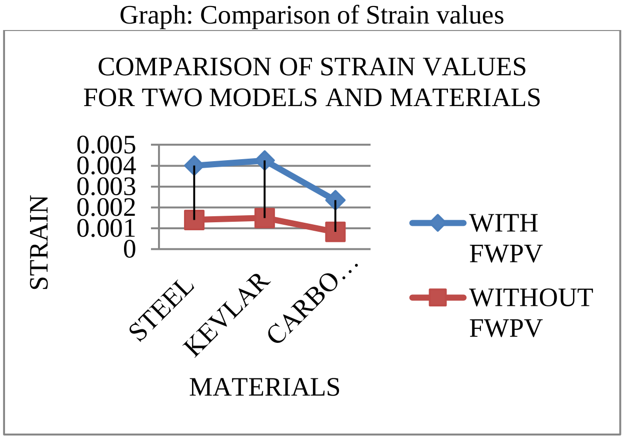
From the above graph it is observed that the total deformation is less for toroidal pressure vessel than Filament wound pressure vessel and it is less for Carbon Fiber material.

Graph: Comparison of Stress values



The stress value is less for toroidal pressure vessel than Filament wound pressure vessel and it is less for Kevlar material.

Graph: Comparison of Strain values



International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
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From the above graph it is observed that the strain is less for toroidal pressure vessel than Filament wound pressure vessel and it is less for Carbon Fiber material.

I. BUCKLING ANALYSIS

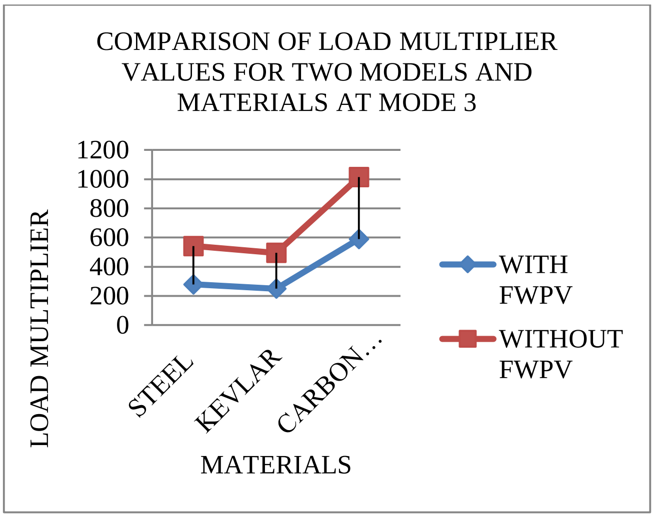
Table – Buckling results of Filament wound toroidal pressure vessel

MATERIALS	VARIABLES	MODE1	MODE2	MODE3
STEEL	Deformation (mm)	1.0771	1.0808	1.0766
	Load multiplier	279.27	279.4	279.43
KEVLAR	Deformation (mm)	1.0996	1.0938	1.0923
	Load multiplier	249.12	249.15	249.29
CARBON FIBER	Deformation (mm)	1.07	1.0709	1.0729
	Load multiplier	589.58	589.98	590.5

Table – Buckling results of Toroidal pressure vessel

MATERIALS	VARIABLES	MODE1	MODE2	MODE3
STEEL	Deformation (mm)	1.1389	1.034	1.0316
	Load multiplier	455.77	522.7	541.89
KEVLAR	Deformation (mm)	1.1263	1.0295	1.0248
	Load multiplier	417.13	476.18	495.03
CARBON FIBER	Deformation (mm)	1.1783	1.054	1.0522
	Load multiplier	845.5	985.68	1014.2

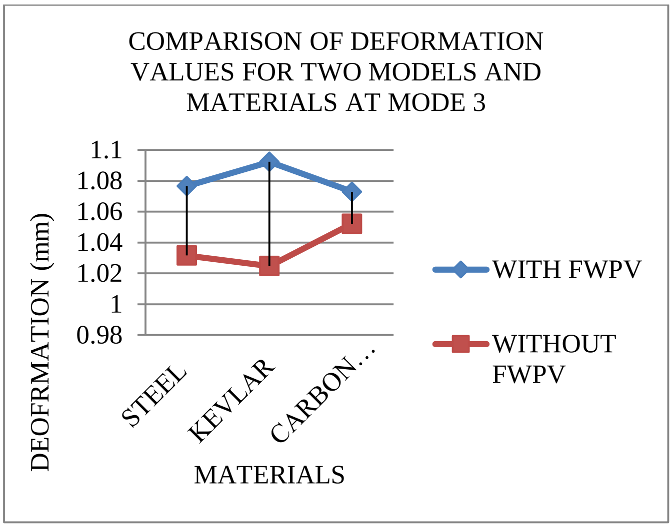
Graph: Comparison of Load multipliers values



The load factor is the factor that multiplies all loads, such that at that load buckling will occur. By observing the graph, it can be observed that the load multiplier value is more for Carbon Fiber, so the pressure vessel buckles faster for Kevlar than Steel and Carbon Fiber. Carbon Fiber buckles at more loads. The toroidal pressure vessel has more load multiplier values than Filament wound toroidal pressure vessel.

From the below graph it is observed that the deformation is less for toroidal pressure vessel than Filament wound pressure vessel and it is less for Kevlar

Graph: Comparison of Deformation values



II. MODAL ANALYSIS

Modal analysis is the study of the dynamic properties of structures under vibrational excitation.

Modal analysis is the field of measuring and analysing the dynamic response of structures and or fluids during excitationThe modal analysis results of results of pressure vessels with different materials are as follows

Table – Modal analysis results for Filament wound Toroidal pressure vessel

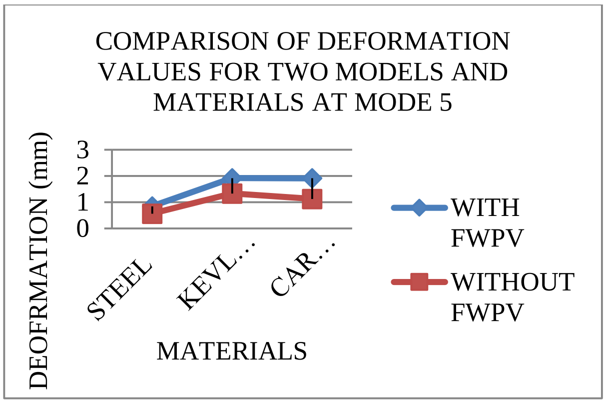
MATERIALS	VARIABLES	MODE1	MODE2	MODE5
STEEL	Deformation (mm)	0.68547	0.60968	0.85018
	Frequency (Hz)	491.89	496.82	729.63
KEVLAR	Deformation (mm)	1.5761	1.4025	1.919
	Frequency (Hz)	1077.9	1089.5	1604.1
CARBON FIBER	Deformation (mm)	1.4594	1.3055	1.9158
	Frequency (Hz)	1450.8	1462.1	2116.3

The above table clearly represents the analysis results for different materials like steel, Kevlar and carbon fiber and comparison can be done for respective results.

Table – Modal analysis results for Toroidal pressure vessel

MATERIALS	VARIABLES	MODE1	MODE2	MODE3
STEEL	Deformation (mm)	0.56699	0.55333	0.64259
	Frequency (Hz)	545.13	545.96	555.31
KEVLAR	Deformation (mm)	1.2632	1.2683	1.434
	Frequency (Hz)	1189.9	1191.4	1220.5
CARBON FIBER	Deformation (mm)	1.4281	1.5201	1.3423
	Frequency (Hz)	1614.6	1626	1631.1

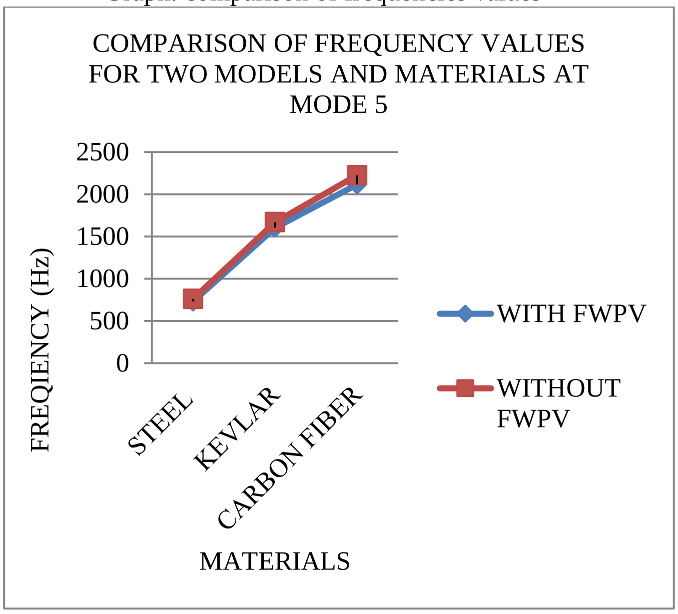
Graph: comparison of deformation values at mode5



From the above graph it is observed that the deformation is less for toroidal pressure vessel than Fialment wound pressure vessel and it is less for Steel.

From the below graph it is observed that the frequency values are less for filament wound toroidal pressure vessel than toroidal pressure vessel, so vibrations are less for filament wound pressure vessel and it is less for Steel.

Graph: comparison of frequencies values



VIII. CONCLUSION

Theoretical calculations are done to determine stress and displacement values for toroidal pressure vessel. By observing the calculations, the displacement is less for Carbon Fiber than Kevlar and Steel. The values are similar with that of analytical results.

By observing the static analysis results, the total deformation is less for toroidal pressure vessel than Filament wound pressure vessel and it is less for Carbon Fiber material. From the stress results it is observed that by using steel for filament wound pressure vessel fails because the stress values are more than its allowable strength but for Kevlar and Carbon Fiber the stress values are less than their respective allowable strength values. The stress value is less for toroidal pressure vessel than Filament wound pressure vessel and it is less for Kevlar material. The strain is less for toroidal pressure vessel than Filament wound pressure vessel and it is less for Carbon Fiber material.

Based on the buckling analysis results, the load factor is the factor that multiplies all loads, such that at that patcular load buckling will takes place. From the results, it can be observed that the load multiplier value is more for Carbon Fiber, so the pressure vessel buckles faster for Kevlar than Steel and Carbon Fiber. Carbon Fiber buckles at more loads. The toroidal pressure vessel has more load multiplier values than Filament wound toroidal pressure vessel. It was found that the deformation is lower for toroidal pressure vessel than Filament wound pressure vessel and it is less for Kevlar.

By observing the modal analysis results, the deformation is less for toroidal pressure vessel than Filament wound pressure vessel and it is less for Steel. The frequency values are less for filament wound toroidal pressure vessel than toroidal pressure vessel, so vibrations are less for filament wound pressure vessel and it is less for Steel.

IX. FUTURE SCOPE

In the present work, comparative analysis is carried between the toroidal pressure vessel and filament wound pressure vessel, by which it is found that filament wound pressure vessel did not yield better for stresses but withstands vibrations. So more experiments has to be done on filament wound pressure vessel so as that the stresses will be reduced. Analytically use of composites is validated for pressure vessel, but practical experimentations has to be done for further investigation.

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