STRUCTURAL DESIGN AND ANALYSIS OF COMPOSITE ROCKET MOTOR CASING (CRMC) FOR HIGH STRENGTH APPLICATIONS

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Abstract: Composite pressure vessels are widely used as rocket motor casings in high performance applications. Due to their high specific strength, stiffness, light weight and tailor made properties composite pressure vessels are fabricated with filament winding technique. Recent studies on hybrid composite shows better mechanical properties for carbon fiber- T700 composite. In the present study light weight prototype carbon composite rocket motor casing (CRMC) was designed and developed with hybrid resin system with carbon fiber-T700. The thickness of laminated structure at various portions are calculated by netting analysis. CRMCs are thin-walled pressure vessels with integrated end domes with varying sizes which are designed to withstand high pressure. In order to optimize the structural performance, CRMCs are designed with cylindrical portion with end domes. Various configurations of end domes profiles are designed for polar openings depending on the geometries of ignition end (IE) and nozzle end (NE).Burst pressure of composite casing is calculated based on classical laminate theory (CLT). A new method has been developed to analyze filament wound composite pressure vessels. In this method, the orthotropic engineering constants are computed on an element-by-element basis to accurately predict the structural response of a CRMC under internal pressure. In addition, 3D layered analyses of CRMC have been performed to predict the behavior of the structure.

***Keywords*:** CRMC, stiffness, hybrid resin, end domes, structural analysis, etc.

1. Introduction

Filament winding is a very popular method to produce composite pressure vessels. Filament wound composite pressure vessels made with carbon fiber reinforced polymers (CFRP) for structural applications in wind power, automotive and aerospace industries. These composites are special attraction and attention towards carbon fiber rocket motor casings. In this process an axisymmetric mandrel with an outside surface similar to the inner surface of the part to be produced is used to produce axisymmetric composite. Fiber from continuous fiber roving gets wetted as it passes through a hybrid resin bath. This resin wet fiber as it exits from resin bath gets wound on a mandrel which continually rotates on its axis of symmetry. During winding care is taken that there is sufficient tension in fiber so that the winding remains taut on the mandrel. The rotational speed of the mandrel and the traverse speed of resin bath fiber are variable process parameters. Choosing appropriate values of these parameters the helix angle of filament wound can be controlled layer by layer in the desired component.

The most important advantage of filament winding is reduced cost with respect to metallic vessels. Most of the CRMCs have hoop and helical windings that are needed to be solved by CAD, ANSYS. To compute parameters like thickness some initial assumptions were made. 2D drawing is developed by using Auto Cad software and structural analysis was carried out with ANSYS. The displacement magnitude, vonmises stresses and strains developed was pictorially visualized and resolved during analysis. This software employs finite element analysis technique to generate the solution.

2. Background

It has been proved that the optimum shape profile for filament wound dome is isotensoid [1], on the basis of the netting theory [2]. The isotensoid which facilitate the dome structure with minimum weight and maximum strength. All the roving fibers have uniform tension throughout their length was designed the major stresses are carried by the fibers of the laminate [3]. Weiming Chen et al[4] explained about theoretical analysis, material selection and proof pressure test. S.Sankar Reddy, Dr.C.Yuvraj, and Dr. K.Prahlada Rao [5] studied experimental characterization of carbon fiber T-700 design and fabrication of structural component. Qingjie Zhang et al[6] Matrix with high modulus proves excellent mechanical and interfacial properties of composites. J.De Carvalho et al[8] and V.Ramanjaneyulu [10] FEA is performed to determine fiber orientation, fiber path, lay up sequence for linear static analysis. M.Madhavi, K.V.J.Rao and K.Narayana Rao [9] Netting analysis is used for calculating for hoop and helical thickness of the shell. A balanced ply sequence is considered for pressure vessel. C.Venkateshwar Reddy and Dr.P.Ramesh Babu[10] influence of hybrid resin on mechanical properties of carbon fiber T700 by filament wound composite. There is an advantage while considering hybrid resin system for design of CRMC. Laminate testing results shows increase in strength as well as stiffness of carbon fiber T700 composite.

3. Mechanical properties of CFRP with hybrid resin

In the present study the matrix has been modified with hybrid resin system with varied weight fraction of resin of LY 556 and LY 5052. The PBW of hybrid resin 80:20, 60:40, 50:50, 40:60, and 20:80 hardener HT972 was used. The ratio of hybrid resin to the hardener is in proportion of 100:27 by weight was maintained. Specimens are prepared by using filament winding method. The carbon fiber strands are unwind and passed continuously through resin tank. These resin impregnated strands are passed on to a rotating cylindrical mandrel. The strands are wound around the mandrel in a controlled manner and in a specific fiber orientation. Fiber tension is critical in filament winding because compaction is achieved through the fiber tension. The fiber tension must be optimal level because high fiber tension may break the fiber completely or fiber fracture at the surface. The summary of tensile strength test results are given in table.1.

Table.1: Summary of Test Results

Ratio of Resin	Density gm/cc	Resin content % by Weight	Fiber content % by Weight	Volume Fraction Vf	Max.Displacement in mm	Max.Load in KN	Tensile Strength (MPa)
50:50	**1.58**	**21.17**	**78.83**	**70**	**6.96**	**41.65**	**1927.33**
60:40	1.51	35.00	65.00	55	6.12	30.68	1393.50
80:20	1.49	34.04	65.96	55	5.99	31.52	1396.00
20:80	1.52	34.50	65.50	56	5.60	40.20	1748.83
40:60	1.50	36.00	64.00	54.5	5.56	36.41	1127.55

4. Design of CRMC with hybrid composite

4.1 Assumptions

The classical laminate theory follows some assumptions in designing CRMC. The casing is under tension and assumptions are peculiar to the pressure vessel.

- Fiber and matrix strains are equal.
- Tensile and compressive deformations are equal.
- Shear stresses developed in the fiber matrix interfaces are low
- Structure obeys hooks law
- The fibers are straight and continuous.

The properties of composite laminate are measured by testing the laminate at experimental level or by using the lamination theory with ply level material properties. The characteristics of longitudinal, transverse of shear strength and shear modulus, strain to failure are tested.

4.2 Design loads

The design factor of safety on ultimate tensile strength for the study is 1.25 and yield strength is 1.125. The pressure vessel is designed for internal pressure. Structural loads are taken care of by the netting system of the fibers. The total thickness of composite casing is obtained by the combination of helical, hoop layers and dollies. The maximum expected operating pressure (MEOP) = 8MPa. The CRMC design requirements are as follows:

- The proof pressure = 1.1 x MEOP = 8.8MPa
- The design pressure =1.25 x MEOP = 10MPa

4.3 Geodesic and non-geodesic winding of CRMC

The composite pressure vessel with equal pole opening can be fabricated by geodesic winding. Non-geodesic winding is considered for un equal pole openings. In geodesic winding, geodesic path between two points on the mandrel surface is the shortest distance between the two points for a given rotational difference between the points. It is the path on the mandrel surface along which the fibre under tension does not slip and no force is required to keep the fiber from the slipping. The angle of winding is constant throughout the length of the cylindrical mandrel. The fibre path on the development on the cylindrical mandrel is indicated as a linear path. The non-geodesic path is slightly deviating from the geodesic path counting on friction to keep the fibre in its proper position. In this winding, the angle of winding varies throughout the length of the cylinder. The fibre path on the development on the cylindrical mandrel is indicated as a nonlinear path. To predict the failure of pressure vessel it is necessary to consider analytical methods and the progressive failure of plies are studied through classical laminate theory

4.4 Netting Analysis for filament wound shell

For the designing of the shell thickness, netting theory is very important. In netting theory the casting comprises of a system of fibers alone neglecting strength contribution of the resin system. A cylinder-dome casing wall thickness consists of single helical and hoop layers. The total thickness of the shell comprises of total helical thickness, total hoop thickness and doily thickness. The design of the test pressure vessel and the wall thickness is obtained based on netting analysis. The plies are arranged to maintain the symmetry with respect to the mid-plane. A balanced symmetry is the best option for the CRMC structures because the loading in a particular plane does not affect deformations in other planes. The required number of helical and hoop plies are calculated with netting analysis. The thickness calculated for helical and hoop layers are as follows:

- Hoop thickness : 0.6 mm
- Helical Thickness : 1.4 mm
- Skirt layers : 0.5 mm
- **Total Thickness at cylinder: 2.5 mm**

4.5 Design of CRMC with end domes

A standard test pressure vessel is designed to substantiate the suitability of high strength CFRP material with hybrid resin. The experimental model is considered with diameter 300mm and length 600mm with un-equal two pole opening. The range for the one side pole opening is approximately 0.2R to 0.58 at the other end. The composite pressure vessel is composed of a cylindrical vessel, closed with forward and aft domes. Different pole opening requires the modification of helical winding with respective to the shell. The fiber path, angle of winding on dome shapes and fiber stress are inter linked. The angle of winding, end dome shapes ply sequence and thickness influence the design parameters. The angle of winding has significant effect on the structure of vessel. Determining the appropriate angle for each part of the vessel is an important issue. The dome openings were reinforced by high strength Al alloy polar bosses. The polar bosses interface the dome openings by means of a rubber shear ply. The configuration design of experimental model are given in figure.1 to 2. Winding angles are calculated using CADWIND software and helical fiber path are given in figure.3 to 4.

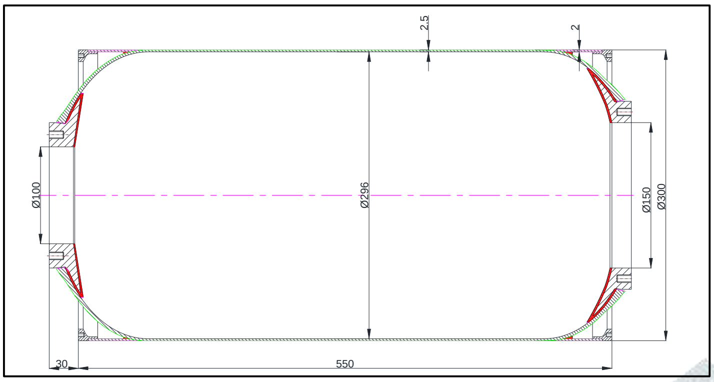

Fig.1 Configuration of CRMC

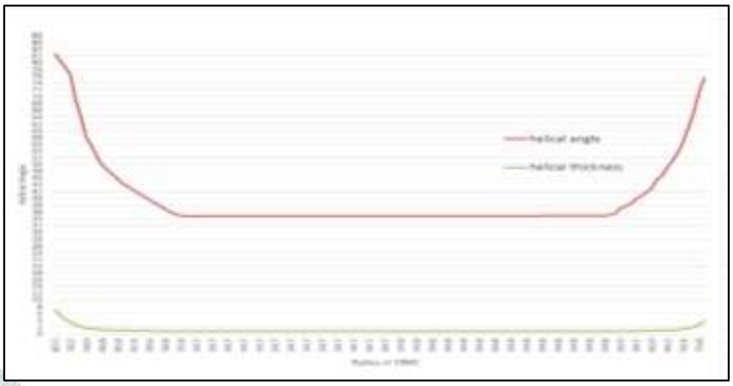

Fig.2 Helical angle & thickness variation along the CRMC

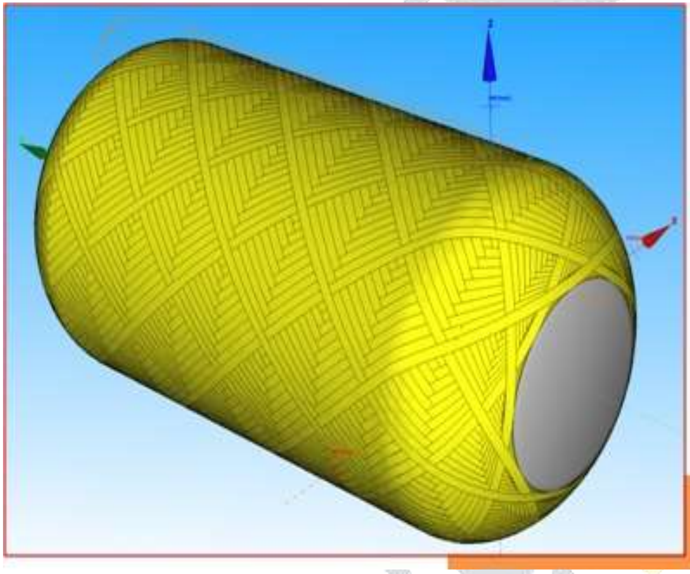

Fig.3 Full coverage of helical winding

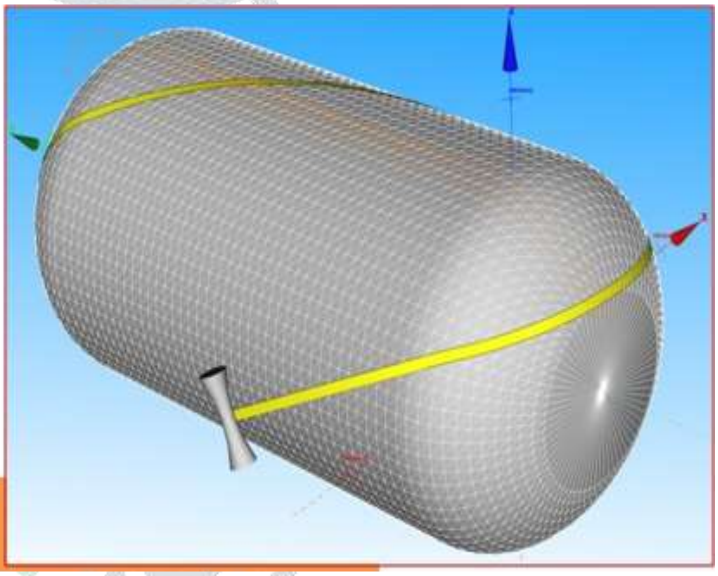

Fig.4 Helical fibre path

5. Structural analysis of CRMC

5.1 Pressure analysis of CRMC

The CRMC has been analyzed with 3D sector modeling is carried out using ANSYS. The structure is discretized into certain number of zones and each zone is assumed to have constant angle of winding such that to each zone unique real constant. 3D layered elements are used for composite whereas solid element is used for isotropic materials. MEOP (8 MPa) acting on the inner surface of the casing. The complete casing is constrained at the extreme flange face of the IE bulkhead. This support is enough to account for all rigid body movements. The element details, loads and boundary conditions applied to the casing is given in figure.5. And pressure analysis results are given in figure.6 to 10.

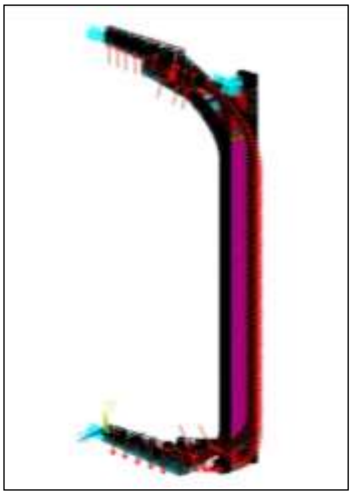

Figure.6: FE Model

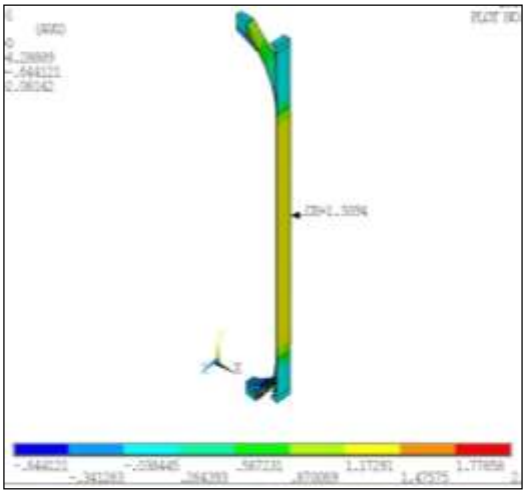

Figure.7: Radial Displacement

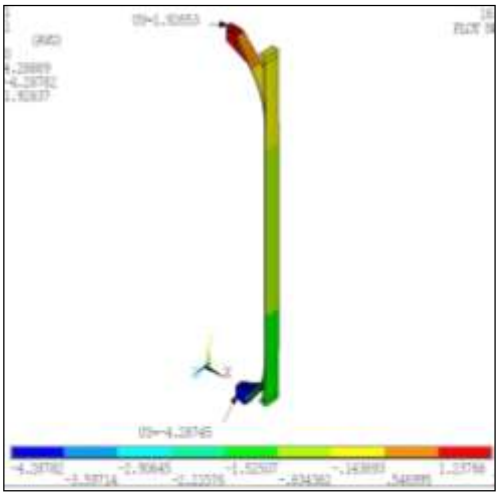

Figure.8: Axial Displacement

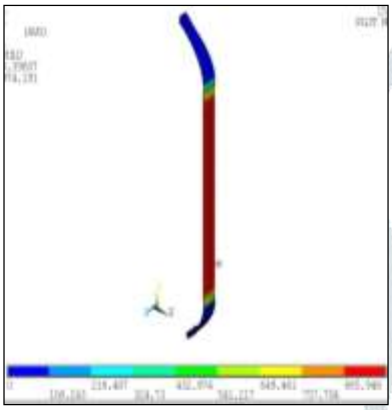

Figure.9:Fibre Stresses on Hoop Layer

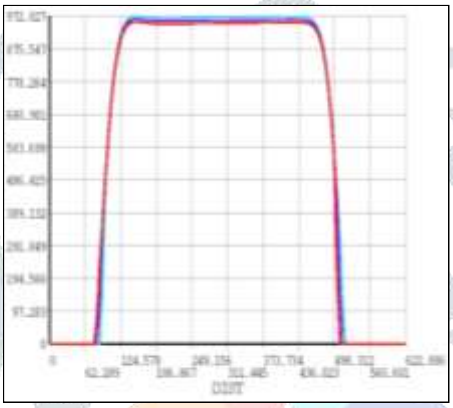

Figure.10: Stress variation along Hoop Layers

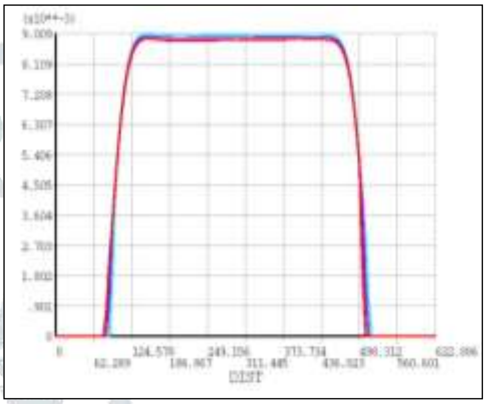

Figure.11:Strain variation along Hoop

Layers

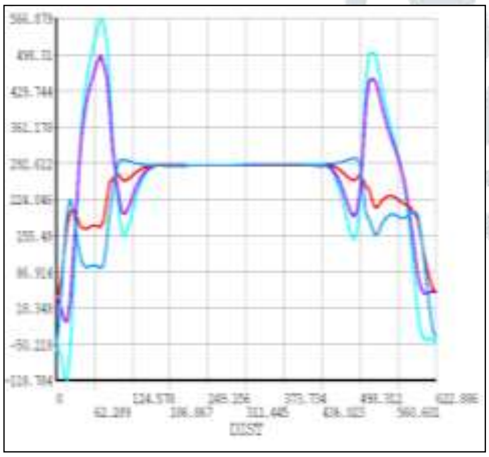

Figure.12: Stress variation along Helical Layers

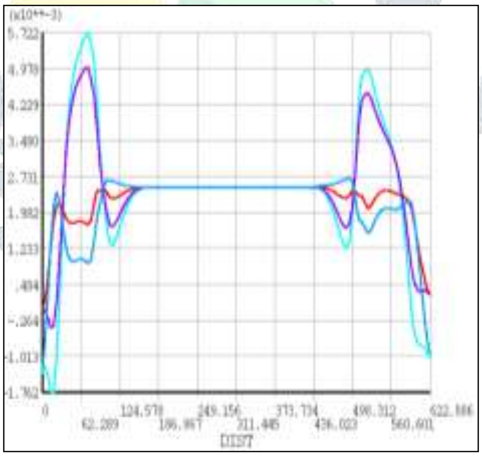

Figure.13:Strains variation along Helical Layers

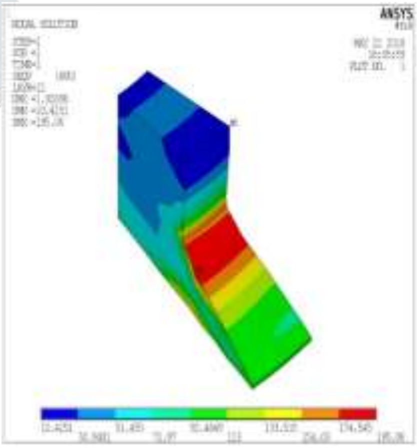

Figure.14: Vonmises stress for IE PB

5.2 Buckling analysis of CRMC

A complete 360° 3D model was built incorporating the ply sequence and thickness of CRMC along with endplates used during testing. ANSYS model using Layered-46 element type for composite including solid45 element type for end rings was taken up. Axial force of 25Tons acting at NE bulkhead and IE bulkhead constraints and Eigen buckling analysis was performed and results of FEA are shown from figure.15 to figure.18.

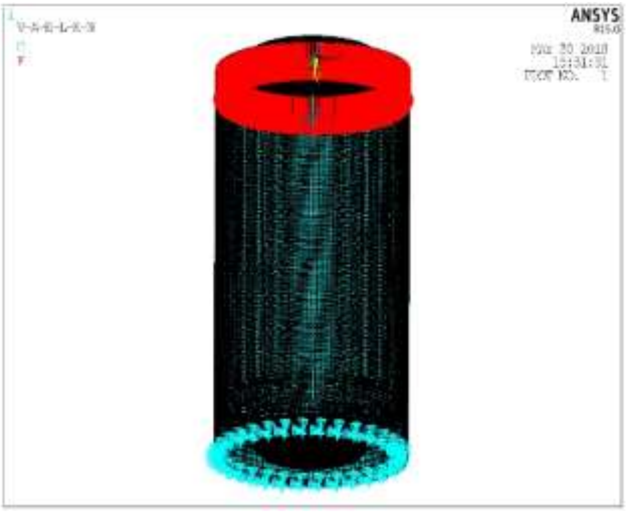

Figure.15: FE 360^0 Model

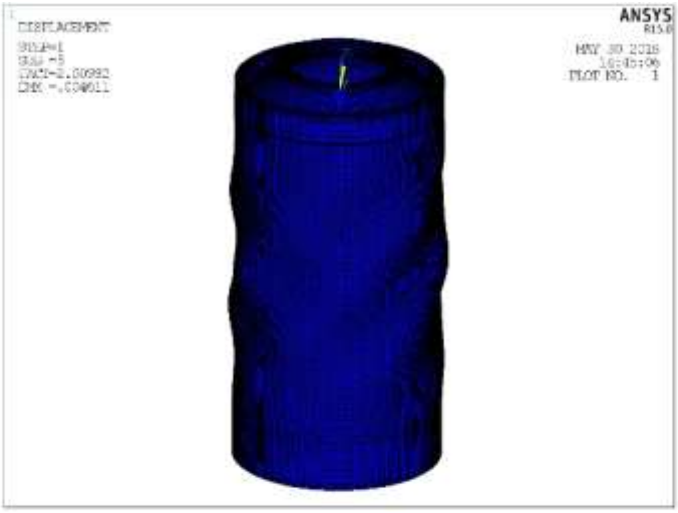

Figure.16: Buckling Mode Shape

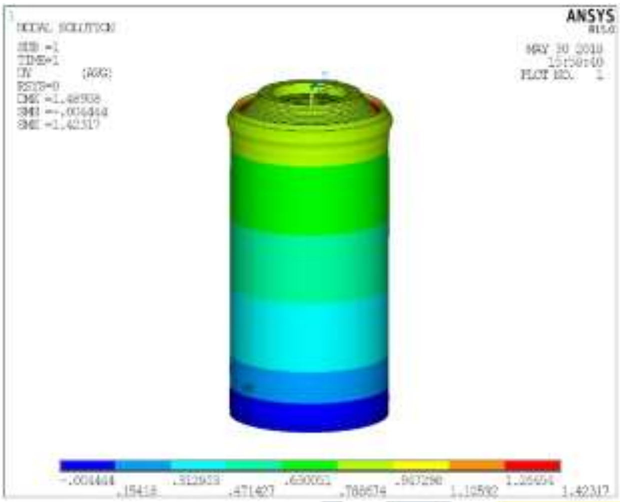

Figure.17: Axial Displacement

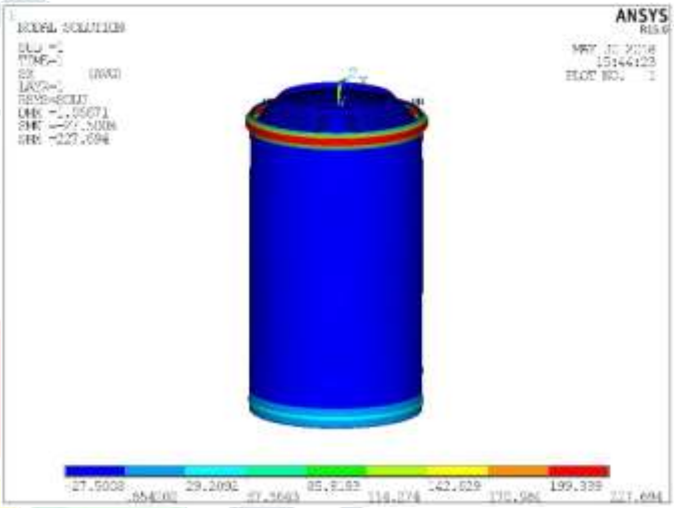

Figure.18: Fibre Stresses Along Hoop Layer

6. Results and discussion

The pressure analysis is also performed for internal pressure load and summary of FE results are given inTable.2 The Failure strain of composite is 14,000 - 16,500 microns, therefore burst pressure can be worked based on FE results are expected around 105- 116 bar. Based on FE analysis, the CRMC was safe and stresses were within limits.

Table.2 . Summary of Pressure test Results from FE analysis

S.No	Parameters	MEOP of 8MPa	Design Pressure of 10 MPa	FS on Design	Material strength and strain
1.	**IE Polar boss stress (MPa)**	186	233	1.88	YS =380 Mpa UTS: 440 MPa
2.	**NE Polar boss stress (MPa)**	285	356	1.23	YS =380 Mpa UTS: 440 MPa
3.	**Max Fiber Stress on hoop layer (MPa)**	972	1215	1.52	Ultimate Fiber stress: 1850 MPa
4.	**Max Fiber Stress on helical layer (MPa)**	566	708	2.09	Ultimate Fiber stress: 1480 MPa
5.	**Max Hoop Strain (Micro strains)**	9009	11,262	1.23	Ultimate Fiber strain: 14000-15,000 micro strain
6.	**Max Helical Strain(Micro strains) fiber direction**	5722	7152	1.95	Ultimate Fiber strain: 15,000 micro strain

The buckling load results Layered-46 element type and from practical test are listed below in table-3. Layered-46 model includes steel polar bosses, which adds local stiffness to CRMC and test boundary conditions are closely simulated. To cater to the manufacturing defects knock down factor of 0.8 is considered and critical buckling load estimated. Final buckling factor is 2.0 and CRMC is safe with axial load condition.

Table.3: Summary of Buckling Analysis Results

S.No	Parameters	Axial Force:250 KN
1.	**Buckling Factor**	2.5 2.0 (after knock down)
2.	**Axial Displacement**	1.4mm
3.	**Fibre Stresses in Hoop Layer**	227MPa

7. Conclusion

The internal pressure acting around the polar boss opening must be transferred towards the cylindrical portion, in dome and cylindrical interface is very high stress levels will be developed. Therefore, it is required to reinforce by UD carbon fiber composite over the entire dome region. The FE results shows stresses and strains in various parts of casing are within the safe limits. Based on the stresses and strains predicted by FE, the burst pressure of casing is estimated to be around 105 bar. Hence CRMC is safe with hybrid resin system.

The finite element analysis and experimental investigation for CFRP materials considered were performed successfully. Finite element procedure gives near to practical test value when practical conditions are accurately reproduced. The spiralling buckling pattern predicted by FE is experimentally found but in localised longitudinal form. It can be concluded that the effectiveness of composite shell in bearing axial load is subject to material stiffness and ply orientation. Symmetry in ply sequence eliminates coupling and shear effects. Layered buckling analysis of composite cylinder could effectively match with tested results. Based on the composite cylinder test results the achieved knock down factor is in the range of 0.18 to 0.2 and same can be considered for design of CRMC for high strength applications.

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REFERENCES:

[1] .Koussios S, Bergsma OK, *Analysis of filament wound pressure vessels considering the laminate thickness variation through the meridional direction*. In: Proceedings of 14th International conference on composite materials (ICCM/14), San Diego, CA, July 2002

[2] V.V.Vasiliev,Composite Pressure Vessel Analysis, Design and Manufacturing Bull Ridge Publishing,2009, Blaksburg,Virginia, USA

[3] G.S.Ger, D.G. Hwang, W.Y. Chen and S.E. Hsu: Design and Fabrication of High Performance Composite Pressure Vessels, Theoretical and Applied Fracture Mechanics 10 (1988) 157-163

[4] Weiming Chen, Yunhua Yu, Peng Li, Chengzhong Wang, Tongyue Zhou, Xiaoping Yang: Effect of New Matrix for T-800 Carbon fiber/epoxy Filament Wound Composites, Composite Science and Technology 67 (2007) 2261-2270

[5] S.Sankar Reddy, Dr.C.Yuvraj, and Dr.K.Prahlada Rao: Experimental Characterization of Carbon Fiber T-700/ Epoxy Towpreg for Space Applications, Int. Journal of Engineering Research and Applications, ISSN: 2248-9622, Vol. 5, Issue 12 (Part-1) December 2015

[6] Qingjie Zhang, Shengbiao Liang, Gang Sui and Xiaoping Yang: Influence of Matrix Modulus on the Mechanical and Interfacial Properties of Carbon Fiber Filament Wound Composites, RSC Adv.,2015, 5, 25208-25214

[7] .J.De Carvalho, M.Lossie, D.Vandepitte, H.Van Brussel: Optimization of Filament Wound Parts on Non-Geodestic Winding, Composites Manufacturing Vol. 6, Issue 2,1995, 79-84

[8] M.Madhavi, K.V.J.Rao and K.Narayana Rao: Design and Analysis of Filament Wound Composite Pressure Vessel with Integrated-end Domes, Defence Science Journal, Vol.59, No.1, January 2009, pp. 73-81

[9] V.Ramanjaneyulu, V.Balakrishna Murthy, R.Chandra Mohan, Ch.Naga Raju, Analysis of Composite Rocket Motor Case using Finite Element Method, Materials Today procedings,Volume 5, Issue 2, part 1,2018, 4920-4929

[11] C.Venkateshwar Reddy, Dr.P.Rameshbabu, Influence of Hybrid resin on Mechanical properties of Carbon fiber T-700 by Filament wound composites, International Conference on Advances in Materials and Manufacturing (ICAMM-2016), UCE,Osmania University, Hyderabad.