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DESIGN AND ANALYSIS OF CFRP COMPOSITE MULTILAYER HIGH PRESSURE VESSELS AND BURST PRESSURE ANALYSIS FOR VARIOUS FIBER ORIENTATION ANGLES

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ABSTRACT:
The main objective of this paper is to design and analysis of multilayer high pressure vessels and the features of multilayered high pressure vessels, their advantages over mono block vessel are discussed and burst pressure analysis of CFRP composite pressure vessels for various fiber orientation angles. Various parameters of Solid Pressure Vessel are designed and checked according to the principles specified in American Society of Mechanical Engineers (A.S.M.E) Sec VIII Division 1. Various parameters of Multilayer Pressure vessels are designed and checked according to the principles specified in American Society of Mechanical Engineers (A.S.M.E) Sec VIII Division 1. The stresses developed in Solid wall pressure vessel and Multilayer pressure vessel is analyzed by using ANSYS, a versatile Finite Element Package. The theoretical values and ANSYS values are compared for both solid wall and multilayer pressure vessels. The pressure vessel is analyzed for its burst pressure is predicted for hoop and helical windings of the fiber using Tsai-Wu failure criteria. The fibers are oriented helically for various orientations such as [+25°/-25°]s, [+35°/-35°]s, [+45°/-45°]s, [+55°/-55°]s, [+65°/-65°]s, and [+75°/-75°]s. The optimum angle of fiber orientation is determined from analysis.

Keywords : Design, Analysis, Solid & Multilayer Pressure vessel, Burst Pressure, Composite Pressure Vessel, Tsai – Wu failure Criteria ANSYS.

INTRODUCTION

The carbon fibers/epoxy pressure vessels are used in various applications these days such as, aerospace, automobiles, aeronautics, chemical engineering industries etc. Besides these, the CFRP pressure vessels have suddenly become an attraction for the piping and sewage as well as oil and gas transport industries. These pressure vessels have a special characteristics of lightweight and high strength because of which the demands for these pressure vessels are increasing drastically in applications where, the weight is a very important concern. These pressure vessels provide an excellent compromise between high mechanical properties and low weight. In most of the applications, these resin matrix composite pressure vessels are subjected to very high pressures during their service life. Therefore, the burst pressure analysis of these pressure vessels becomes vital for safety purposes..

In Process Industries, like chemical and petroleum industries designers have recognized the limitations involved for confining large volumes of high internal pressures in single wall cylindrical metallic vessels. In process engineering as the pressure of the operating fluid increases, increment in the thickness of the vessel intended to hold that fluid is an automatic choice. The increment in the thickness beyond a certain value not only possesses fabrication difficulties but also demands stronger material for the vessel construction. The media which a pressure vessel contains produce critical changes to the physical properties of the vessel material during service. One of these that is often encountered is hydrogen, which under the action of high pressure and / or high temperature produces two effects: (1) A diffusion into the metal as atomic hydrogen and a process of recombining to its molecular form within the metal, thereby creating extremely high pressures with resulting surface bulging or blistering, and (2) a mechanical decarburizing, and reducing effect on sulfides or oxides present in the steel creating a brittleness and resultant cracking under high stress. These points out the fundamental importance of both minimizing stress concentrations in vessels designed to low factors of safety and considering the various media to which these vessels are to be subjected throughout their life.

With increasing demands from industrial processes for higher operating pressures and higher temperature, new technologies have been developed to handle the present day specialized requirements. Multilayer Pressure Vessels have extended the art of pressure vessel construction and presented the process designer with a reliable piece of equipment useful in a wide range of operating conditions for the problems generated by the storage of hydrogen and hydrogenation processes The term pressure vessel referred to those reservoirs or containers, which are subjected to internal or external pressures. The pressure vessels are used to store fluids under pressure. The fluid being stored may undergo a change of state inside the pressure vessels as in case of steam boilers or it may combine with other reagents as in chemical plants. Pressure vessels find wide applications in thermal and nuclear power plants, process and chemical industries, in space and ocean depths, and in water, steam, gas and air supply system in industries. High Pressure vessels are used as reactors, separators and heat exchangers. They are vessel with an integral bottom and a removable top head, and are generally provided with an inlet, heating and cooling system and also an agitator system. High Pressure vessels are used for a pressure range of 15 N/mm2 to a maximum of 300 N/mm2. These are essentially thick walled cylindrical vessels,

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ranging in size from small tubes to several meters diameter. Both the size of the vessel and the pressure involved will dictate the type of construction used. A solid wall vessel consists of a single cylindrical shell, with closed ends. Due to high internal are governed by the ratio of diameter to wall thickness and the shell is designed as thick cylinder, if its wall thickness exceeds one-tenth of the inside diameter. A solid wall vessel is also termed as Mono Block pressure vessel.

2.0 DESIGN OF MULTILAYER HIGH PRESSURE VESSEL

Multi layer vessels are built up by wrapping a series of sheets over a core tube. The construction involves the use of several layers of material, usually for the purpose of quality control and optimum properties. Multi layer construction is used for higher pressures. It provides inbuilt safety, utilizes material economically, no stress relief is required. For corrosive applications the inner liner is made of special material and is not considered for strength criteria. The outer load bearing shells can be made of high tensile strength material

2.1 DESIGN OBJECTIVES

1. To show that multilayer pressure vessels are suitable for high operating pressures than solid wall pressure vessels.
2. To show a significant saving in weight of material may be made by use of a multilayer vessel in place of a solid wall vessel.
3. To show there may be a uniform stress distribution over the entire shell, which is the indication for most effective use of the material in the shell.
4. To check the suitability of using different materials for Liner shell and remaining layers for reducing the cost of the construction of the vessel.
5. To verify the theoretical stress distribution caused by internal pressure at outside surface of the shell and to ascertain that the stresses do not reach yield point value during testing.
6. Finally check the design parameters with FEM analysis by using ANSYS package to ascertain that FEM analysis is suitable for multilayer

2.2 DESIGN CONSIDERATIONS

1. A multilayer Vessel is designed to ASME Code Section VIII division I.
2. A Safety Factor of on Ultimate Tensile Strength is considered in the design of the multi layer shell only. For other parts th at room temperature.
3. A joint efficiency of 100% for longitudinal seam on liner shell is taken.
4. 100% radiography for longitudinal seam of liner shell.
5. Fully ultrasonic test for dished end plates is considered.
6. Dished ends to be stress relieved after attachment of boss, nozzle etc.,
7. The longitudinal welds in a multilayered shell were staggered.
8. The number segments (longitudinal welds) in a layer are taken as “3”
9. The coefficient of weld shrinkage is taken as 10%.(From Devis R.L, “Circumferential welds in multilayer pressure vessel” Paper. 70 - WA/PVP – 6)
10. The thickness of the liner shell is taken as 12 mm.
11. The thickness of subsequent layers is 6 mm.

3.0 DESIGN DATA OF THE VESSEL:

Design Pressure, P - 21 N/mm2, Hydrogen.
Design Temperature, T - 20°C
Hydrostatic Pressure P_H - 27.3 N/mm2

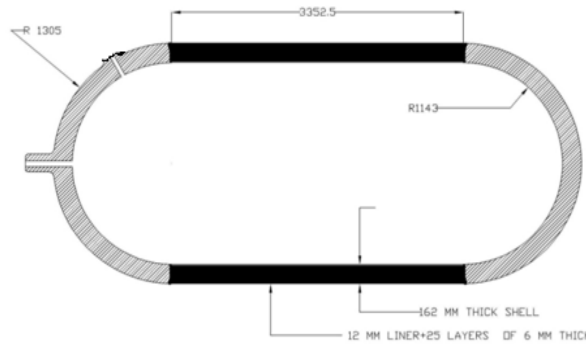

Fig. 1 Drawing of Multilayer Pressure Vessel

CASE-1: MATERIAL OF CONSTRUCTION FOR SOLID PRESSURE VESSELS

Description	Material	UTS (min) MPa	YS MPa (Min)
Vessel	SA 515 GR 70	492	260
Dished Ends	SA 515 GR 70	492	260

Allowable Design Stress value for Vessel: 123 N/mm^2

Allowable Design Stress value for Dished Ends : 123 N/mm^2

CASE-2: MATERIAL CONSTRUCTION OF MULTILAYER PRESSURE VESSEL OF SA - 515 GR 70 MATERIALS

Description	Material	UTS Mpa (Min)	YP (Min) N/mm^2
Shell Liner	S2 GLASS	2297	-
Shell Layers	SA 515 GR 70	492	260
Dished Ends	SA 515 GR 70	492	260

Allowable Design Stress values for Liner : 766 N/mm^2

Allowable Design Stress values for Shell : 164 N/mm^2

Allowable Design Stress values for Dish end 123 N/mm^2

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CASE-3: MATERIAL CONSTRUCTION OF MULTILAYER PRESSURE VESSEL OF CFRP MATERIAL

Description	Material	UTS, Mpa
Shell Liner	S2 GLASS	2297
Shell Layers	CFRP(T300/LY5052)	1210
Dished Ends	CFRP(T300/LY5052)	1210

Allowable Design Stress values for Liner : 766 N/mm^2
Allowable Design Stress values for Shell : 403 N/mm^2
Allowable Design Stress values for Dish end : 303 N/mm^2

MECHANICAL PROPERTIES OF SA 515 GR70

	SA515 Grade 70 Mechanical Properties			
Grade	Thick ness	Yield (Min)	Tensile	Elongation
	Mm	Mpa	Mpa	Min %
SA515 Grade 70	200	260	492-620	17
	50	260	492-620	21

MATERIAL PROPERTIES AND TRENGTH CONSTANTS OF CFRP

Properties of Carban/Epoxy (T300/LY5052)	Values
Ex	135 GPa
$E_y = E_z$	8 GPa
Gxy = Gxz	3.8 GPa
Gzx	2.6845 GPa
xy = xz	0.27
Yz	0.49
Tensile Strength (X_t)	1860 MPa
Transverse Tensile Strength (Y_t)	76 MPa
Compressive Strength (X_c)	1470 MPa
Transverse Compressive Strength Y_c)	85 MPa
Shear Strength (S)	98 MPa

The basic properties of T300/LY5052 composite.

Properties	Carbon Fiber T300	Epoxy Araldite LY5052
Elastic Modulus	230 GPa	3 GPa
Tensile Strength	3.5 GPa	71 MPa
Density	1760 Kg/m^3	1140 Kg/m^3

PROPERTIES OF S2 GLASS MATERIAL

Properties	Values
Ultimate Tensile Strength	2297 Mpa
Modulus of Elasticity	86.9 GPa
Poisons Ratio	0.230
Density	2480 Kg/m^3
Elongation at Break	5.7 %

FINITE EEMENT METHOD

4.1 The CFRP Pressure Vessel

This study deals with a resin matrix composite pressure vessel. The multilayered pressure vessel is orthotropic in nature and cylindrical in shape. It consists of carbon fibers as the reinforcement material into a polymeric epoxy matrix. Because of the orthotropic nature of the composite materials, the finite element modelling of the pressure vessel requires the determination of nine different properties. The material properties of fiber reinforced composite depends upon the properties of both the matrix and the fibers. The angle of orientation of the fibers in the composite also plays a very important role determination of the properties and the behaviour of the composite, since the fibers have superior mechanical properties along its length.

4.2SELECTION OF APPROPRIATE ELEMENT TYPE

It is very necessary to select the appropriate element type for the accurate finite element analysis of the composite pressure vessel. The finite element software, ANSYS 12.1 provides the various shell and solid element types to model layered composite materials. A solid element can be utilized to model thick layered composites but it requires that the mesh divisions in thickness directions must be the same as the number of material layers. This increases the analysis and the calculation time for these elements. While, the shell elements does not require the mesh divisions in thickness direction and the calculation as well as the analysis time for these elements is much lesser than for the solid elements. Because of this property of the shell elements we have selected SHELL 99 as the appropriate element type for the purpose of our study. SHELL 99 is a linear layered structure shell element. Very thin to moderately thick layers can be modeled with this element. It may be used for the purpose of modelling layered structures and up to 250 uniform thickness layers can be modeled by this element. It is a 3D shell element and consists of 8 - nodes, with six degrees of freedom at

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each node. Among the 8 – nodes, four nodes are the corner nodes and the remaining four are the mid - side nodes. This element allows the user to define elastic properties, layer orientation and density for each layer.

5.0 STRUCTURAL ANALYSIS RESULTS

5.1 SOLID WALL PRESSURE VESSEL

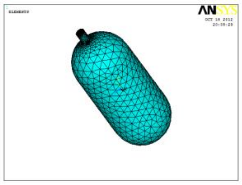
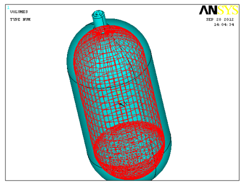


Fig. No.1



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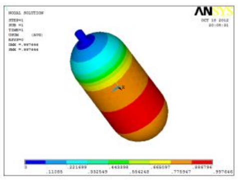

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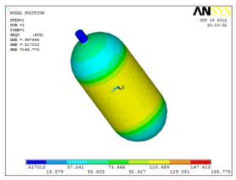

Fig. No. 4

Fig. No.	Title of the Figure
Fig. No. 1	Finite Element meshed Model of solid wall pressure vessel
Fig. No. 2	Application of hydrostatic pressure 27.3 Mpa
Fig. No. 3	Vector sum displacement
Fig. No. 4	Von - Mises Stresses

Deformation over three axes

Defomation	Mimimum in mm	Maximum in mm
Vector sum deformation	0.0000	0.997646
X – axis deformation	-0.827963	0.828678
Y – axis deformation	-0.99709	0.028251
Z – axis deformation	-0.825078	0.826709

Equivalent Von Mises stresses over three axes

Stresses	Minimum, Mpa	Maximum, Mpa
Von Mises Stresses	0.517013	165.775
X – axis stresses	-30.189	161.309
Y – axis stresses	-31.873	92.148
Z – axis stresses	-29.023	161.133

5.2 MULTILAYER PRESSURE VESSEL-SA515 GR.70 STEEL MATERIAL

Total No. of layers = 26, (25 shell layers +1Liner)

Total Thickness = 162 mm

Liner thickness = 12 mm & Each Shell layer thickness, t = 6 mm

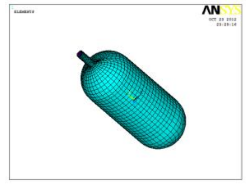

Fig. No.5

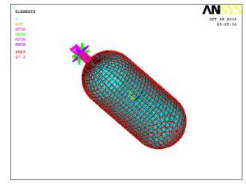

Fig. No. 6

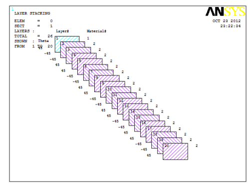

Fig. No.7

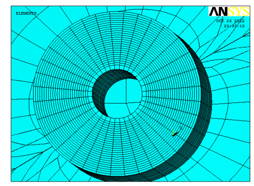

Fig. No. 8

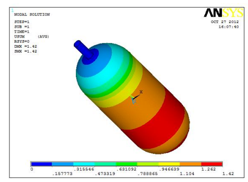

Fig. No.9

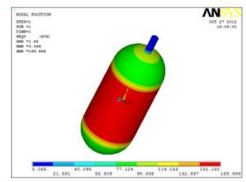

Fig. No. 10

Fig. No.	Title of the Figure
Fig. No.5	Finite Element Model of multi layer pressure Vessel
Fig. No.6	Application of hydrostatic pressure 27.3 Mpa
Fig. No.7	Layer stacking sequence for 25 layers
Fig. No.8	Meshed model for 25-layers
Fig. No.9	Vector sum displacement
Fig. No.10	Von - Mises Stresses

Deformation over three axes

Defomation	Mimimum in mm	Maximum in mm
Vector sum deformation	0.0000	1.42
X – axis deformation	-0.973757	0.973628
Y – axis deformation	-1.42	0.0000
Z – axis deformation	-0.971919	0.972126

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Equivalent Von Mises stresses over three axes

Defomation	Mimimum in mm	Maximum in mm
Vector sum deformation	3.066	169.696
X – axis deformation	-27.212	194.769
Y – axis deformation	-27.257	127.967
Z – axis deformation	-26.882	195.452

5.3 MULTILAYER PRESSURE VESSEL-CFRP MATERIAL

Total No. of layers = 9, (8 shell layers +1Liner)

Total Thickness = 64 mm

Liner thickness = 12 mm & Each Shell layer thickness, t = 6.5 mm

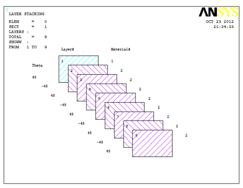

Fig. No.11

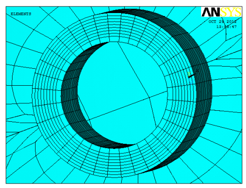

Fig. No. 12

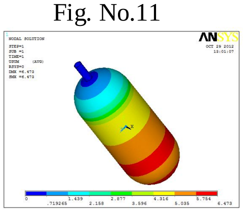

Fig. No.13

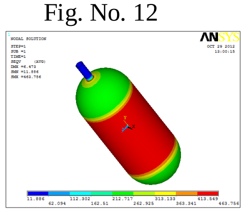

Fig. No. 14

Fig. No.	Title of the Figure
Fig. No.11	Layer stacking sequence for 8 layers
Fig. No.12	Meshed model for 25-layers
Fig. No.13	Vector sum displacement
Fig. No.14	Von - Mises Stresses

Deformation over three axes

Defomation	Mimimum in mm	Maximum in mm
Vector sum deformation	0.0000	6.473
X – axis deformation	-3.914	3.914
Y – axis deformation	-6.473	0.0000
Z – axis deformation	-3.906	3.909

Equivalent Von Mises stresses over three axes

Defomation	Mimimum in mm	Maximum in mm
Vector sum deformation	11.886	463.756
X – axis deformation	-81.852	528.485
Y – axis deformation	-155.587	341.607
Z – axis deformation	-80.307	530.07

6.0 DETERMINATION OF OPTIMUM ANGLE OF FIBER ORIENTATION FROM ANALYSIS

The finite element model of the composite pressure vessel shown in Fig. 15

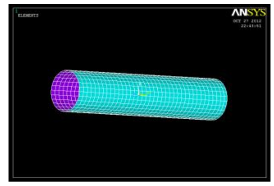

Fig.15. Finite Element model of composite pressure vessel

The cylindrical composite pressure vessel is designed for various fiber orientations. The modeling is performed for the CFRP cylindrical pressure vessel for both, the hoop and the helical windings of the carbon fiber. For the hoop windings of the carbon fibers, the fibers are oriented at an angle of 0° with the axis of the cylindrical pressure vessel. For helical windings the fibers are oriented for various fiber orientations such as ± 25°, ± 35°, ± 45°, ± 55°, ± 65° and ± 75°, in symmetrical stacking sequence. The Fig.16 shows the stacking sequence for ± 25° fiber orientation.

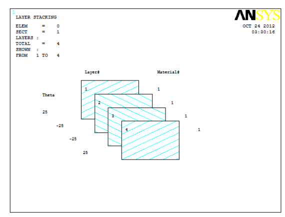

Fig.16 The layer stacking sequence for ± 25° fiber orientation

The cylindrical composite pressure vessel is modeled for four uniform thickness layers and the number of integration points are taken as three to define the layered configuration completely. The CFRP pressure vessel is analyzed by loading it by high internal pressures. The Tsai-Wu failure criterion is utilized for the purpose of analysis. The analysis is performed for the calculation of burst pressure for the pressure vessel. The burst pressure for the pressure vessel is predicted for various fiber orientation angles (0 °, ± 25°, ± 35°, ± 45°, ± 55°, ± 65° and ± 75°). The calculation of the burst pressure for each fiber orientation requires separate model formation. The burst pressures are predicted by incrementally increasing the internal pressure from the working value of 35 MPa to the value of burst pressure step by step. For every increment in the internal pressure it is required to compare the value of maximum stress obtained with value of ultimate stress for the pressure vessel by the relation given by the Eq. 1

$\sigma_{max} \leq \sigma_u$ ----------- (1)

Here, σ_{max}, σ_u are the maximum stress and ultimate stress of the pressure vessel, respectively. The value of ultimate stress for the CFRP pressure vessel is 1210 MPa

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The Fig.17 gives the stress distribution for this pressure vessel for ± 25° fiber orientation at their burst pressure.

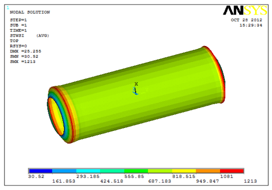
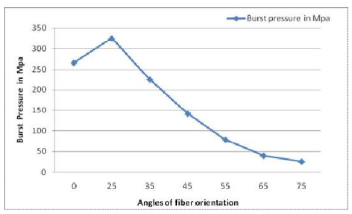


Fig. 17. The stress distribution for ±25° fiber orientation at its burst pressure.

After the analysis for the burst pressure for various fiber orientation angles, the maximum burst pressure for the cylindrical composite pressure vessel is found to be maximum for ± 25° fiber orientation angle. The Fig.18 shows the graph between the burst pressure and the different fiber orientations.



The graph gives an increasing slope from hoop to ± 25° and the slope decreases from ± 25° to ± 75° fiber orientations. It can be further predicted that the pressure vessel can sustain the maximum internal pressure of 207 MPa when, the fibers are orientated at ± 25° in symmetrical stacking sequence, which is regarded as its burst pressure at ± 25° fiber orientation. The Fig. 17 shows the stress distribution in the composite pressure vessel at ±25° fiber orientation angle when, the pressure vessel is subjected to its burst pressure of 325 MPa. It can be seen from the fig. that, the maximum stress obtained is 1213 MPa which is more than 1210 MPa.

CONCLUSIONS

1. At present multilayered vessels are being used extensively in many industries when compare to solid wall pressure vessels. Because, there is a huge difference in weight of the vessel and uniform stress distribution among the vessel wall thickness.
2. There is a percentage saving in material of **28.48%** by using multilayered vessels in the place of solid walled vessel when both the vessels are manufactured with same material i.e. SA515 Grade 70 steel **.**
3. There is a percentage saving in material of **91.62%** by using multilayered CFRP material vessels when compared to multilayered SA515 Grade 70 steel material vessels.
4. This decreases not only the overall weight of the component but also the cost of the material required to manufacture the pressure vessel. This is one of the main aspects of designer to keep the weight and cost as low as possible.
5. The Stress variation from inner side to outer side of the multilayered pressure vessel is around **11.76%,** where as to that of solid wall vessel is **17.32%.** This means that the stress distribution is uniform when compared to that of solid wall vessel.
6. Minimization of stress concentration is another most important aspect of the designer. It also shows that the material is utilized most effectively in the fabrication of shell.
7. Owing to the advantages of the multi layered pressure vessels over the conventional single walls pressure vessels, it is concluded that multi layered pressure vessels are superior for high pressures and high temperature operating conditions.
8. The burst pressures for various fiber orientations are predicted using the Tsai-Wu failure criteria. The ± 25° fiber orientation angle is obtained as the optimum fiber orientation angle for the composite pressure vessel subjected to high internal pressure loading.

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