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Analysis of a Composite Overwrapped Pressure Vessel by Analytical and Finite Elemental Approach

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Abstract

Finite element analysis (FEA) was used to examine the effect of metal and composite thickness on burst pressure and deformation of composite over wrapped pressure vessel (COPV) under fluid pressure. Low carbon steel and carbon-epoxy had been selected for the metal and composite vessel respectively. A constant fiber orientation angle had been considered. FEA results were compared and found to be in good agreement with those obtained from analytical equations to validate the final element approach. Analysis had been extended to metal pressure vessel, composite pressure vessel and COPV to study the effect of overwrapping. Metal and composite vessel thickness were varied. The composite vessel exhibited bursting strength higher than metallic pressure vessel and COPV considered for the analysis. The results showed that composite vessel possess greatest bursting strength.

Keywords: *Pressure Vessel; Finite Elemental Analysis; Composite material; Bursting strength; Deformation.*

1.0 Introduction

A pressure vessel is a sealed container that bear gases or liquids at a pressure that is significantly higher pressure than atmosphere. Pressure vessels are used in a variety of fields. Previously, pressure vessels were only made of one type of material, but with the advancement of technology over the last four decades, it is now possible to make pressure vessels out of multiple materials. There is different classification of pressure vessel. In many applications where, high structural efficiency is required, metallic pressure vessels made of various materials such as stainless steel, aluminium and titanium alloys are frequently used to hold high pressure gases and fluids. It is necessary to maintain a thick wall in fully metallic pressure vessels to achieve high strength and stiffness. This increases the weight of the pressure vessel, which has implications in fields where weight is a key criterion, such as aerospace, marine, deep-sea diving and automobiles. Traditional metallic pressure vessels are no longer capable of meeting the demands for high strength/ stiffness to weight ratios.

The composite vessels operate at high-pressure, high-temperature environment. Composite vessel fabricated by Filament-winding technique[1] are widely used not only in army and aerospace applications, but also in civilian applications. The classical lamination theory was used by[1] and[2] to model the composite vessel. The filament winding process entails winding filament around a mandrel and then removing it. The pressure vessel's inner surface had a thick layer of resin with a smooth surface. Filament winding composite pressure vessels are intended to subject the fibre to high stress levels in order to improve performance. Despite the fact that

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Figure 1: Composite Overwrapped Pressure Vessel

composite vessels are lighter and stronger than conventional materials, the manufacturing process is more difficult and expensive than that of metallic pressure vessels.

A composite overwrapped pressure vessel (COPV) shown in Figure 1 is a new type of pressure cylinder in which a continuous fibre composite is wrapped (via the filament winding technique) around a metal (liner) that acts as a fluid permeability barrier i,e the combination of metallic and composite pressure vessel. Because of their advantages such as high specific strength, excellent fatigue resistance, and so on, COPVs are widely used in a variety of application sectors such as aerospace, chemical and aviation.

On COPV, a variety of examination are carried out, including a burst test, stress rupture lifetime and non-destructive testing. Burst strength of COPV research was undertaken based on the influence of changes in winding angle, number of layers, and layer sequence[3] and the outcomes of finite elemental analysis were compared to experimental data and were in close agreement. To forecast the behaviour of COPV, Tsai-Wu failure criteria were used, which take in to account the optimum winding angle, total deformation, stress generation and failure analysis of composite pressure vessels[4]. The composite overwrap can be differentiated into several layers or plies during filament winding, which is a continuous process. Netting theory is widely utilized for a prior investigation due to a physical network of fibres[5,6]. A pressure vessel with a thickness of 6mm[7] is investigated and it has been discovered that COPV has greater strength than metallic and composite vessels. This research work focuses on reducing the thickness of the vessel by 1mm and 2mm for metallic, composite and COPV to study the bursting strength.

The effect of varying thickness of metallic, composite and COPV is limited, whereas the thickness of the vessel has a significant impact on the vessel's strength. Investigation has been conducted for metallic, composite and COPV of thicknesses of 5mm and 4mm. Research has been conducted by series of trials for the burst pressure by finite element and theoretical approach. The effect of decreasing the thickness of metallic, composite and COPV on burst pressure was investigated and the results were compared in order to determine the vessel's maximum strength. Also, the deformation reducing thickness of vessel was studied. Comparing the finite element results with those obtained from a theoretical approach, the finite element approach used to predict COPV burst pressure was validated.

2.0 Materials

2.1 Materials

Pressure vessel metal liner material is a low carbon steel Q235-A is used as the material of the liner. The mechanical characteristics of the material that are used for the analysis are presented in Table 1[3].

Table 1: Material parameters of Q235-A

Property	Value
Yield strength, MPa	339.4
Ultimate strength, MPa	485
Young's modulus, MPa	200
Poisson's ratio	0.3

Composite shell material: Carbon 700/0164 epoxy composite with 60% fiber volume fraction was used as a winding material over the Q235-A metallic liner. The parameters of this material are listed in Table 2[4].

Table 2: Material parameters of Q235-A

Property	Value
Ultimate Tensile Strength, MPa	2150
Ultimate Compressive Strength, MPa	2150
Yield Tensile Strength, MPa	298
Yield Compressive Strength, MPa	298
Shear Strength, MPa	778
Longitudinal Young's Modulus, GPa	181
Transverse Young's Modulus, GPa	10.3
Shear Modulus, GPa	5.17

Different type of pressure vessel opted for the both theoretical and FEA are shown in Table 3.

Table 3: Different types of pressure vessel

Cases	Property	Value
1	Metallic	05
2	Composite	05
3	COPV	Metal 01, Composite 04
4	COPV	Metal 02, Composite 02

Dimensions of Cylindrical Shell: Table 4 shows the dimensions of the cylindrical shell[3]. Ending effect could be eliminated on burst pressure as the shell was long (since L/D=3). A minor flaw was introduced on the cylinder to promote failure admission without influencing the immensity of the burst pressure. A small hole was created at the center of the cylinder with the diameter is 6mm.

Table 4: Dimensions of Cylindrical Shell

Parameter	Value
Diameter, mm	600
Length, mm	2400
Thickness, mm	5
Diameter of small hole (dh), mm	6

Selection of optimum winding angle: The burst pressure rises as the angle of winding rises to 55°, indicating that the laminate is more resistant to hoop stress than axial stress. For winding angles greater than 55°, the situation is reversed[8]. Hence, this angle was considered as optimum angle and was adopted in the analysis.

3.0 Finite Element Analysis (FEA)

Assumption made in the FEA were as follows :

- In comparison with the vessels other dimension, the wall was assumed to be very thin.
- The geometry and loading of cylindrical vessels were both symmetric. As a result, the stresses could be assumed to be independent of the cylindrical coordinate system's angular coordinate.
- At all points, the internal pressure, denoted by P, was uniform and positive.
- Supports and cylinder end caps were examples of features that may affect the symmetry assumptions are ignored.
- Each ply thickness of was 0.5 mm.

FEA was done by using ANSYS Workbench-17, analysis involves construction of geometry, defining material property, generation of mesh, applying load, obtaining solution and presenting the results. An add-on module called ANSYS Composite PrepPost (ACP) was specifically designed for modelling layered composite structures. For the purpose of the study, ACP (Pre) was used to analyze COPV. Steps involved in ACP are define composite fabrics, define composite laminates, create element set, define the rosette, define the element orientation and define the ply sequence and finally obtaining the solution. ANSYS design modular was used to create the symmetric surface model. The symmetric model for metal pressure vessel and meshed model using 3-noded triangular shell element are shown in Figure 2. For boundary conditions, both ends of the cylinder were considered as fixed.

Composite pressure vessels and COPVs had a surface model created in the design modular of ACP (pre) modular, with 4-noded quadrilateral shell elements[9] used to generate the FE model except in the vicinity of the defect introduced, where 3-noded triangular shell elements[9] were used. Figure 3 describes a COPV finite element mesh model. For boundary conditions, both ends of the cylinder were considered as fixed.

4.0 Theoretical Prediction

The researchers proposed a number of equations for theoretically predicting burst pressure for thin cylindrical shells. Cooper equation, modified Svensson equation, Barlow's equation and others are examples of these equations. For cylindrical shells, however, Barlow's equation had given a good prediction of burst pressure[10] for COPV

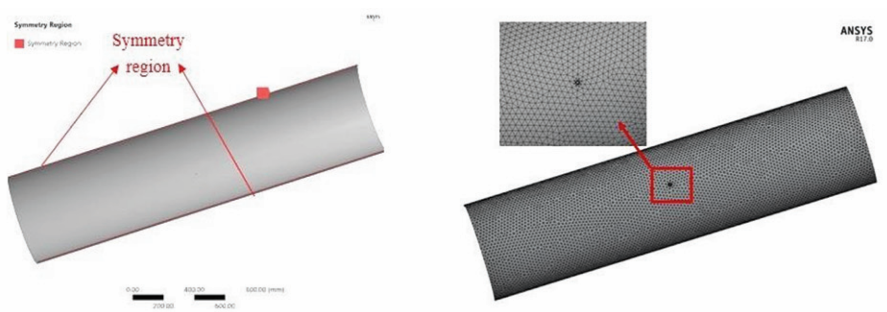

Figure 2: Symmetric and Meshed model of metal cylinder

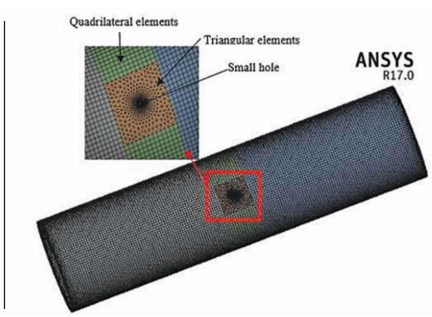

Figure 3: Meshed model of COPV

comprising both metallic and composite shells.

For metallic cylindrical shell, the burst pressure can be calculated using equation 1[10].

$$P_B = \frac{2\sigma_u T}{D} \quad \text{... (1)}$$

Where, P_B = *Burst Pressure, MPa*

σ_u = *Ultimate strength of material, MPa*

T = *Pressure vessel thickness, mm*

D = *Inner diameter of pressure vessel, mm*

For COPV comprising both metallic and composite shells, the burst pressure can be calculated using equation 2[5].

$$P_B = (P_B)_L + (PB)_C \quad \text{... (2)}$$

Where, $(PB)_L$ = *Burst Pressure of metal, MP*

$(PB)_C$ = *Burst Pressure of composite layers, MPa*

The Barlow's equation for burst pressure of layered composite shell is given by equation 3.

$$(P_B)c = \frac{2(\sigma_U^C)T}{\sum_{i=1}^{n} D_i} \quad \text{... (3)}$$

Where, σ_U^C = *Ultimate tensile strength of composite, MPa*

T = *thickness of each layer*

D_i = *Inner diameter of i^{th} layer*

Table 5 gives the numerically predicted burst pressure values for different types of pressure vessels namely, metallic, composite and COPV by varying the wall thickness.

Table 5: Theoretically predicted burst pressure

Case	Burst Pressure (Theoretical) MPa
1	8.08
2	55.31
3	35.58
4	20.24

5.0 Results and Discussions

For various types of pressure vessels, namely, metal, composite and COPV, the pressure vessel deformation also recorded by the incremental internal pressure component using software was composed for different wall thicknesses.

Case 1: The deformed pressure vessel along with the value of maximum deformation as obtained from ANSYS is shown in Figure 4(a) for metallic pressure vessel. Typical plot obtained from the software is shown in Figure 4(b) reveals that, the deformation of metallic pressure vessel was negligible at the beginning followed by significant deformation for small incremental pressure as indicated by the plateau region. The pressure corresponding to sudden rise in the curve was the indication of burst pressure. At this point, the pressure vessel lost its capability to resist deformation.

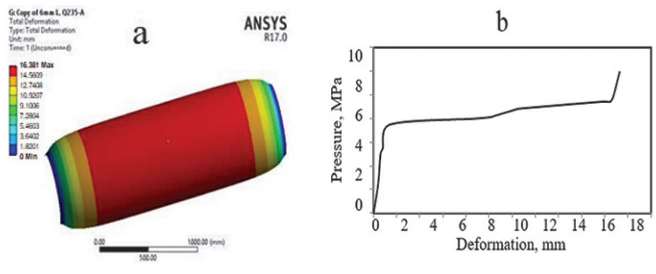

Figure 4: Deformation (a) and plot of Pressure vs Deformation (b) for metallic pressure vessel

From the analysis it was evident that the pressure vessel was failed at an internal pressure of 8.08 MPa and the corresponding deformation was 16.38 mm. Hence burst pressure for fully metallic pressure vessel having 5mm thickness was 8.96 MPa.

Case 2: The deformed pressure vessel along with the maximum value of deformation as obtained from ANSYS is shown in Figure 5(a) for composite pressure vessel. Characteristic plot obtained from the software is shown in Figure 5(b) it reveals that, the deformation of composite pressure vessel was linear, increase in the deformation with the incremental increase in the pressure. The pressure corresponding to deviation in the curve was the indication of burst pressure. At this point, the pressure vessel fails by losing its ability to resist deformation. In this case from the analysis, the pressure vessel was failed at an internal pressure of 53.82 MPa and deformation of 10.007 mm. Hence burst pressure for composite pressure vessel having 5mm thickness was 53.82 MPa.

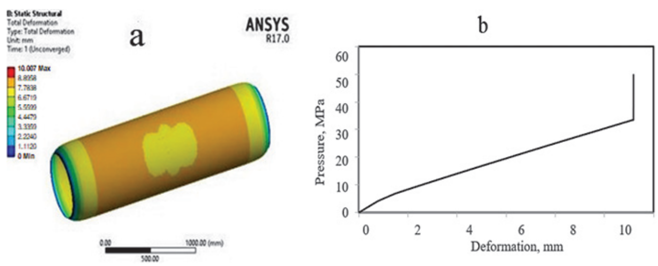

Figure 5: Deformation (a) and plot of Pressure vs Deformation (b) for composite pressure vessel

Case 3: The deformed pressure vessel along with the value of maximum deformation as obtained from ANSYS is shown in Figure 6(a) for COPV with 1 mm metallic and 4 mm composite pressure vessel. Typical plot obtained from the software is shown in Figure 6(b) reveal that, the deformation of 1 mm metallic and 4 mm composite pressure vessel was linear, increase in the deformation with the incremental increase in the pressure. The pressure corresponding to sudden growth in the curve was the indication of burst pressure. At this point, the pressure vessel loses its capability to resist deformation. From the analysis it was clear that the pressure vessel was failed at an internal pressure of 35.58 MPa and the corresponding deformation was 11.18 mm. Hence burst pressure for 1 mm metallic and 4 mm composite pressure vessel was 33.56 MPa.

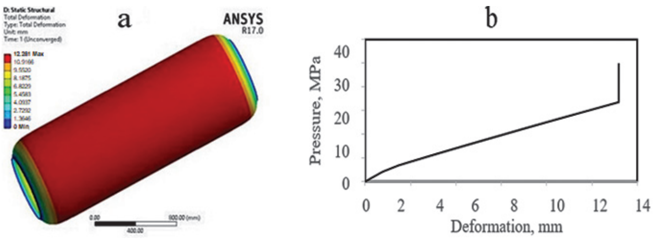

Figure 6: Deformation (a) and plot of Pressure vs Deformation (b) for COPV

Case 4: The deformed pressure vessel along with the maximum value of deformation as found from ANSYS is shown in Figure 7(a) for COPV with 2 mm metallic and 2 mm composite pressure vessel. Descriptive plot of total deformation and pressure obtained from the software is presented in Figure 7(b) it gave that, the deformation of 2 mm metallic and 2 mm composite pressure vessel was linear increase in the deformation with the incremental increase in the pressure. The pressure corresponding to sudden rise in the curve was the indication of burst pressure. At this point, the pressure vessel failed by losing its ability to resist deformation. In this case the pressure vessel was failed at an internal pressure of 22.01 MPa and deformation of 13.812 mm. Hence burst pressure of 2 mm metallic and 2 mm composite pressure vessel was 22.01 MPa.

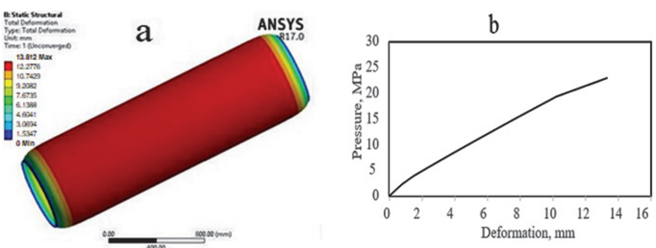

Figure 7: Deformation (a) and plot of Pressure vs Deformation (b) for COPV

Table 6 gives the values of burst pressure and corresponding deformation for different types of pressure vessels namely, metallic, composite and COPV by varying the wall thickness.

From the deformation corresponding to the burst pressure for various types of pressure vessels considered in the study, it was clear that the deformation of metallic pressure vessel was significantly higher than COPV and composite pressure vessels. This was due to the ductile nature of metal. The

Table 6: Burst pressure and deformation of Ansys results

Case	Burst Pressure, MPa	Deformation, mm
1	8.96	16.381
2	53.82	10.007
3	33.56	12.281
4	22.01	13.812

deformation of composite vessel was 10.007 mm which was 63.74% lesser than metallic pressure vessel. Lesser deformation was the indication of greater stiffness of COPV which was a measure of better resistance to deformation.

Table 7 shows the correlation between the theoretically and numerically predicted values of burst pressure. It could be seen from the table that the theoretical values were in positive acceptance with those obtained FEA, thus validating the finite element approach. The COPV showed bursting strength higher than that of metallic and composite vessels. The results exhibited that COPV with minimal metal layer and maximal composite layer had the greatest bursting strength of 39.61 MPa (average value) which was more than 315% of the bursting strength of metallic pressure vessel for the same overall wall thickness and more than 100% of the bursting strength of composite pressure vessel with 6 mm wall thickness.

Table 6: Correlation between theoretically and numerically predicted burst pressures

Case	Burst pressure (Theoretical), MPa	Burst pressure (ANSYS), MPa	% Error
1	8.08	8.96	9.8
2	55.31	53.82	2.7
3	35.58	33.56	5.6
4	20.24	22.01	8.7

6.0 Conclusions

Finite element and analytical approach have been examined for the effect burst pressure on reducing thickness in metallic, composite and COPV. Burst pressure was predicted for metallic and composite pressure vessels to study the overwrapping effect on burst strength. Following were the major conclusions from the results of the investigation.

- The composite vessel offers greater strength and stiffness when compared to metallic and COPV for the thickness of 5mm considered for the analysis.
- The numerically predicted results of burst pressure were observed to be in superior agreement with analytical

predictions for the types of pressure vessels considered.
- The strength of COPV can be increased by increasing the thickness of both metal and composite.
- Because of highest specific strength and stiffness of carbon/epoxy composite, composite can be recommended for weight sensitive applications.

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