EFFECT OF CONSTITUENT SHELL THICKNESS ON BURST PRESSURE OF COMPOSITE OVERWRAPPED PRESSURE VESSEL

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Abstract-In this paper, the effect of thickness of the liner and composite on the burst pressure and deformation of composite over wrapped pressure vessel under fluid pressure has been investigated by finite element method. Low carbon steel (Q235-A) and Carbon 700/0164 epoxy has been chosen as the materials for the liner and composite respectively. The angle of orientation of the fiber has been considered as constant. The results of finite element analysis are compared with those obtained from analytical equations for validation of finite element approach and are found to be in good agreement. Analysis has been extended to all metal(only liner) and all composite (only composite) pressure vessels in order to study the effect of overwrapping. The thickness of the liner was varied from 1 to 6 mmwhereas the composite thickness was varied from 3 to 5 mm. The composite overwrapped pressure vessel exhibited bursting strength greater than that of all metal and all composite pressure vessels considered in the study. The results showed that composite overwrapped pressure vessel with minimum liner thickness and maximum composite thicknesshas the highest bursting strength.

Keywords: burst pressure, composite, pressure vessel

1. Introduction

Composite overwrapped pressure vessel (COPV) is a new generation of pressure cylinder in which a continuous fiber composite is wrapped (by filament winding technique) around a liner that acts as a barrier for the permeability of fluid. Fibers provide the tensile strength whereas the matrix carries the shear load in the composite and retain the fibers in position. COPV's are extensively used in various application sectors like aerospace, chemical, aviation etcbecause of their advantages like high specific strength,excellent fatigue resistance etc. The liner material may be metallic (aluminium, steel etc) or non-metallic (rubber, plastic etc) and fibers used in composite are high performance fibers like Carbon, Kevlar, Aramid etc.

The design of pressure vessel is based on the consideration of failure due to excessive plastic deformation or excessive pressure (burst pressure). Hence it is essential to determine the burst pressure for safe functioning of pressure vessel. Several investigations have been carried out on pressure vessels made of metals, alloys, composite materials and in recent years composite overwrapped pressure vessels. Chang (2000) analyzed laminated graphite/epoxy composite pressure vessel for first-ply failure, both experimentally and theoretically. The effect of number of layers, radius-to-thickness ratio and material properties on failure pressure was investigated. They found that for all the cases, Hill Criterion predicted failure pressure with an error of less than 1% with experimental failure pressure. Liping Xue et al (2008) evaluated the burst pressure of pressure vessel made of low carbon steel Q235-Aby finite element analysis and the results were checked with empirical formulae. A minor defect in the form of slight variation in the thickness and introduction of small hole in the middle of the cylinder was introduced in the pressure vessel in order to initiate the failure without affecting the magnitude of burst pressure. They concluded that the finite element results are in good agreement with Barlow's formula. Zheng and Liu (2008) calculated the burst strength Al-carbon fiber/epoxy composite by varying the winding angles and no.of layers in composite shell. They used theoretical model based on classical lamination theory and theory of plasticity to obtain elasto-plastic stress solution of composite laminated pressure vessel. The results revealed that, with the increase in the winding angle, the radial displacement and shear-stress decrease, whereas the radial stress increases. Shivamurthy et al (2010) conducted cyclic pressure teststo determine the burst pressure in composite overwrapped pressure vessel with aluminum alloy 6063 as liner material and glass/epoxy as composite cylinder material. They found that the burst pressure of cylinders lies between 10 to 13 MPa. Jose Humberto S Almeida Jr et al [2014] investigated the influence of liner thickness on the load sharing ability of aluminium and stainless steel liner for similar COPV geometries, numerically using FEM. The stress/strain relationships for different liner thickness and material conditions were analyzed. They proposed a stress function parameter which can be effectively used as a practical tool for analyzing the liner contribution in overall structure. TakalkarAtul S et al[2016] studied the effect of winding angle on COPV manufactured by filament winding technique, using FE analysis. A COPV cylinder for hydrogen storage tank for application in fuel cell car was designed with an operating pressure of 20 MPa and sustainable pressure of 40 MPa. The optimum winding angle for the selected design was evaluated by altering the stacking sequence by considering various ply angles. They found good correlation of results between numerical and analytical (Tsai-Wu failure criterion) approach.

In this paper, the burst pressure of composite overwrapped pressure vessel with low carbon steel liner and carbon/epoxy composite is predicted by finite element approach and the effect of liner and composite thickness on bursting strength of the composite is studied. Analysis has also been extended to all metal (only liner) and all composite (only composite) pressure vessels in order to study the effect of overwrapping.

2. Methodology

2.1 Materials

Low carbon steel Q235-A is used as the material of the liner. The mechanical properties and the multi linear hardening parameters (plastic properties) of this material that are needed in the analysis are presented in Table 1 and Table 2 respectively [2].

Table 1 Properties of Q235-A

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

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Table 2 Multi linear parameters

Plastic Stress (MPa)	Plastic strain
251.00	0.00125
340.47	0.003135
345.31	0.01725
374.29	0.028976
429.58	0.038644
486.79	0.067098
522.43	0.094765
552.50	0.13050

Carbon 700/0164 epoxy composite with 60% fiber volume fraction is used as a winding material over the Q235-A liner. The properties of this material are listed in Table 3 [3].

Table 3 Properties of Carbon/Epoxy Composite

Property	Value
Ultimate Tensile Strength	2150 MPa
Ultimate Compressive Strength	2150 MPa
Yield Tensile Strength	298 MPa
Yield Compressive Strength	298 MPa
Shear Strength	778 MPa
Longitudinal Young's Modulus	181GPa
Transverse Young's Modulus	10.3GPa
Shear Modulus	5.17GPa
Poisson's ratio	0.28

2.2 Finite Element Analysis

2.2.1 Assumptions

Following assumptions are made in the finite element analysis.

1. The wall is assumed to be very thin compared to other dimensions of the vessel.
2. The geometry and the loading are symmetric.
3. The internal pressure is uniform and positive at all points.
4. End effects are neglected.
5. Pressure inside the vessel produces a hoop-to-axial stress in the ratio of 2:1.
6. The thickness of each ply is0.5 mm.

2.2.2 Geometry of the Cylindrical Shell

Without affecting the magnitude of the burst pressure, a minor defect in the form of a small hole is introduced on the cylinder to promote the failure initiation. A study of the effect of this defect on the burst pressure of the cylinder is outside the interest of the study. The geometry of the cylindrical shell along with the dimension of defect is shown in Table 4 [2]. In this analysis, the diameter of the small hole $d_h$is equal the thickness of the cylinder i.e. d_h/D =0.01.

Table 4 Geometry of the Cylindrical Shell

Diameter (D) Mm	Length (L) mm	Thickness (T) mm	Diameter of small hole (d_h), mm
600	2400	6	6

2.2.3 Winding angle

It has been shown that the burst pressure increases with the increase in the angle of winding up to 55° as the laminate show more resistance to hoop stress than the axial stress. It is vice versa for winding angle greater than 55° [7]. This trend is shown in figure 1. Hence, this angle is considered as optimum angle and is adopted in the analysis.

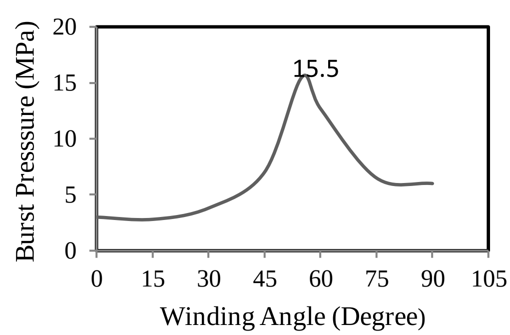


Figure 1 Burst pressure versus winding angle

ISSN 2229-5518

2.2.4 Finite Element Models

For all metal (only liner) pressure vessel, 3-noded triangular shell element whereas for COPV and all composite pressure vessel,4-noded quadrilateral shell element were used to generate the finite element model except at the vicinity of the defect, where 3-noded triangular shell element was used. Finite element meshed models for liner and COPV are shown in figures 2 and 3 respectively. For boundary conditions, both ends of the cylinder are considered as fixed.

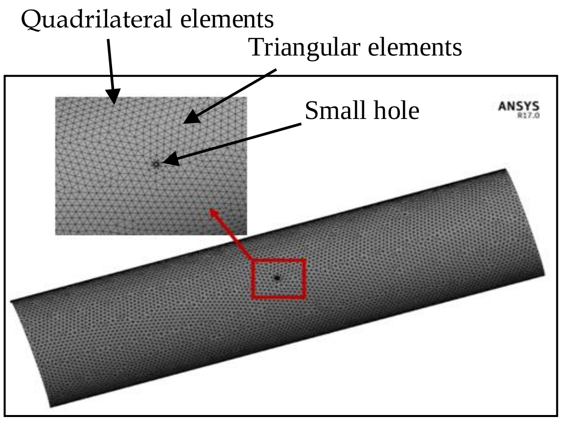


Figure 2 Meshed model of all metal cylinder

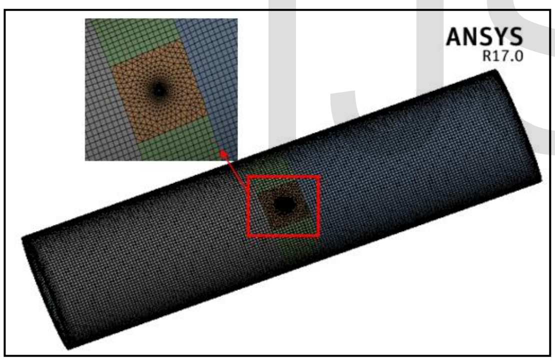


Figure 3 Meshed model of COPV

2.2.5 Procedure

The step-by-step procedure adopted for the prediction of burst pressure by finite element analysis is given in flow chart (Figure 4). ANSYS Composite PrepPost(ACP), an add-on module is exclusively designed for modeling of layered composite structures. In the present work, ACP(Pre) is used for the analysis of COPV.

2.3 Theoretical Prediction

The finite element approach adopted for the prediction of burst pressure of COPV is validated by comparing the finite element results with those obtained from theoretical approach. Various equations have been proposed by the researchers for the theoretical prediction of burst pressure for thin cylindrical shells. These equations include Cooper equation, modified Svensson equation, Barlow's equation etc. However, Barlow's equation (1) gives good prediction of burst pressure for cylindrical shell [2].

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

Where, PB is the burst pressure, MPa, σu is the ultimate strength of material, MPa, T is the thickness of pressure vessel, mm and D is the inner diameter of pressure vessel, mm

For COPV comprising of both liner and composite shells, the burst pressure can be calculated using equation (2) [8].

$$P_B = (P_B)_L + (P_B)_C \quad (2)$$

Where, (PB)L= Burst pressure of liner, MPa,

(PB)C = Burst pressure of composite layers, MPa

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

$$(P_B)_C = \sum_{i=1}^{n} \frac{2(\sigma_u^c)t}{D_i} \quad (3)$$

Where, σuc is the ultimate tensile strength of the composite, MPa (Table 3), 't' is the thickness of each layer, mm, 'n' is the number of layers in composite shell,Di is the inner diameter of i^{th} layer.

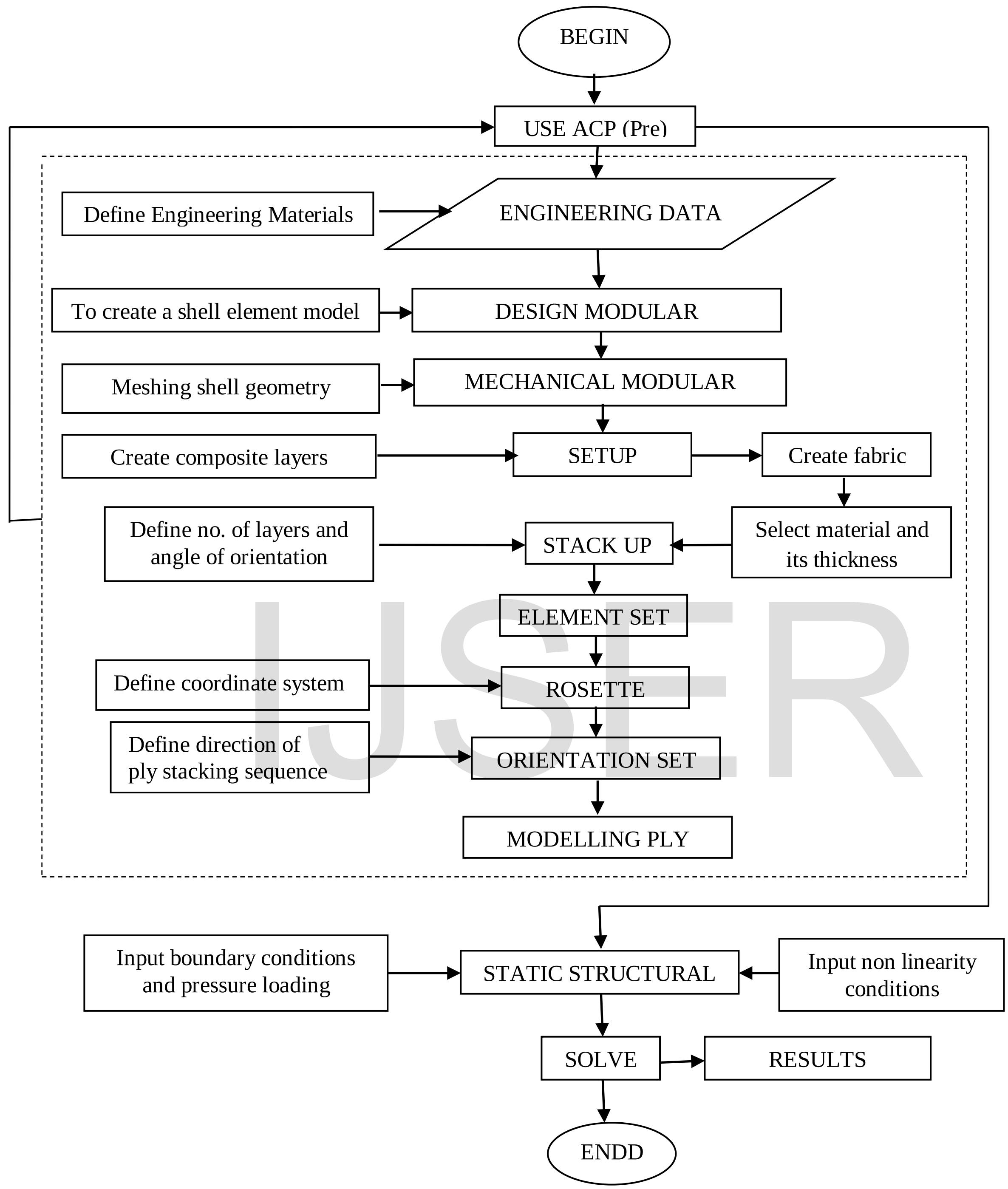
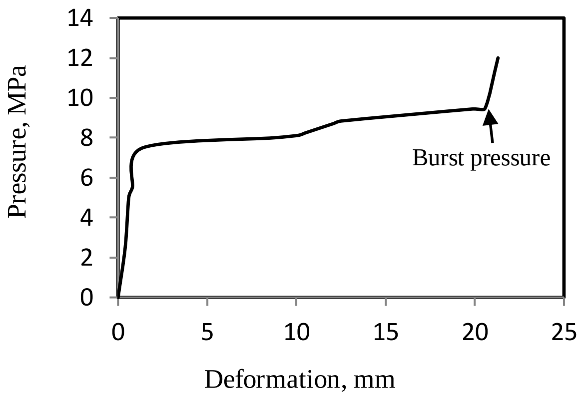


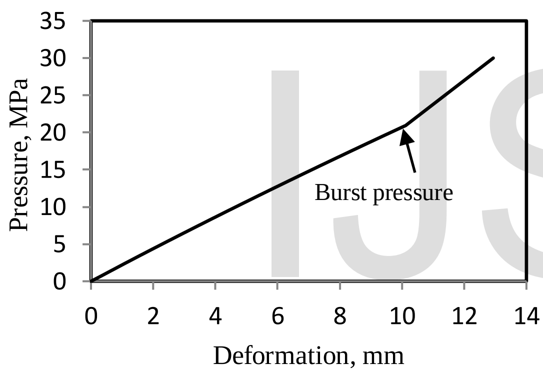
Figure 4 FE procedure for prediction of burst pressure

2.4 Results and discussion

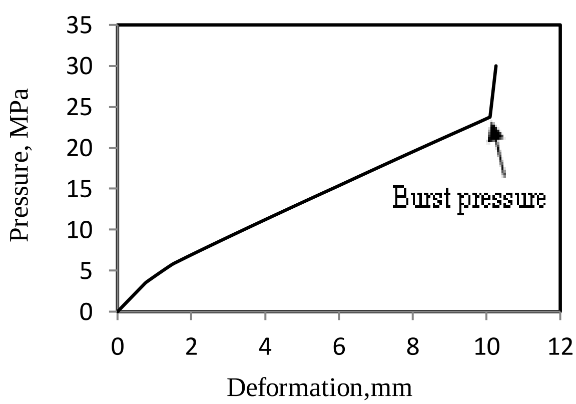
The deformation of the pressure vessel recorded by the software for the incremental internal pressure are plotted for different types of pressure vessels namely., all metal, all composite and COPV by varying the wall thickness. Typical plots obtained from the software are shown in Figure 5.



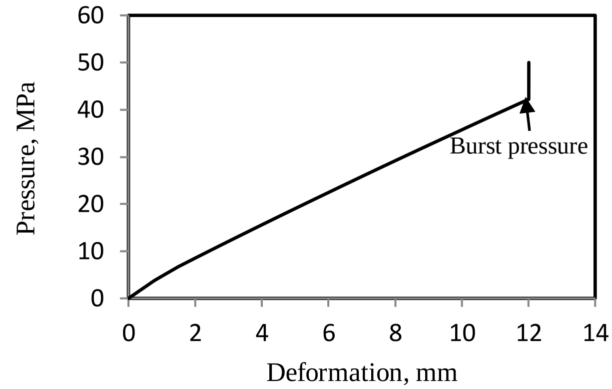
(a) Liner (6 mm thickness)



(b) All composite (3mm thickness)



(c) COPV (2 mm liner, 3 mm composite)



(d) COPV (1mm liner, 5 mm composite)

Figure 5 Indication of burst pressure

Figure 5(a) reveal that, the deformation of all metal (liner) pressure vessel is negligible at the beginning followed by significant deformation for small incremental pressure as indicated by the plateau region. The pressure versus deformation plots for all composite and COPV pressure vessels showed almost identical trend with linear increase in the deformation with the incremental increase in the pressure (Figures 5(b), 5(c) and 5(d)). Firstly, we calculate the burst pressure theoretically for all the cases and mention some more value in the FE analysis. In FE analysis the software will take incremental value of pressure for every time step and the pressure versus deformation graph will plotted. At a particular pressure when the elements are deformed plastically and fails to withstand that pressure and that pressure is burst pressure and very next iteration software will take the maximum value of pressure that we mentioned in the software that's why the change of slope in the curve will occurs. The pressure corresponding to sudden rise and change in slope of the curve is the indication of burst pressure. At this point, the pressure vessel loses its capability to resist deformation.

Table 5 shows the correlation between the theoretically and numerically predicted values of burst pressure. It can be seen from the table that the theoretical values are in good agreement with those obtained from finite element analysis, thus validating the finite element approach.The COPV exhibited bursting strength greater than that of all metal and all composite (3 mm thickness) pressure vessels. The results showed that COPV with minimum liner thickness and maximum composite thickness has the highest bursting strength of 40 MPa (average value) which is more than 300% of the bursting strength of all metal pressure vessel for the same overall wall thickness and more than 100% of the bursting strength of all composite pressure vessel with 3 mm wall thickness.

Table 5 Correlation between Theoretical and Numerically Predicted burst pressure

Type of Pressure vessel	Wall thickness mm	Burst Pressure (Theoretical) MPa	Burst Pressure (ANSYS) MPa	% error
All metal (Liner)	06	9.7	9.5246	1.8
All composite	03	21.4112	20.927	2.26
COPV	Liner 03, Composite 03	26.05	24.818	4.7
COPV	Liner 02, Composite 03	24.5032	23.756	3.04
COPV	Liner 01, Composite 03	22.9036	22.575	1.43
COPV	Liner 02, Composite 04	31.5466	33.56	5.99
COPV	Liner 01, Composite 05	37.0134	42.208	12.3

Figure 6 compares the deformation corresponding to the burst pressure for various types of pressure vessels considered in the study.

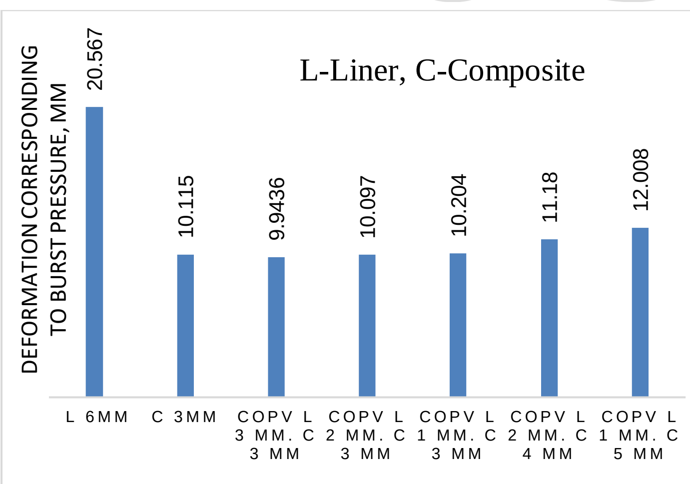


Figure 6 Deformation corresponding to burst pressure

It is clear from the figure that the deformation of all metal (liner) pressure vessel is significantly higher than COPV and all composite pressure vessels. This is due to the ductile nature of liner material. The variation in thickness of liner and composite in COPV has marginal effect on the deformation of pressure vessel corresponding to burst pressure. The deformation of COPV with liner thickness of 1mm and composite thickness of 5 mm is 12 mm which is 58.38% lesser than all metal pressure vessel. Lesser deformation is the indication of greater stiffness of COPV which is a measure of better resistance to deformation. The deformed pressure vessel along with the value of maximum deformation as obtained from ANSYS is shown in figure 7 for all metal pressure vessel and COPV with 1 mm liner and 5 mm composite wall thickness.

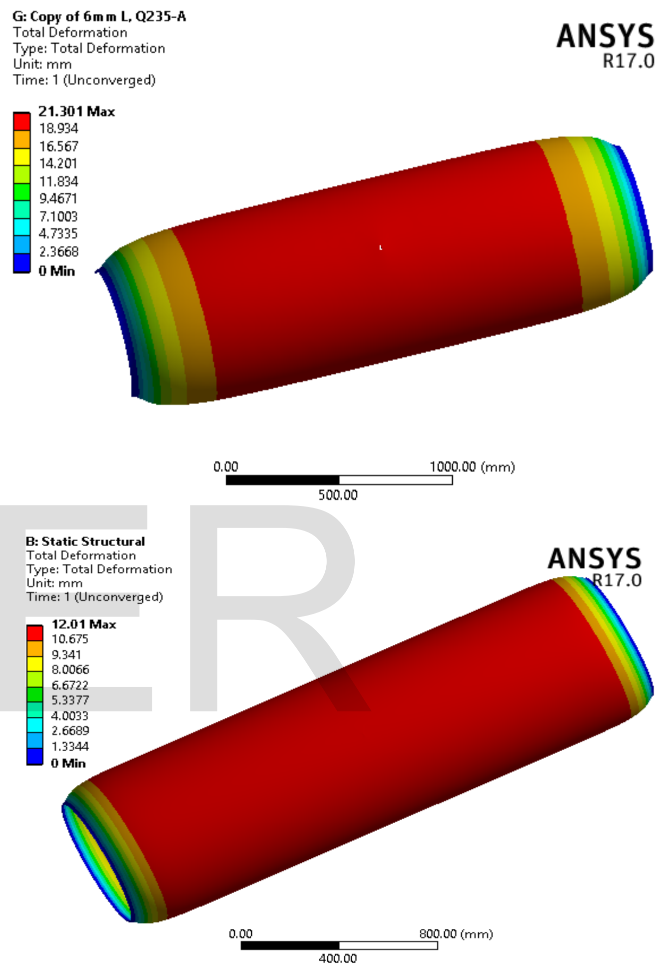


Figure 7 Deformation in pressure vessels

2.5 Conclusions

The effect of thickness of liner and composite shell on burst pressure of composite overwrapped pressure vessel was investigated by finite element and analytical approach. Burst pressure was also predicted for all metal and all composite pressure vessels in order to study the effect of overwrapping on burst strength. Following are the major conclusions from the results of the investigation.

- The composite overwrapped pressure vessel offers greater strength and stiffness when compared to all metal and all composite pressure vessels considered in the study.

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- The numerically predicted results of burst pressure are found to be in good agreement with analytical predictions for all types of pressure vessels considered.
- COPVwith different thicknesses of liner and composite shells exhibited marginal variation in deformation corresponding to burst pressure. This indicates that the thickness of constituent shells has no significant effect on the stiffness of COPV. However, COPV with equal thicknesses of liner and composite shells offer highest stiffness.
- COPV with minimum liner shell thickness and maximum composite shell thickness provides highest bursting strength.
- Because of highest specific strength and stiffness of carbon/epoxy composite, pressure vessels with steel liner overwrapped with carbon/epoxy composite can be recommended for weight sensitive applications.

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