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Finite element analysis of filament-wound composite pressure vessel under internal pressure

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Abstract. In this study, finite element analysis (FEA) of composite overwrapped pressure vessel (COPV), using commercial software ABAQUS 6.12 was performed. The study deals with the simulation of aluminum pressure vessel overwrapping by Carbon/Epoxy fiber reinforced polymer (CFRP). Finite element method (FEM) was utilized to investigate the effects of winding angle on filament-wound pressure vessel. Burst pressure, maximum shell displacement and the optimum winding angle of the composite vessel under pure internal pressure were determined. The Laminae were oriented asymmetrically for $[0^0,0^0]_s$,$[15^0,-15^0]_s$,$[30^0,-30^0]_s$,$[45^0,-45^0]_s$,$[55^0,-55^0]_s$, $[60^0,-60^0]_s$,$[75^0,-75^0]_s$,$[90^0,-90^0]_s$ orientations. An exact elastic solution along with the Tsai-Wu, Tsai-Hill and maximum stress failure criteria were employed for analyzing data. Investigations exposed that the optimum winding angle happens at 55^0 winding angle. Results were compared with the experimental ones and there was a good agreement between them.

1. Introduction

The wide range of pressure vessel applications turned it into one of the most important equipment of industry. Today composite pressure vessels known as new generation vessels have been widely used in many industrial zones. The superior characteristics of a composite vessel such as light weight, high stiffness, corrosion resistance and long lifetime make it a perfect replacement for metallic vessels [1-2]. Although composite vessels were first used for military cases and aerospace functions, nowadays they have many civilian applications including oxygen and hydrogen gas storage cylinders, scuba and fire-fighter tanks [3-7].

Filament winding is the usual considered process for fabricating composite structures. It is the process in which continuous filaments of fiber are wound on a supporting mandrel. The mandrel rotates with the spinning wheel on a horizontal axis then carriage begins to move linearly so fibers are laid down in the predetermined path. The most conventional uses of filament winding process are in high-pressure storage tanks, rocket motor cases, launch tubes, and for commercial applications, such as golf club shafts [8].

A thin-walled (the ratio of outside to the inside diameter of the vessel less than 1.1) composite vessel has been studied in this present work. The composite vessel is made of inside aluminum liner overwrapping with Carbon fiber/Epoxy composite. This type of vessel is placed in the third type of composite vessel usually used has higher corrosion resistance, more safety and longer lifetime [9].

Barboza Neto et al. [10] investigated the behaviour of LLDPE and HDPE composite pressure vessel under burst testing. The experimental and finite element analyses were applied to determine the proper composite thickness based on the value of burst pressure. Studies estimated the required vessel thickness and proper stacking sequences according to the burst pressure. Liu et al. [11] focused on predicting the burst pressure and lifetime of composite pressure vessels. Damage modeling and progressive failure analysis were utilized to determine the strength reliability, stiffness degradation and failure properties of composite vessel. Sayman et al. [12] did the experimental study at GRP composite cylinders to survey the effects of temperature and winding angle on strength of composite vessels. Studies demonstrated the optimum stacking sequence and also proved that the strength of composite vessels decreases with increasing temperature. Gohari et al. [13] compared finite element analysis with theoretical studies to ascertain that static internal pressure and fiber angle orientation have the direct effect on stress distribution of composite vessel. Tabakov and Summers [14] introduced a 3-D elasticity solution to study the behaviour of multi-layered cylinder subjected to asymmetric internal and external pressure along with the axial force. The analyses demonstrated that for thin-wall and thick-wall single-layered cylinders the optimum winding angle is in the range of 54^0-57^0. Xu et al. [15] utilized finite element analysis to predict burst pressure of the composite storage vessel. Tsai-Wu failure theory was applied to predict the damage evolution and failure strength in composite vessel subjected under internal pressure. Bhavya et al. [16] investigated the effects of diameter-to-thickness ratio and surveyed the variation of failure pressure with respect to fiber angle using finite element software. Marzbanrad et al. [17] employed "unit load method" to predict the burst pressure and fatigue lifetime of composite vessel. The simulation results obtained from ABAQUS were in good agreement with the experimental ones. In this present research attempts have been made to:

- Determine the burst pressure and the maximum shell displacement for asymmetric fiber orientations of composite vessel.
- Determine optimum winding angle according to diverse failure criteria.
- Compare simulation results with the experimental ones.

2. Theoretical Studies

2.1. Winding Angle

Winding angle has significant effects on the structure of filament-wound vessels; so determining the appropriate angle for each part of the vessel is an important issue. The winding angle is defined for the two types of geodesic and non-geodesic winding based on the need for friction between fibers and the shell as in Eq. (1). The second part of the following relation relates to the non-geodesic winding method [11, 18-21]:

$$\alpha(R)=sin^{-1}\left(\frac{R_0}{R}\right) \mp \delta\left(\frac{R-R_0}{R_{tl}-R_0}\right)^n \tag{1}$$

Here, R is the radial distance from the center line to a point in the layer, R_0 is the radius of the polar axis, and R_{tl} is the radius at the dome-cylinder tangent line. A geodesic winding pattern, as in this research is obtained by choosing $\delta= 0$.

2.2. Optimum Winding Angle

Netting analysis is one of the most popular analytical techniques used for investigating the behavior of multi-layered composite materials, especially for filament-wound pressure vessels. The main assumption in netting analysis is that all loads are carried by the fibers neglecting the stiffness of the matrix and internal pressure subjected to the vessel produces a hoop-to-axial-stress ratio of 2:1 [22].

Figure 1 indicates the thin-wall cylindrical vessel with the thickness of "t" and length of "L" which is subjected into the internal pressure of "P". In order to calculate the axial (longitudinal) and hoop stresses at the cylinder with the radius of "R", Eq. (2) can be utilized [23-25]:

$$N_{\emptyset} = \frac{PR}{2} \quad , \quad N_{\theta} = PR \tag{2}$$

Axial and hoop stresses can be calculated as in Eq. (3):

$$\sigma_{axial} = \frac{N_{\emptyset}}{t} = \frac{PR}{2t} \quad , \quad \sigma_{hoop} = \frac{N_{\theta}}{t} = \frac{PR}{t} \tag{3}$$

Axial and hoop stresses can be calculated according to equilibrium across the cut section too as in Eqs. (4) and (5):

$$PL\ (2R) = 2\sigma_{hoop}Lt \quad \Longrightarrow \quad \sigma_{hoop} = \frac{PR}{t} \tag{4}$$

$$P\pi r^2 = \sigma_{axial}(2\pi Rt) \quad \Longrightarrow \quad \sigma_{axial} = \frac{PR}{2t} \tag{5}$$

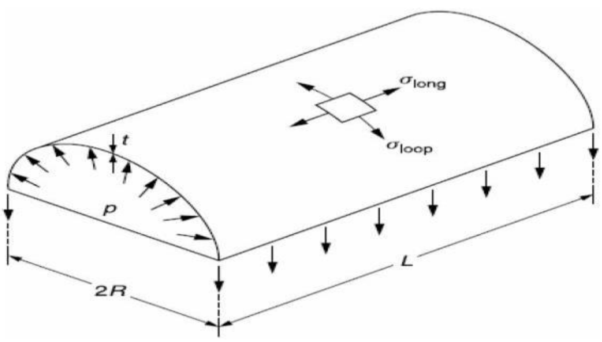

Figure 1. Thin cylindrical shell [23].

Optimum winding angle can be estimated by using ultimate tensile strength along with applying netting analysis respect to 2:1 hoop-to-axial stress ratio as it is shown at Eqs. (6) and (7)., as it is shown in figure 2. The body diagram of the cylinder consists of axial and hoop forces wrapped with the fibers at the angle of "α" is indicated at figure 2.

$$N_{\theta} = \sigma_u t \sin^2\alpha \quad , \quad N_{\emptyset} = \sigma_u t \cos^2\alpha \tag{6}$$

$$\frac{N_{\theta}}{N_{\emptyset}} = \tan^2 \alpha = 2 \quad \Longrightarrow \quad \alpha = \arctan(\sqrt{2}\,) = 54.7^0 \tag{7}$$

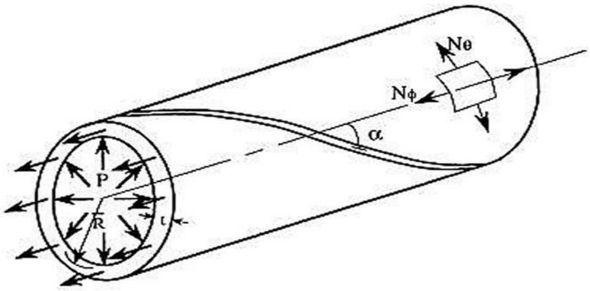

Figure 2. Body diagram of axial and hoop forces and internal pressure [26].

2.3. Failure Theories

Precise analyzing the strength of composite layers requires employing failure criteria. Different types of failure analyses can be used for evaluating the strength of composites laminae.

2.3.1. Tsai-wu failure criterion

Satisfying the Eq. (8) is essential for Tsai-Wu theory to predict failure in an orthotropic lamina under plane stress condition [27]:

$$F_{11}\sigma_1^2 + F_{22}\sigma_2^2 + F_{66}\tau_{12}^2 + F_1\sigma_1 + F_2\sigma_2 + 2F_{12}\sigma_1\sigma_2 \geq 1 \tag{8}$$

Elastic characteristics consist of four independent elastic constants (E_{11},E_{22},G_{12},υ_{12}). Strength properties are divided into five independent strength properties:

X_t = longitudinal tensile strength, Y_t = transverse tensile strength
X_c = longitudinal compressive strength, Y_c = transverse compressive strength
S = in-plane shear strength

F_1, F_2 are the strength coefficients and are given by, it should be considered that F_1, F_2, F_{11} , F_{22} , F_{12} , F_{66} can be calculated by using the tensile, compressive and shear strength properties in the principal material directions at the Eq. (9):

$$F_1 = \frac{1}{X_t} - \frac{1}{X_c} \quad , \quad F_2 = \frac{1}{Y_t} - \frac{1}{Y_c} \quad , \quad F_{11} = \frac{1}{X_t X_c} \quad ,$$

$$F_{22} = \frac{1}{Y_t Y_c} \quad , F_{66} = \frac{1}{S^2} \ , \quad F_{12} = -\frac{1}{2}\sqrt{F_{11}\,F_{22}} \tag{9}$$

2.3.2. Tsai-hill failure criterion

Tsai-Hill failure criterion can be explained at Eq. (10) [28]:

$$F_{11}\sigma_1^2 + F_{22}\sigma_2^2 + F_{66}\tau_{12}^2 + 2F_{12}\sigma_1\sigma_2 \geq 1 \tag{10}$$

The strength parameters F_{11}, F_{22} , F_{66} and F_{12} are given by at Eq. (11):

$$F_{11} = \frac{1}{X^2} \quad , \quad F_{22} = \frac{1}{Y^2} \quad , \quad F_{66} = \frac{1}{S^2} \quad , \quad F_{12} = -\frac{1}{2}\left(\frac{1}{X^2} + \frac{1}{Y^2}\right) \tag{11}$$

2.3.3. Maximum stress failure criterion

This theory, Eq. (12), expresses that the failure occurrences when at least one of the following criteria is satisfied [15]:

$$\left|\frac{\sigma_1}{X}\right| \geq 1 \ , \left|\frac{\sigma_2}{Y}\right| \geq 1, \left|\frac{\tau_{12}}{S}\right| \geq 1 \tag{12}$$

3. Simulation Details

The considered pressure vessel is the vertical one designed for low capacity applications. The vessel is sketched with 1200 mm length, 300 mm diameter at the center point and the wall thickness of (0.3-4) mm based on the geometry .The material of this cylindrical vessel consist of the aluminum alloy inside layer reinforced with six layers of Carbon/Epoxy T300/LY5052 fiber. The wall thickness of vessel in center section of the vessel is 0.3 mm and each lamina thickness is 0.762. The inner radius of the vessel is 150 mm, considering six composite layers (4.572 mm); the outer radius of the vessel becomes 154.872 mm. Tables 1 and 2 indicate material properties of aluminum alloy [29] and CFRP [3] respectively.

Table 1. Mechanical properties of Al 6061 and CFRP.

	Density(kg/m^3)	E_1 (GPa)	E_2 (GPa)	υ_{12}	G_{12} (GPa)	τ (MPa)
AL 6061	2750*	70	70	0.3	27	600
CFRP	1570*	135	8	0.27	3.8	-

*.Yingjun et al., 2010

Table 2. Strength parameters for CFRP composite.

X_t (MPa)	X_c (MPa)	Y_t (MPa)	Y_c (MPa)	S (MPa)
1860	1470	76	85	98

In this research finite element analysis software has been used to collect the proper data. In order to analyze the effects of variables on filament wound structures “ABAQUS” software is utilized for modeling the vessel. In order to reduce the time of calculation, the finite element model has been made for half the composite pressure vessel as it is indicated at the figure 3.The mesh is constant for the whole part and because the model has been made due to the revolving process, the “Quad-dominated” meshing type has been selected. For obtaining precise results meshing with global size of 0.01 has been used. This mesh consists of 4290 nodes and 7872 elements.

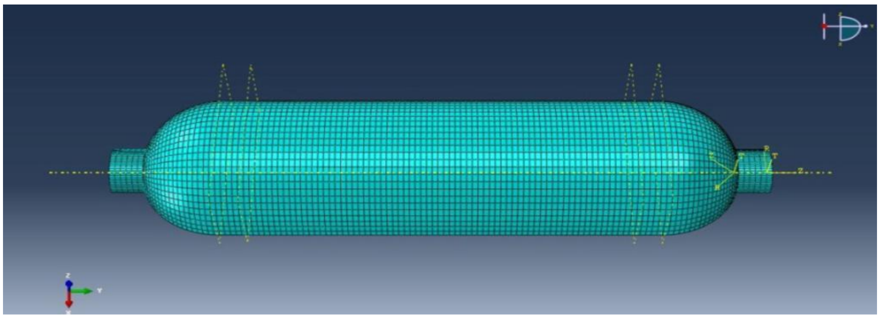

Figure 3. The finite element model of composite vessel.

Internal pressure load has been applied for subjecting to model to estimate the burst pressure and maximum shell displacement in two cases; first non-constant pressure to find the burst pressure and second constant pressure to find the shell displacement. In order to consider the effects of winding angle, the data should be evaluated based on failure theories. According to what was mentioned before Tsai-Wu, Tsai-Hill and maximum stress failure theories have been utilized for analysing data. In composite pressure vessels the burst pressure is determined by investigating the first-ply failure strength. Although the ultimate burst strength is usually higher than the first-ply failure strength, determining the first-ply failure of composite layer is safe enough to design the vessel [30].

According to the mentioned failure theories the method for obtaining the outputs are different. In order to analyse the model based on Tsai-Wu and Tsai-Hill failure criteria, after defining the Winding Angle it is essential to select the appropriate amount of internal pressure. This means that the quantity of internal pressure should be set to reach the proper failure coefficient (slightly higher than one) and then the outputs can be calculated. Subsequently the internal pressure can be submitted as burst pressure which is one of the main outputs of research. Maximum stress failure theory follows the philosophy that the maximum stress of composite first-ply should be always less than the ultimate stress ($\sigma_{\max} \leq \sigma_{u}$) [3,31].

In this present work, asymmetric fiber orientation,[θ /- θ / θ /- θ / θ /- θ], has been presented for $[0^0,0^0]_s$,$[15^0,-15^0]_s$,$[30^0,-30^0]_s$,$[45^0,-45^0]_s$,$[55^0,-55^0]_s$, $[60^0,-60^0]_s$,$[75^0,-75^0]_s$,$[90^0,-90^0]_s$. Figure 4 shows the stacking sequences for 55^0 winding angle:

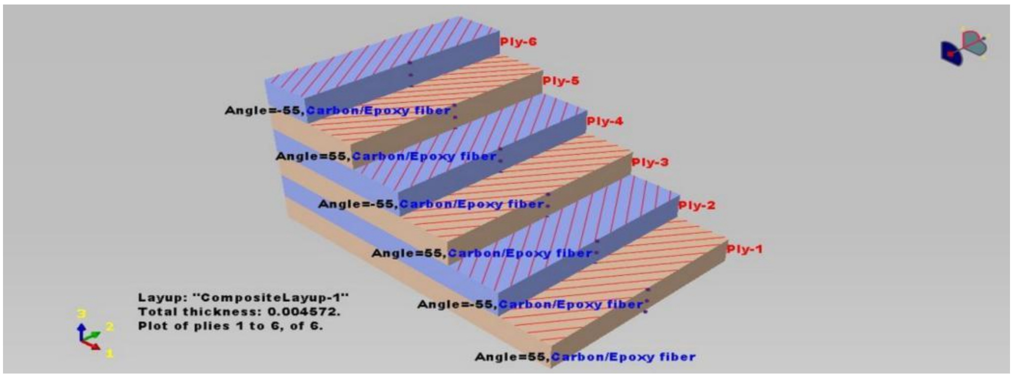

Figure 4. The stacking sequences for 55^0 winding angle.

4. Results And Discussion

The following results are extracted from analysing aluminum alloy which is strengthened by six layers of Carbon/Epoxy fiber with constant thickness of 0.762 mm for each layer. Figure 5 shows that in asymmetric fiber orientation the graph is not following a steady manner. According to failure criteria, the burst pressure displays increasing trend for 0^0 to 55^0 angle degrees, after 55^0 angle degrees the graph follows the decreasing trend up to reach 90^0 angle degrees. As it is clear at figure 5, the maximum burst pressure which vessel can withstand happens in 55^0 degrees (The optimum winding angle) based on failure theories. The maximum burst pressures have been obtained 15.5 MPa, 15.6 MPa and 16 MPa for Tsai-Wu, Tsai-Hill and maximum stress theories respectively. This angle has a good agreement with the winding angle calculated with netting analysis for composite laminates (54.7^0 degrees) [22].

Internal pressure is a combined load which produces axial and hoop stresses in materials. In order to find the optimum angle which withstands the maximum burst pressure, it is essential to search for the fiber angle which can tolerate hoop and axial stresses under the internal pressure. The burst pressure increases with increasing winding angle up to 55^0 degrees because laminates show more resistance to hoop stress than the axial stress. As the curve reaches to its maximum in 55^0 degrees, the amount of burst pressure decreases due to fiber higher resistance to axial stress and its lower resistance to hoop stress [32].

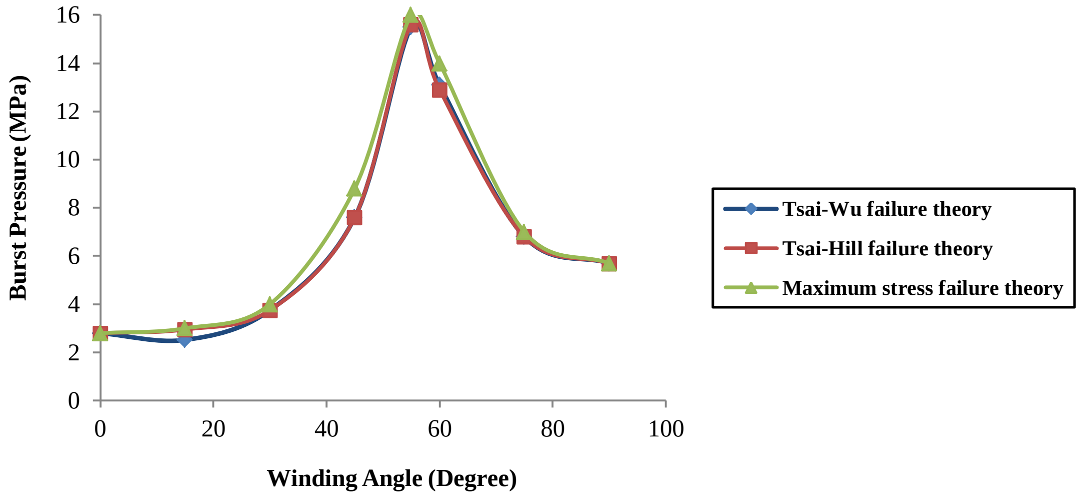

Figure 5. Variation of burst pressure with increasing winding angle.

As it is obvious at figure 5 Tsai-Wu and Tsai-Hill failure theories present more conservative results than maximum stress failure criteria but the difference can be negligible. Figure 6 exposes the maximum normal stress and the maximum stress failure failure coefficient for the 55^0 fiber angle orientation. The results based on failure theories are in good correlation with the experimental ones [4,12, 32].

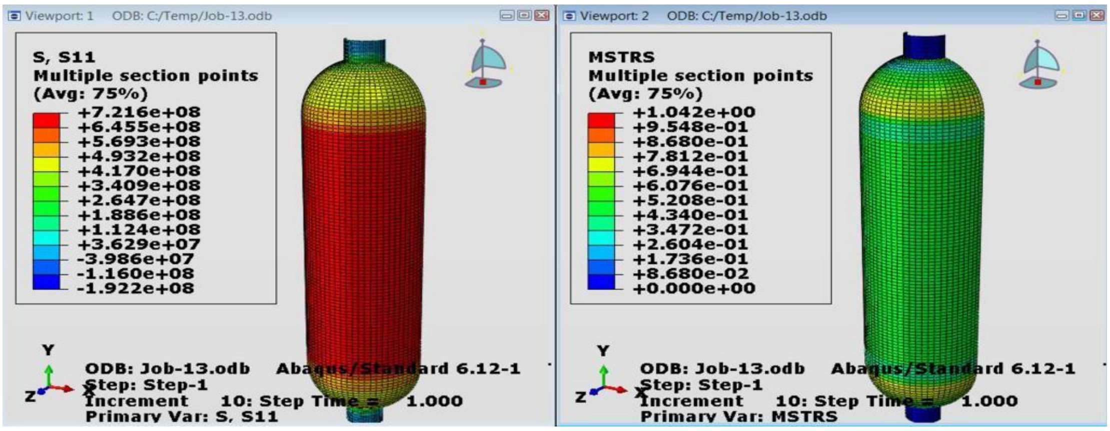

Figure 6. The maximum stress and failure coefficient at 55^0 winding angle.

At the second case with applying the constant pressure in model, the 15 MPa internal pressure has been subjected in vessel. As it is shown at figure 7 the minimum shell displacement belongs to 55^0 winding angle which proves the claim that 55^0 is the optimum angle and this is in good correlation with the experimental results [34-35].The FE model for the vessel shell displacement at 55^0 is presented at figure 8.

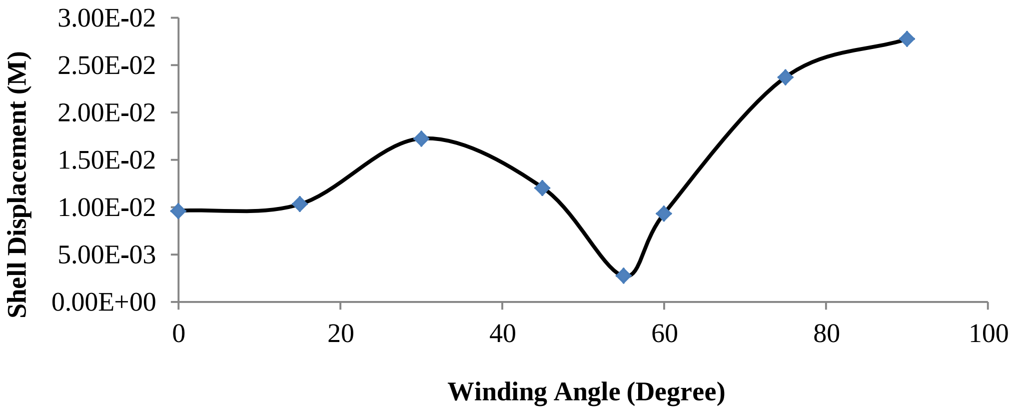

Figure 7. Variation of shell displacement with increasing winding angle

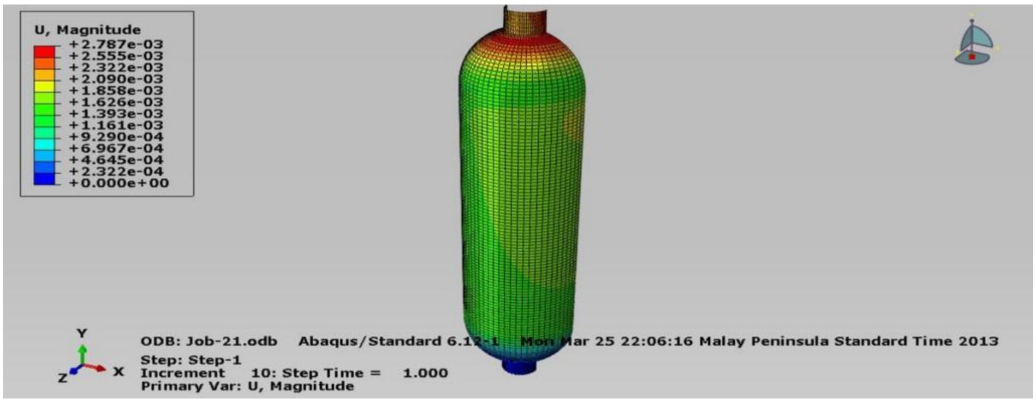

Figure 8. The shell displacement at 55^0 angle.

5. Conclusion

In this work, Finite element analysis was employed for investigating the structural behavior of pressure vessels. Aluminum alloy was utilized as the inside layer covered with Carbon/Epoxy fiber which was roving at different winding angles. FEA employed failure criteria such as Tsai-Wu, Tsai-Hill and maximum stress to predict the burst pressure, maximum shell displacement and determine the optimum winding angle.

Results and discussions were resulted in the following findings:

- Based on Tsai-Wu and Tsai-Hill failure criteria, 55^0 winding angle was approved as the optimum winding angle due to its maximum burst pressure and minimum shell displacement. This optimum angle was in good correlation with the experimental results trend and the netting analysis (54.7^0).
- Determining burst pressure using maximum stress failure theory was lead to less conservative results and higher burst pressure due to estimating the burst pressure based on ultimate strength of Carbon/Epoxy fiber.

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