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Burst strength analysis of composite overwrapped pressure vessel using finite element method

Y Regassa[1, *], H G Lemu[2] and B Sirhabizu[1]

[1] Addis Ababa Science and Technology University, Dept. of Mechanical Engineering, Addis Ababa, Ethiopia
[2] University of Stavanger, Faculty of Science and Technology, Norway

* Corresponding author: yohannes.regassa@aastu.edu.et

Abstract. The purpose of this numerical study was to investigate the burst performance of a type III composite overwrapped pressure vessel (COPV) using finite element methods. An Aluminum overwrapped composites pressure vessel was modeled from four layers of carbon fiber/epoxy ply with 0.762 mm and arranged in two different sequences and orientations. The overwrap composite pressure vessel burst performance was examined by applying an internal pressure of 55 MPa on a ply arrangement of [-15°/0°/+15°/90°] and other research findings on [+55°/-55°] as an optimum filament winding angle were used for comparison purpose. Moreover a ply level orientation effect analysis, which is a superior feature of ABAQUS, was used for the composite modelling. The designed ply sequence and orientation exhibit a higher burst pressure at [0°] ply and minimum at [90°] ply orientation. The vertical COPV design displays a maximum stress along the axial direction that leads to the consideration of maximum vessel thickness to be along axial direction for burst resistant design of COPV.

Keywords: Burst, Composite design, fiber orientation, Ply sequence, Pressure vessel

1. Introduction

Composite pressure vessels are increasingly being used in the renewable energy sector, primarily as a storage container for compressed natural gas (CNG). The restrictions on metallic pressure vessels due to weight and corrosion problemshas increased the demand of composite pressure vessel opens for the wide research opportunities to supply an optimized composite pressure vessel [1]. Usually, compacted hydrogen air is kept in Type I pressure vessel (metallic cylinders), whose storage capacity is limited to a pressure below 25 MPa. The capacity limitation and hydrogen embrittlement for raising micro-cracks in the cylinder is one of the factors not to use Type-I pressure vessel at large scale. The fiber reinforced composite were developed by overwrapping a fiber in the hoop direction of metallic fiber emerged as Type II pressure vessel to fill the gap of the less weight demand of such structure.

However, there is still a significant demand for weight reduction of pressure vessels by automotive industry, which is not met yet by existing types of hydrogen storage vessels to enhance usage of compressed gas as source of energy [2]. Type III: Metal liner (usually aluminum) and Type IV: Polymer liner (typically polyamide or polyethylene-based) with complete composite overwrap containers have been introduced to suit market demand for least weight and increased storage capacity. Such types of pressure vessels are produced through either polar, helical or hoop types of filament winding method [1],[2]. In the overwrapped pressure vessel, an inside layer is used as a mandrel and fiber with strength of 5-6 GPa and low density is used as an overwrapping material to cove the liner in the hoop and axial directions. The hoop and axial filaments are wound to bear axial and hoop loading of the cylinders. The pattern of ply in the hoop and axial direction can be determined by the designer. Depending on the liner types used for production of vessels, the vessel with metallic liner is labeled as type-III while type-IV vessel is produced with polymer liner like, Linear Low Density Polyethylene (LLDPE) and High

Density Polyethylene (HDPE) [2], [3]. The fact that composite pressure vessels are corrosion-resistant and provide reduced weight for the same volume of type-I (metallic vessel) is one of the reasons for the huge attraction of composite pressure vessel (COPV). However, composite pressure vessels demand a serious evaluation of mechanical design, appropriate materials, and manufacturing methods selection, and testing requirements are major challenges of the product that hinder the mass production and utilization of COPV [3].

One of the remarkable characteristics of COPV is the demand for the complex mechanical property; there should be proper attention to the interchangeability between the inner liner and lamina of the composite. Usually, the metal type liner is utilized as inner section of the vessel to act as a wall to fluid infiltration. Although there is the widespread use of overwrapped COPV, the design development and manufacturing of many overwrapped pressure vessels is at a primitive stage. Consequently, various research efforts have been undertaken on the performance analysis of COPV through different numerical and experimental techniques that qualify the product for the designed purpose. Burst strength evaluation of COPV is one of the major attentions that attract scholars to outline the optimum design parameters [1]–[3].

The current study deals with the evaluation of burst strength of thin cylindrical pressure vessels and the failure phenomena evaluation owing to circumferential or hoop stress along their direction in the pressure vessel construction. Accordingly , the study aims to:

- determine the axial and hoop stress developed on four plies with an aluminum liner made pressure vessel,
- determine the developed displacement and elastic strain on the overwrapped composite pressure vessel made from the Aluminum liner by overwrapping a carbon/epoxy fiber oriented at $15^\circ/0^\circ/-15^\circ/90^\circ$ and $\pm 55/ 55$ to produce a cylindrical pressure vessel
- evaluate the optimum winding angle used to resist the burst pressure on each plies and
- compare the obtained simulation results with the other measured experimental works.

2. Theoretical analysis of burst strength for pressure vessels

Construction machinery trucks, ship body building, aerospace part construction, and other dome-type civil structures are made of shell-type structures. Moreover, the pressure vessel of compressed gas or chemical container is made from shell structures [3]. Since the vital engineering structures are made from shell structures that are suspected to be exposed to bursting phenomena, numerous investigations have been conducted to discover the optimum method that can precisely foresee the rupture pressure vessels. To determine the specific value of the burst pressure and the precise place of rapture, a number of theoretical models, concepts, and procedures are established [4]. Typically, a restricted analysis is performed to acquire the basic design parameters, and then the design is advanced through many fabrication and burst iterations procedures, resulting in a significant investment cost for experimental investigation. Although finite element analysis (FEA) is a very strong method for pressure vessel research, it necessitates a lot of computing capacity.

Through an estimation based on the average equivalent plastic strain development over the thickness by arc length approach, FEA can be used to pinpoint the specific region of failure, as a result, pressure vessels are constructed with a thickness proportionate to the vessel's radius and pressure, and inversely proportional to the maximum permitted normal stress of the material used in the container's walls [5]. Pressure vessels are exposed to longitudinal forces within the walls of the vessel. The normal stress in the walls of the vessel is proportional to the pressure and radius of the vessel and inversely proportional to the thickness of the walls. When the stress level in the wall surpasses some stated failure criterion, pressure vessels fail. As a result, it is crucial for designers to study and quantify stresses in pressure vessel features [6]. FEA is a potential tool to conduct an accurate prediction of any type of stress that leads to the bursting of composite pressure vessels. According to experiments [7], the majority of burst testing data is between Tresca and von Mises burst pressure projections, necessitating the adoption of an alternative prediction. Zhu et al [8] proposed a novel multiaxial yield criteria based on average shear stress to achieve this goal. For advanced prediction of isotropic hardening material, the average shear

stress yield (ASSY) is established as a multi-axial yield theory, whereas the Tresca and von-Mises yield theories are used for the prediction of lower and upper bounds of burst pressure, respectively [4]. Several attempts to develop alternate equations for measuring burst pressure have been attempted, in which some of them discussed here.

In the literature, different equations are recommended to calculate burst pressure. For instance, Cooper [9] determined the burst pressure using equation (1).

$$Pb = 2 * 3^{\frac{-(n+1)}{2}} * \frac{2\sigma_{ult} * t}{D} \tag{1}$$

Where, P_b = burst pressure of vessel, σ_{ult} = ultimate tensile strength, t = thickness, n = strain hardening exponent and D is mean diameter of vessel.

The alias sum of square criterion (ASSC)[9] recommends also equation (2) to calculate the burst pressure at the mean diameter as:.

$$Pb = 2 * 0.54^n * \frac{2\sigma_{ult} * t}{D} \tag{2}$$

On the other hand, Barlow [10] stated that the burst pressure development across a composite pressure vessel can be calculated using equation (3).

$$Pb = \frac{2\sigma_{ult} * t}{D} \tag{3}$$

And ASME Boiler code also provides a method of mean burst pressure (P_m) assessment that is given by equation (4) [10]

$$P_m = \sigma_{ult} * \left(\frac{k^2 - 1}{k^2 + 1}\right) \tag{4}$$

Where k stands for the pressure vessel's diameter ratio (D_o/D_i). According to the criterion of maximal stress [11], the mean burst pressure can be determined by equation (5).

$$P_m = \sigma_{ult} * (k - 1) \tag{5}$$

On the other hand, the European standard states equation (6) [9] to be used to evaluate the burst pressure phenomena of metallic vessel.

$$P_{max} = \frac{2 * f * z * e_a}{D_m} \tag{6}$$

Where f = stress in the nominal design, z = coefficient of weld, e_a = thickness of investigation and D_m = mean diameter of the pressure vessel.

In the equations given above (equation (1) to (6)) it is observed that the burst pressure is a function of vessel diameter, wall thickness, material hardening and the ultimate tensile strength of the material used. ASSY as a new theory is a failure analysis criterion that includes the von-Mises equivalent stress criterion, the maximum primary stress criterion, the von-Mises equivalent strain criterion, and the maximum tensile strain criterion. Assessing failure pressure of composite pressure vessels requires applying theories of failure alike Tsai-Wu failure theory that stated in equation (7), which is used to predict the burst pressure of composite materials [12].

$$F_{11} * \sigma1^2 + F_{22} * \sigma_2^2 + F_{66} * \tau_{12}^2 + F_1 * \sigma_1 + F_2 * \sigma_2 + 2F_{12} * \sigma_1 * \sigma_2 \geq 1 \tag{7}$$

In this equation; F_1, F_2, F_{11}, F_{22}, F_{12}, F_{66} are determined based on the used composite materials strength parameters given as:

$$F_1 = \frac{1}{X_{tensilet}} - \frac{1}{X_{compresive}}, F_2 = \frac{1}{Y_t} - \frac{1}{Y_c},$$

$$F_{11} = \frac{1}{X_t X_c}, F_{22} = \frac{1}{Y_t Y_c}, F_{12} = -\frac{1}{2}\sqrt{F_{11}F_{22}}, F_{66} = \frac{1}{S^2} \tag{8}$$

In the contemporary design analysis of either metallic or composite pressure vessel analysis, numerical methods are favored in many ways to obtain an optimized and efficient results with less cost of time. One of the most powerful numerical tools for studying the mechanical behavior of pressure vessels under internal pressure to failure is the commercial software ABAQUS [13]. An experimental and numerical-based study reported by [14] verified that $\pm 55^o$ ply orientation provides an optimal wound pattern for the construction of pressure containers that can withstand a burst and then first-ply failure of the composite pressure vessel determined by using finite element method (FEM) in ANSYS.

One of the major opportunities and benefits of composite materials is the flexibility offered for user-defined fiber placement. Using commercial software such as ABAQUS and ANSYS, an ideal design for less material utilization and improved strength can be achieved by rearranging sequence and orientation of plies, these commercial software programs can anticipate the failure of the first ply in a laminated composite [15]. The first-ply failure (FPF) that triggers the last-ply failure (LPF), i.e. bursting stage, in composite pressure vessels can be determined, for instance, using the acoustic emission approach. Because thermal stresses occur at high temperatures, the composite material's strength reduces for succeeding plies [16]. Hence, Type III and IV composite pressure vessels produced with an inner liner made of aluminum and LDPE respectively, the inner pressure at high-temperature increases the speed of the last ply rapture of fiber reinforced composite made pressure vessel with inner liner of LDPE [17].

Even though pressure vessel made by filament winding provides outstanding performance, they have their complexity while analyzing the whole geometry. Moreover, the variation of fiber angles due to the fiber path design leads to a variety of thicknesses [18]. First Order Shear Deformation Theory (FOSDT) and Third Order Shear Deformation Theory (TOSDT) in FEM approach were successful tools to predict the transverse shear strains and stresses that cause the laminar de-lamination for failures to happen at end pole opening and junctions of pressure vessel structure [19]. The future investment for hyper pressure utilization of composite pressure vessels needs structural health monitoring that is used for first lamina rapture remediation or decision for last lamina failure. The binding matrices crack initiation or the load bearer fiber breakage can be recorded by acoustic emission sensor and strain sensing devices [20].

3. Numerical modeling and bursting study

3.1. Modeling of composite pressure vessels

The vertical overwrapped pressure vessel shown in Figure 1 is used for numerical analysis in this work. The pressure vessel is drawn with a 4 mm thick aluminum liner of 1000 mm length and a 200 mm diameter, as the inner core and carbon/epoxy plies overwrapping the liner. The commercial software ABAQUS 6.14 was chosen to model and simulate the pressure vessel's geometry. The material properties given in Table 1 and 2 are adopted from [21] and used to model the composite pressure vessel. The ply sequence from inner to outward consisted of aluminum (AL6060) alloy at the inner side with a subsequent four layers of carbon/Epoxy reinforced plies with respective fiber patterns as shown in Figures 2 (a) and (b).

Table 1. Characteristics of carbon fiber reinforced polymer composite (CFRPC) material and AL6061

Materials	Density (kg/m^3)	E$_1$ (GPa)	E$_2$ (GPa)	N12	G12	τ (MPa)
CFRPC	1570	135	8	0.27	3.8	
AL 6061	2700	74.12	74.12	0.3	27	600

Table 2. Carbon fiber reinforced polymer composite strength properties

Materials	X_t [MPa]	X$_c$ [MPa]	Y$_t$ [MPa]	Y$_c$ [MPa]	S [MPa]
CFRPC	1860	1470	76	85	98

NB: X_t, X_c, Y_t, Y_c are tensile and compressive strengths in X and Y directions resp., and S is the shear strength of CFRP.

3.2. FEM modelling details

The FEM analysis is performed on the 1/8th section part of Figure 1(a) to reduce the computational resources. The dimension of the model, the loading and boundary condition definitions as well as the meshed model are shown in Figure 1 (b), (c) and (d), respectively.
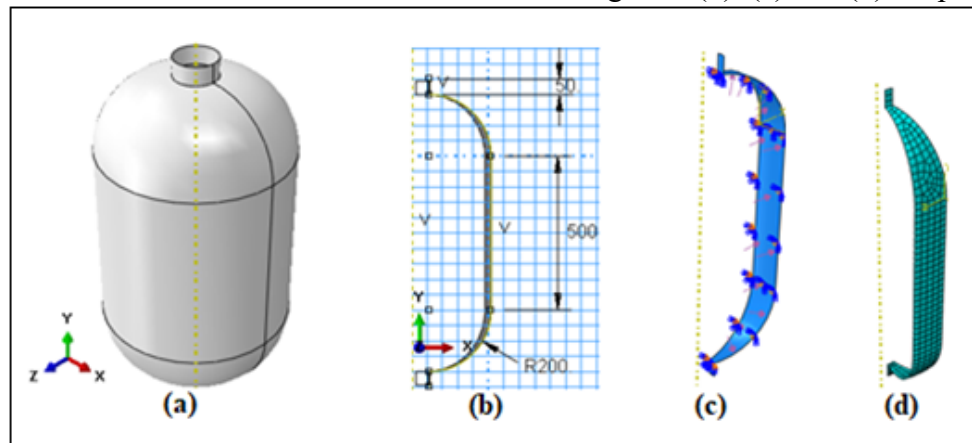

Figure 1. (a) 3D model of COPV, (b) dimension layout, (c) Loading and boundary condition, and (d) Meshed model

3.3. Ply stacking Sequence Modelling

The overwrapped composite was modeled and simulated by the five layers that are arranged as shown in Figure 2 (a) and (b) with a ply orientation of [+55/-55]$_2$, [$\pm$ 15º/0º/90º] and the inner core of aluminum liner oriented at [0º] from the x-axis. Because of the COPV's symmetrical features, only the 1/8th segment depicted in Figure 1(d) is used for finite element modeling, which helps to reduce computational time and improve efficiency. In this study, the pressure vessel is sketched by shell structure with S4R element type. The FEA for Test 1 is undertaken at a ply sequence of [-15º/0º/+15º/90º] and Test 2 is conducted at the ply sequence of [-55º/+55]. The FEM model consists of 282 elements and 342 nodes that help to reduce the CPU time of the conventional computer used in this study. Tables 3 and 4 list the parameters used in the finite element modeling of the aluminum overwrapped composite pressure vessel.
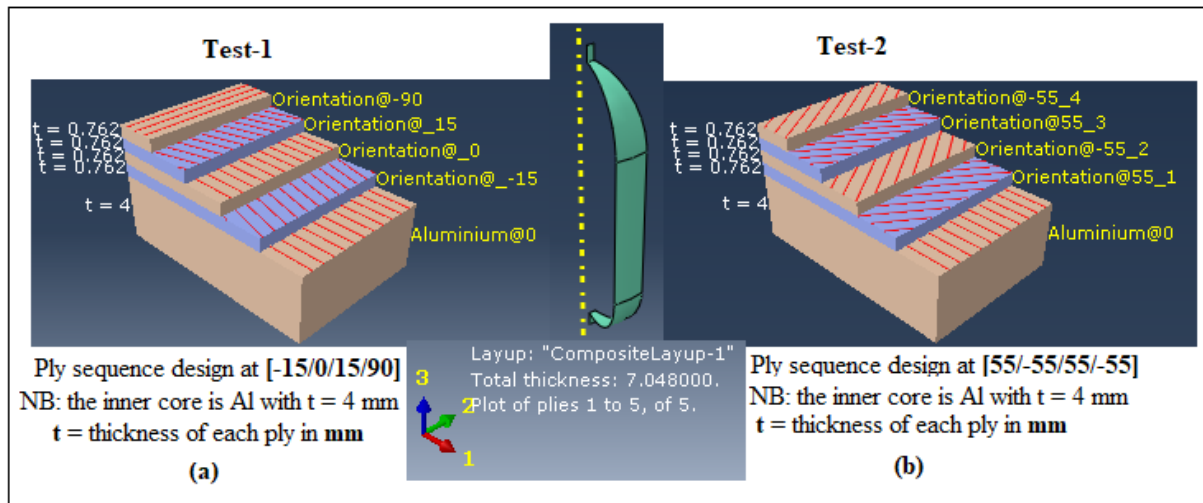
Figure 2. (a) Ply orientation of Test-1 , and and (b) Test-2 of COPV

Table 3. Details of Stack sequence of the COPV design for Test-1

No.	Sel.	Ply Name	Region	Material	Thickness, mm	CSYS	Rotation angle	Integration point
1	√	Aluminium@0	(Picked)	Aluminum	4	\<Layup\>	0	3
2	√	Orientation@-15	(Picked)	Composite	0.762	\<Layup\>	-15	3
3	√	Orientation@0	(Picked)	Composite	0.762	\<Layup\>	0	3
4	√	Orientation@15	(Picked)	Composite	0.762	\<Layup\>	15	3
5	√	Orientation@90	(Picked)	Composite	0.762	\<Layup\>	90	3

Table 4. Details of Stack sequence of the COPV design for Test-2

No.	Sel.	Ply Name	Region	Material	Thickness, mm	CSYS	Rotation angle	Integration point
1	√	Aluminium@0	(Picked)	Aluminum	4	\<Layup\>	0	3
2	√	Orientation@55	(Picked)	Composite	0.762	\<Layup\>	55	3
3	√	Orientation@-55	(Picked)	Composite	0.762	\<Layup\>	-55	3
4	√	Orientation@55	(Picked)	Composite	0.762	\<Layup\>	55	3
5	√	Orientation@-55	(Picked)	Composite	0.762	\<Layup\>	-55	3

4. Discussion of Results

The present numerical burst strength analysis is carried out on composite overwrapped pressure vessel designed with a geometrical dimension of 1000 mm long and a cylinder radius of 100 mm vertical erected pressure. A broad range of researchers have focused on the study of structural performance either on the axial body of the cylindrical or the dome part of pressure vessel, [22]–[24].. In this study, the whole part of the overwrapped composite pressure vessel with effective computation techniques has been studied numerically in two scenarios of Test-1 and Test-2 categories which are given in Table 3 and 4. Burst pressure is a pressure that a vessel can absorb before the total rapture of the whole structure. The failure of fiber leads to laminar failure of vessels. The fiber pattern is also a critical parameter on the stress-bearing capacity of the pressure vessel [25].

The structural performance of Aluminum overwrapped composite pressure vessel made of four plies that is oriented as shown in Table 3 of Test-1 has been conducted by loading with internal pressure of 55 MPa and using appropriate boundary conditions for vertically erected type pressure vessel, consequently, a maximum of 893.1 MPa of In-Plane Principal stress, shown in Figure 3 (a) is induced in the COPV made by Test-1 category ply orientation. The hoop and axial stress developed in this category is 272 MPa and 893 MPa, as shown in Figures 3b and 3 (c), respectively.
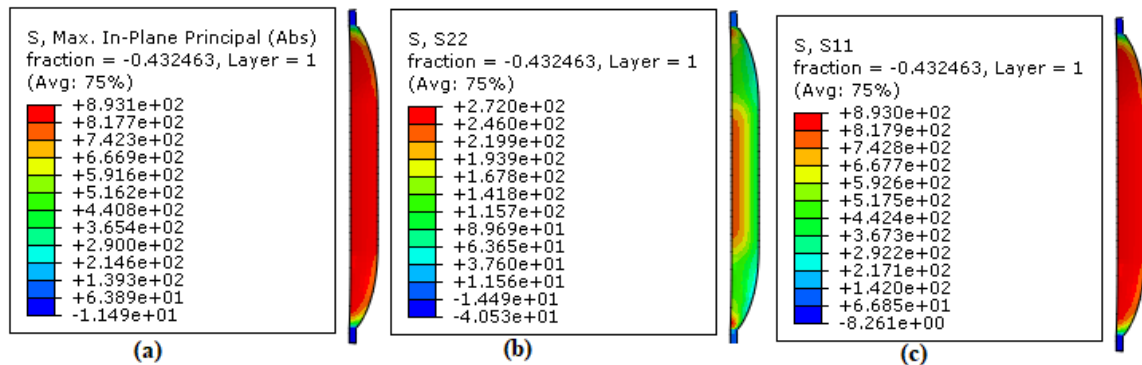
Figure 3. Stress distribution of COPV for Test-1 (a) Max. In -plane stress (b) hoop stress and (c) axial stress

Figures 4 (a)-(c) show the Test-1 category evaluation of strain level for overwrapped composite pressure with the highest induced in-plane principal strain of 1.21 percent, and the fiber (E11) and hoop (E22) direction strains of 1.20 percent, which are similar in values but not in distribution.
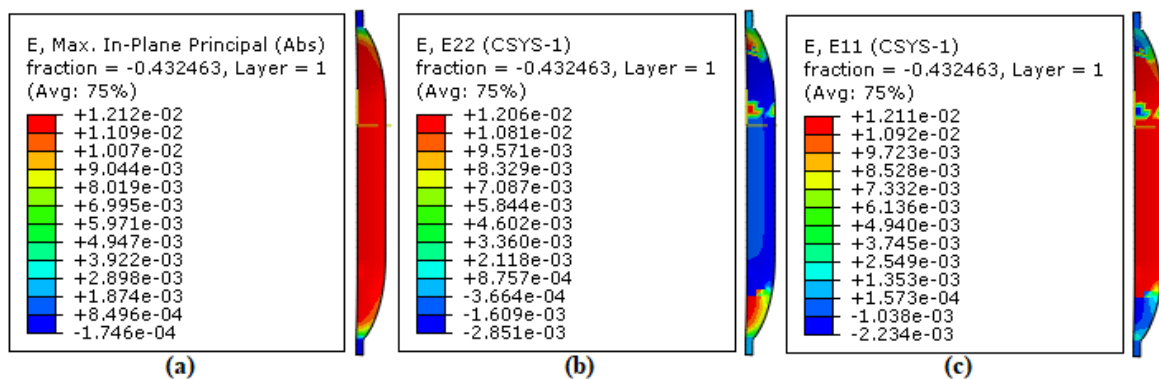

Figure 4. Strain distribution of COPV for Test-1 (a) Max.In-plane strain (b) hoop strain (c) axial strain

4.1. Ply-wise failure assessment of overwrapped composite pressure vessel: Test-1 category
While Tsai-Wu failure theory is a gauge that was applicable for analyzing composite structure [24], maximum strain and stress is considered in this study, to compute the burst pressure and effect of ply orientation by the internal pressure on the Aluminum liner. The last ply strain (burst strain) shown in Figure 5 and last ply stress (burst stress) that is shown in Figure 9 indicates that Test-1 ply orientation is stronger than Test-2 ply orientation.
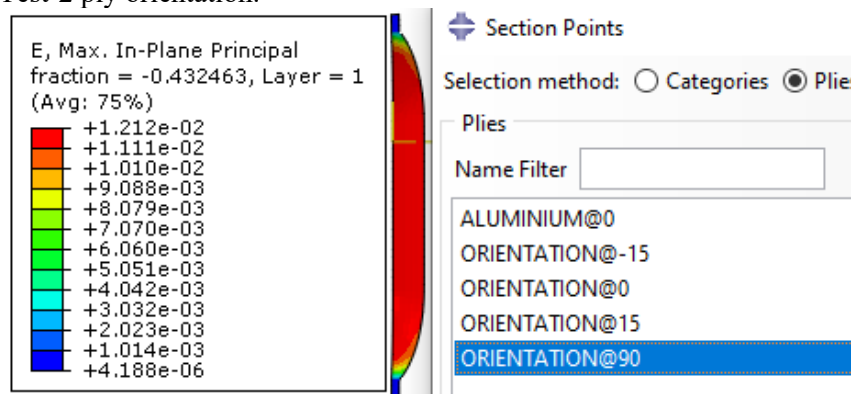

Figure 5. Max. In-plane principal strain on the last ply: Burst strain.

4.2. Ply-wise failure assessment of overwrapped composite pressure vessel: Test-2 category
According to current research on the best filament winding angle for wound composite pressure vessels,
$\pm55^o$ is the best angle [26]. This optimum winding angle is used as a benchmark in this study to compare
the burst performance of the proposed ply orientation shown in Table 3. This optimal winding angle for
filament-wound composite pressure induced max. In-plane stress, shown in Figure 6 (a), exhibits about
1553 MPa which is higher than Test-1 type ply orientation :[-15°/0°/+15°/90°]. Similarly, the hoop and
axial stress shown in Figure 6 (b) and (c) are around 243.9 MPa and 1553 MPa respectively. The induced
strain showed in Figure 7 (a)-(c) are 2.2%, 2.1%, and 2.2 respectively. Figure 8 depicts the structural
burst performance of Test-2 ply sequence and orientation is less than the proposed ply sequence in Table
3. From this graphical result, the induced axial and hoop stress indicate a clue for design consideration
that higher thickness of the dome of the vessel can better absorb higher pressure along the axial direction.

   The laminate failure by burst pressure is the most dangerous mode of failure of COPV. Accordingly,
diverse explorations were shown to develop an optimum parameter that increases their burst pressure
[24]. Since ply orientation and sequence is one of the major parameters for increasing the burst pressure
of vessels, an alternative novel ply sequence and orientation was proposed in this study. The stacking
sequence proposed in Test-1 category for the design of ply orientation at [-15°/0°/+15°/90°] shows better
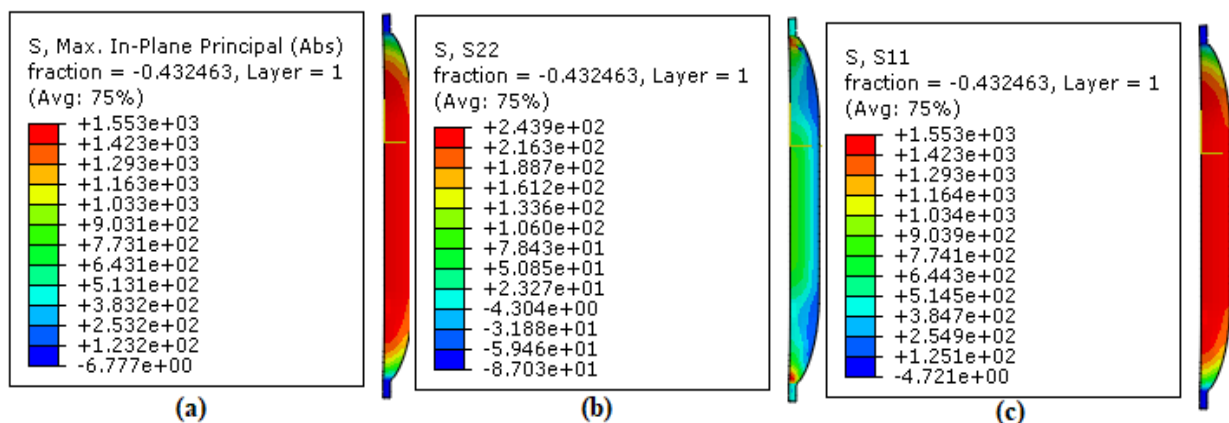performance than that of Test-2 design of ply orientation at [+/-55].

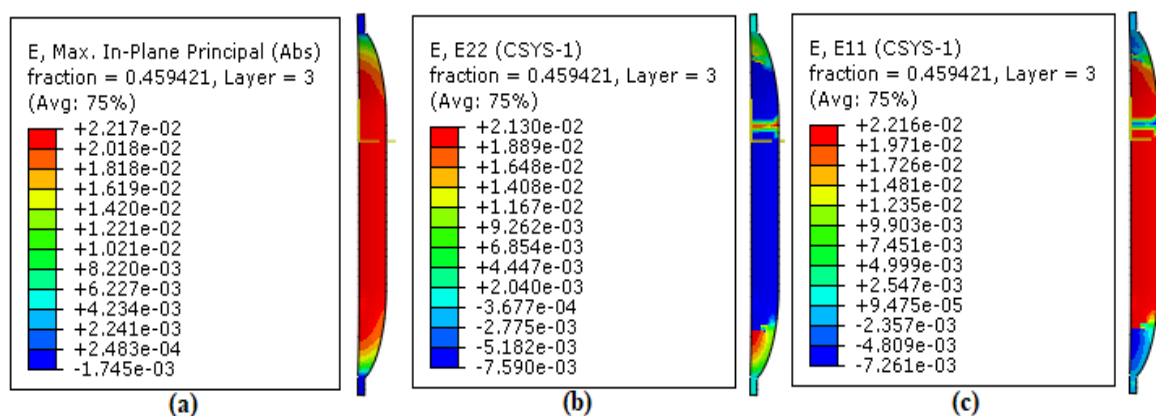**Figure 6**. (a) Max.In-plane stress, (b) hoop stress, (c) axial stress, distribution of COPV for test-2

Figure 7. (a) Maximum In-plane principal strain, (b) hoop strain, (c) axial strain of COPV for test-2
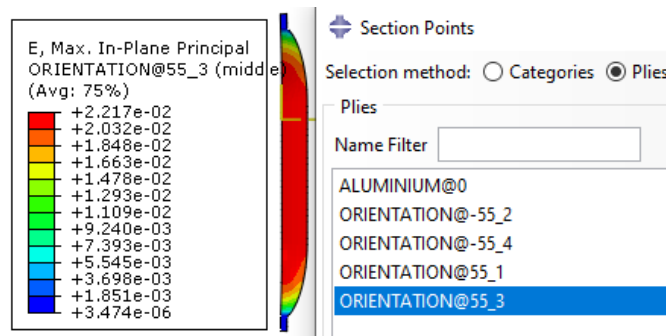
Figure 8. Last ply strain for LPF

The maximum stress-bearing capacity which is proportional to burst pressure of each ply for Test-1 and 2 ply sequence is depicted in Figure 9. The ply orientation at [0°] and [15°], second and first ply exhibit maximum in-plane stress of 1625 MPa and 1506 MPa, while the second ply orientation at [-55°] and fourth ply orientation at [+55°] results about 486.2 MPa and 464.3 MPa respectively. From the induced maximum stress shown in Figure 9, the performance of the two category ply sequence and patterns for Test-1 and Test-2 show dissimilar stress-bearing capacity trends. Since the composite structure is strong along the fiber direction, that coincides with the result obtained at [0°], and fiber strength increases with decreasing orientation, which is also shown by the result of ply that is oriented at [15°]. Moreover, the obtained result is a clear indication for the maximum stress decrement as the ply orientation increases i.e. at [0°] the max. stress is 1625 MPa while at [90°] it is about 161 MPa. As the COPV wound angle raises the induced stress becomes lower values, this indicates that there is a direct relationship between burst and stresses. The increase of ply orientation angles resulted in a decrease in burst pressure. Nonlinearity response design for multidimensional dynamic loading has sparked a lot of research interest, as well as a rise in composite product demand from various industries [27].
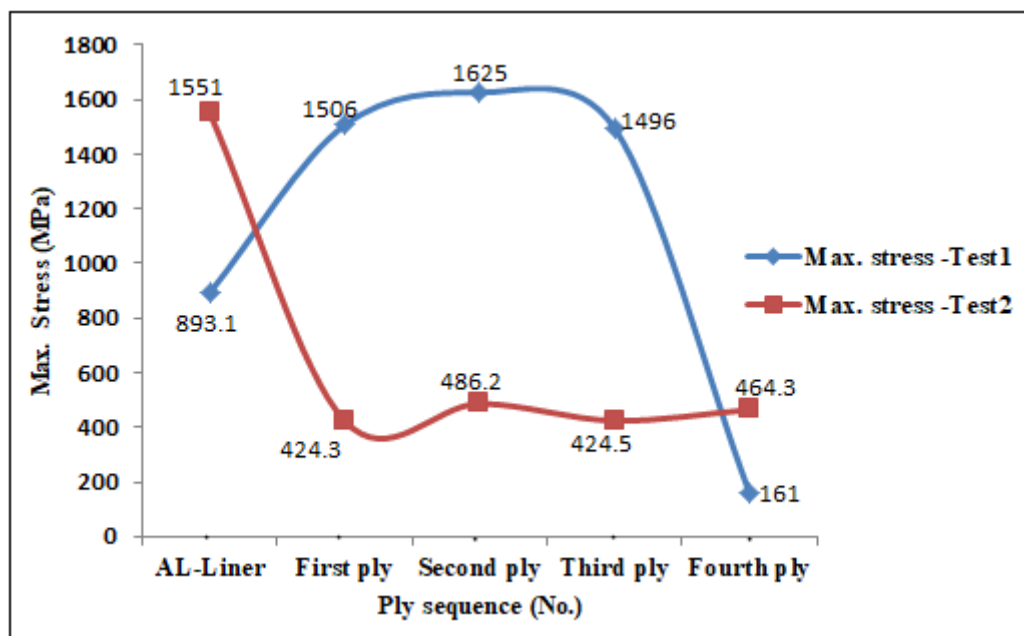

Figure 9. Max. In-plane stress distribution for Test1 and 2 ply sequence

5. Conclusions

The burst performance of type III composite overwrapped pressure vessels was investigated using the finite element approach in this computational study. Al 6060 liner was overwrapped by four layers of carbon fiber reinforced polymer composite in two distinct ply sequences and orientations, labeled as Test-1 and Test-2, and the stated parameters were studied using FEM. The hoop and axial direction stresses, as well as the maximum stress and strain, were examined. The acquired results were used to investigate the effect of internal pressure on ply orientation in the two test categories. Test-1 category ply sequence $[-15^{\circ}/0^{\circ}/+15^{\circ}/90^{\circ}]$ has a higher strength in burst pressure than that of the ply sequence $[-55^{\circ}/+55^{\circ}]$. The obtained maximum stress corresponds to the fact that a higher degree of ply orientation results in the lowest burst pressure. Since the axial direction of the proposed vertical COPV has the highest stress, the vessel's shell thickness should be in this direction to absorb the burst pressure. This numerical analysis contradicts with the literature's conclusion about the best winding angle for burst-resistant vessel design. The obtained burst pressure exceeds experimental test results on [-/+55] ply orientation, although the current paper lacks experimental validation. ABAQUS-based FEM is a strong design tool that provided the flexibility to knob the composite overwrap pressure vessel to model an overwrapped dissimilar material properties as a single component. Moreover, a ply level orientation analysis is a superior feature of ABAQUS to be used for such composite modeling. Finally, while the numerical results obtained from this work can be used to better understand the structural behavior of overwrap composite pressure vessels, the proposed innovative ply sequence and orientation will require further testing.

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