Influence of the filament winding process variables on the mechanical behavior of a composite pressure vessel

G. Vargas[1] & A. Miravete[2]
[1] *Universidad Pontificia Bolivariana, Facultad de Ingeniería Mecánica, Colombia*
[2] *Universidad de Zaragoza, Departamento de Ingeniería Mecánica, España*

Abstract

A numerical analysis of a composite internally pressurized cylindrical vessel with spherical domes is presented. The structure is considered a filament winding process vessel in which a continuous strand of fiber is wound over a rotating male mandrel. During the winding process a variable thickness is created in the dome region which considerably alters its mechanical performance. Additionally, the fiber path depends on the surface where the fibers are wound; as a result the winding angle varies in the dome with regards to its longitudinal direction. The vessel is modeled as a non-structural internal liner reinforced with an orthotropic composite: carbon fiber reinforced plastic. Stress was calculated by applying the first-order shear deformation theory, and the Tsai-Wu failure criterion was considered as the limit state function of the laminate. The structure's optimum design is performed taking into account the main process variables, the winding angle and layer thickness. A finite element analysis was performed considering the winding angles as well as the thickness change through the dome, in order to study the effects of the winding process variables on the mechanical behavior of the composite vessel. A convergence study was carried out in order to verify the finite element analysis. It considered several shell element types. In order to model the structure, quadrilateral stress/displacement shell elements with 8-nodes (6-degrees of freedom each), quadratic interpolation and reduced integration were used.

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1 Introduction

Fiber reinforced composite materials are generally used in highly-efficient structures such as aircraft, automotive parts and pressure vessels due to their high specific strength and stiffness. Pressure vessels can be widely observed in civilian industries for instance in fire extinguishers, oxygen gas tanks, natural gas cylinders, etc. A common feature among these products is that they must withstand high pressure under working conditions, while considering an appropriate standard safety factor [1]. The vessels are generally made through a filament winding process, in which continuous resin-impregnated rovings or tows are wound over a rotating male mandrel. The mandrel can be any shape that does not have reentrant curvature. Its reinforcement may be wrapped either in adjacent or overlapping bands which cover the mandrel's surface. The technique has the capability of changing the winding tension, winding angle, or resin content in each layer of the reinforcement until the desired thickness of the composite and the required direction of strength is obtained [2].

The composite, made by using the filament winding method is an anti-symmetric laminate, and it is considered an orthotropic material. In such case, the material is symmetric in its three orthogonal planes and there are 9 components or constants which completely describe it by means of the generalized Hooke's law. It defines the linear stress-strain relation for an anisotropic material [3].

Failure criteria is necessary to design and guide material's improvements. By establishing appropriate failure criteria, the strength of an orthotropic ply subject to combined stress can be predicted. One of the simplest failure criteria for anisotropic materials is the extension of the von Mises criterion to a quadratic criterion, which is based on scalar products of stress or strain components. The Tsai – Wu criterion, a quadratic criterion, which takes into account the strength data and the interaction term [4], is one of the most common criteria. Tsai [4] states that the quadratic criterion is likely to provide the most consistent failure prediction.

The main purpose of the this paper is to study the influence of the filament winding process variables, considering both the winding angle variation and the laminate thickness change, on the mechanical behavior of a composite pressure vessel. The Tsai-Wu failure criterion was considered as the criterion for the vessel design. The ABAQUS finite element program was applied to the numerical analysis in order to study the mechanical performance.

2 Numerical simulation

The variables that define the composite vessel and the discretization type needed for its numerical simulation, are presented in this section. The model's geometry, the discretization techniques, the loads and boundary conditions as well as the materials used are as follows.

Consider a cylindrical pressure vessel of length L = 1200 mm with closed spherical domes of radius R = 120 mm and thickness t subject to an internal

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pressure p. The vessel has a polar boss of radius r = 20 mm at the dome's end in order to couple the measurement and flow control systems. The vessel must be discretized by meshing model's geometry, using a preprocess program. MSC / Patran commercial program [5] was used on this stage. ABAQUS Standard finite element program [6] was applied to the vessel's numerical analysis. Considering the element, five aspects characterize its behavior: family, degrees of freedom, number of nodes, formulation, and integration. Besides, the FE program contains elements for modeling a wide range of spatial dimensionality, as follows: 1-D elements, 2-D elements, 3-D elements, and axisymmetric elements. Furthermore, ABAQUS has different types of elements which are appropriate for several analyses. Stress/displacement elements were employed due to the structural application considered. In particular, 3-D stress/displacement elements were used in this study. Those elements are used in the modeling of linear or nonlinear mechanical analyses. For structural applications, the program provides several element types including plane stress elements and plane strain elements.

In vessel's simulation, plane stress elements were considered since the stress state which the system is subject. The stresses are function only of planar coordinates, and the out-of-plane normal and shear stresses are equal to zero. This modeling method generally applies to thin or flat bodies, as the vessel case. For anisotropic materials, the axis normal to the stress plane must be a principal material direction. That situation corresponds with an orthotropic filament winding laminate. In addition, the simulation carried out coincides with a quasi-static analysis due to the working conditions. Therefore, to model the structure quadrilateral stress/displacement shell elements were used in the 3-D analysis, using quadratic interpolation and reduced integration. Thick shells are needed in cases where transverse shear flexibility is important and 2nd-order interpolation is desired. The vessel corresponds with this case, due to the presence of an heterogeneous material and to the element curvature since vessel's geometry.

Taking into account the axial symmetry of the system, only half a vessel was considered in the simulation. In that case, the loads and boundary conditions regarded were displacements (translations and rotations) in the middle of the vessel, and uniform internal pressure in the surface. The internal pressure considered according to the standard [1] was 24.83 MPa.

The composite pressure vessel comprised of a plastic inner liner reinforced by a Carbon/Epoxy composite. Plastic liners have low permeation rates and virtually unlimited fatigue life, and carry no load. High-Density Polyethylene is an excellent performer as a liner material. Though inexpensive, it is easily formed and has good environmental resistance [7]. Carbon fiber is known for its high elastic modulus, high strength, low density and excellent fatigue performance. Even though, it is expensive [3]. Epoxy resin can be formulated for low cure temperature and time, and has excellent environment resistance and high compatibility with carbon fibers. The composite properties used for this study are given by Chang [8] and correspond with an unidirectional lamina (orthotropic material). Those properties are listed in Table 1, where the subscripts t and c indicate tension and compression.

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Table 1: Mechanical properties of carbon/epoxy unidirectional lamina.

E_1	E_2	G_{12} - G_{13}	G_{23}	ν_{12} - ν_{13}	X_t	X_c	Y_t	Y_c	S
(GPa)	(GPa)	(GPa)	(GPa)	-	(MPa)	(MPa)	(MPa)	(MPa)	(MPa)
142.5	9.79	4.72	1.192	0.27	2193.5	2457	41.3	206.8	78.78

3 Results and discussion

3.1 Convergence analysis

In order to determine the shell element type to consider into the numerical analysis, according to the ABAQUS library, a convergence analysis [9, 10] were carried out. The element types regarded are shown below. S4R: 4-node doubly curved general-purpose shell, linear interpolation, reduced integration, finite membrane strains, S4: 4-node doubly curved general-purpose shell, linear interpolation, complete integration, finite membrane strains, and S8R: 8-node doubly curved thick shell, quadratic interpolation, reduced integration.

Furthermore, the convergence analysis were done to establish the density mesh, considering several number of elements through the vessel surface. The number of elements taken were 200, 800, 3200 and 12800, for the three shell element types. Reference variables on the convergence analysis were referred with respect to the following coordinate system, according to the post-process program: Axis 1, through the fiber direction, Axis 2, perpendicular to the fiber direction on the laminate plane, and Axis 3, normal to the laminate plane. The reference variables are the displacement on direction 1, U1, the normal stress in direction 1 and in direction 2, S11 and S22, and the Tsai – Wu coefficient, TW. The TW coefficient indicates the failure condition of the laminate, and represents the inverse number of the safety factor. Figures 1 to 3 show the results.

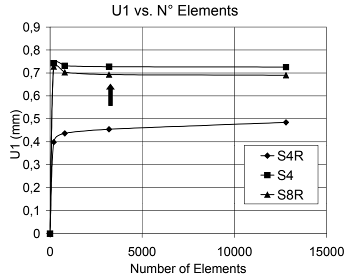
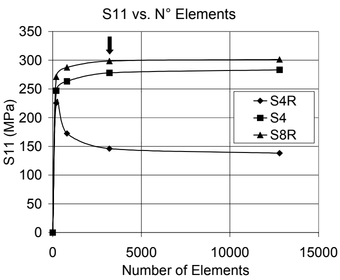
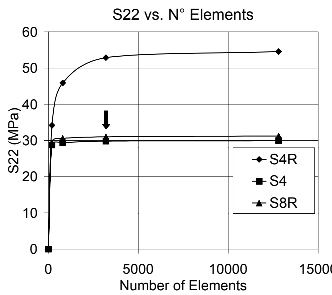


Figure 1: Comparison of the element types. Displacement 1 vs. Number of elements.

The analysis points that the variable responses are convergent between 2000 and 4000 elements. Consequently, 3200 is the number of elements taken for the simulation. Furthermore, considering the element type, the results show that S4 and S8R elements are similar. However, for S4R the results are quite different, due to the use of linear interpolation and reduced integration. On that case, the use of the S4R elements is discarded. Now, comparing S4 and S8R, the results reveal that stress components and TW coefficients obtained with S8R are higher. That implies that the use of S8R is more conservative. Moreover, the S8R second-order elements, with quadratic interpolation, are used when transverse shear flexibility is important as the thick shell case [6]. Hence, the S8R were the element type selected in this study to the numerical simulations.



(a)



(b)

Figure 2: Comparison of the element types. (a) Stress 1 vs. Number of elements. (b) Stress 2 vs. Number of elements.

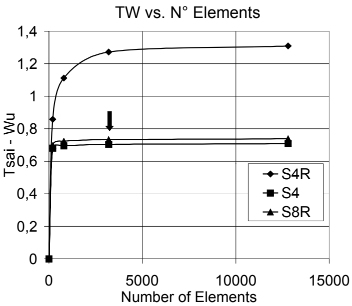


Figure 3: Comparison of the element types. TW coefficient vs. Number of elements.

3.2 Winding angle

Considering the cylindrical vessel with closed spherical domes, the first design variable to determine by means the numerical analysis was the helical winding angle, α. The winding angle is assumed as a constant for both the cylinder and the sphere. The initial laminate sequence consist of 36 helical and 12 hoop layers at the cylinder, and only 36 helical layers at the sphere. Therefore, several numerical simulations were carried out varying the winding angle and fixing other design variables as geometry, material properties and laminate sequence.

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The influence of the α angle was analyzed with respect to the TW coefficient. The results are shown in Figure 4. The main result was the minimal Tsai – Wu coefficient, maximum safety factor, reached when $\alpha = 45°$. In that angle value, the shear stress S12 tends to zero, suggesting that the principal directions correspond with this orientation. In addition, the TW has the same behavior that the normal stress in direction 2, with respect to the winding angle, indicating that the component S22 rules the vessel failure response. This behavior is caused by the low laminate strength on the perpendicular direction to the fiber. Consequently, the optimum winding angle of the laminate composite is 45°.

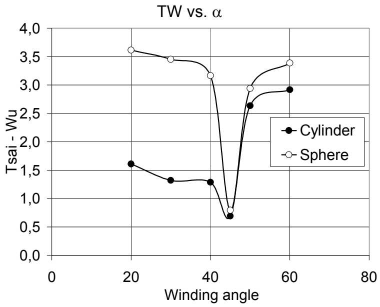

Figure 4: Influence of the winding angle. TW coefficient vs. Winding angle.

In spite of the previous result, the winding angle is not constant through the dome due to the characteristics of the filament winding method. In particular, on the cylinder – sphere joint, winding angle takes the same value that the angle on the cylinder, $\alpha = 45°$. Then the angle increases as the winding process progress, until 90° at vessel's end where the polar boss is placed. Consequently, the variation on the winding angle at the sphere must be taken into account.

The geodesic path theory discussed by Kabir [11] affirms that ideally, a filament-wound structure should cover the mandrel surface completely with no voids or twisting. In other words, to obtain the most efficient fiber use, it may slip during the process. This limits design optimization as the winding trajectories are constrained to follow near geodesic curves (the shortest path between two points on a curved surface) to prevent fiber slippage. The geodesic paths on the domes during the winding process have been solved as functions of the initial angle on the cylinder-sphere joint, α_0, and the radial position on the dome, x, as shown in Figure 5. These paths define the winding angle through the sphere, α_n, considering the vessel radius, R (maximum x), and satisfy the equation (1). Based on the solution given by Kabir [11], the geodesic trajectories were determined as functions of the dome polar angle, ϕ. The winding angle variations through the sphere are indicated in Figure 6, considering several initial winding angles.

$$Sen\,\alpha_n = \frac{R\,Sen\,\alpha_0}{x} \tag{1}$$

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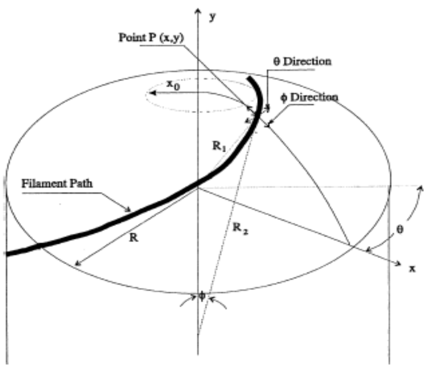

Figure 5: Helical winding in spherical dome vessel. Geodesic path.

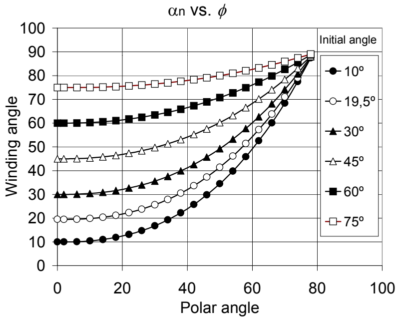

Figure 6: Sphere winding angle as a function of the polar angle.

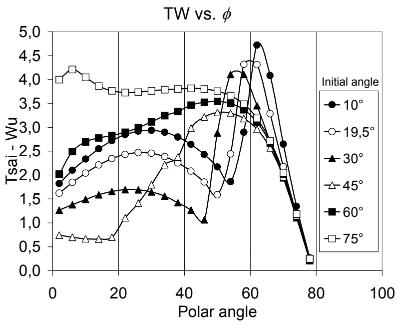

Figure 7: Influence of the initial winding angle on the sphere Tsai – Wu coefficient.

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Considering the winding angle changes, numerical evaluations were done. Tsai – Wu coefficient was the reference result to evaluate the optimum winding trajectory on the dome, as shown in Figure 7. These results indicate high TW for the lowest initial angles, 10°, 19.5° and 30°, due to the high stresses on fiber direction, S11, for such angles. Moreover, for $\alpha_0 = 75°$ the Tsai – Wu coefficient is quite high, as well as the stress S22, specially near to the cylinder where polar angle takes values between 0° and 40°. Nevertheless, when initial angle reaches 45° the lowest TW coefficient is obtained, suggesting the optimum winding path through the sphere. Figure 8 reveals the TW graphic results for $\alpha_0 = 45°$, according to the ABAQUS/Post program. For all the initial winding angles the stress components, S11, S22 and S12, and the TW coefficient tend to zero as the polar angle approaches to 80°, at vessel's end.

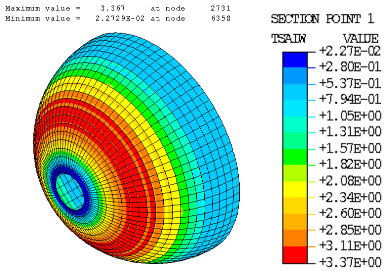


Figure 8: Tsai–Wu coefficient behavior on the sphere. Initial winding angle 45°.

3.3 Laminate thickness

Once the optimum winding angle has been determined, not only for the cylinder but also the sphere, laminate thickness must be found by means the simulations. To reach standard requirements, the thickness was increased. The standard affirms that the vessel must be designed to withstand a pressure 2.25 times the design service pressure [1]. In other words, TW coefficient must overtake a value equal to 0.4444. In that case, the initial laminate is increased by the addition of helical layers. Must be taken into account that the thickness is not constant during the filament winding process. Laminate thickness is a function of the winding radius, given by the mandrel shape. Therefore, thickness remains constant during cylinder winding. Nevertheless, thickness varies through the dome as fiber moves towards the end. On that sense, thickness increases as winding radius decreases, according to equation (2). R is the cylindrical radius, x is the radial position on the dome (winding radius), t_c is the cylindrical laminate thickness, and t_x indicates the changing on the dome laminate thickness as a function of the winding radius.

$$t_x = \frac{R}{x} t_c \tag{2}$$

Hence, several simulations were done regarding thickness increases. Once more, Tsai – Wu coefficient was the reference result to define the required thickness. Figure 9 indicates the relation between TW and laminate thickness, as a function of the number of helical layers. Figure 9 shows that TW is always higher on the sphere than the cylinder, because stress components, S11, S22 and S12, are more critical on the vessel dome. Such result points that the TW sphere curve is the design reference. As a result, the cylinder zone is over designed. Nevertheless, is not possible to manufacture a vessel that had less helical layers on the cylinder than the dome, according to the filament winding conditions considered. Figure 9 also reveals that TW decrease exponentially as number of helical layers increases. The desired TW value was reached with 163 helical layers, according to the standard requirements [1].

Tsai – Wu coefficient result is shown in Figure 10, not only for the cylinder but also the sphere. These results indicate that TW remains almost constant along the cylinder, but a rise at the vessel center, and a drop at the cylinder-sphere joint is noticed. Dome results denote that the TW has a low value at the joint region. Sphere critical behavior takes place around central zone. Finally, Tsai – Wu coefficient decreases progressively until vessel's end.

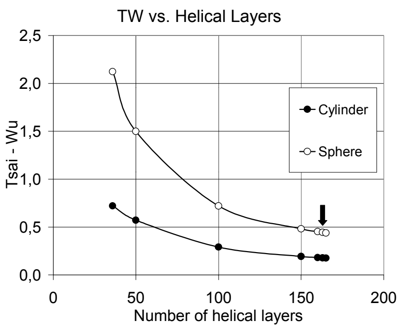
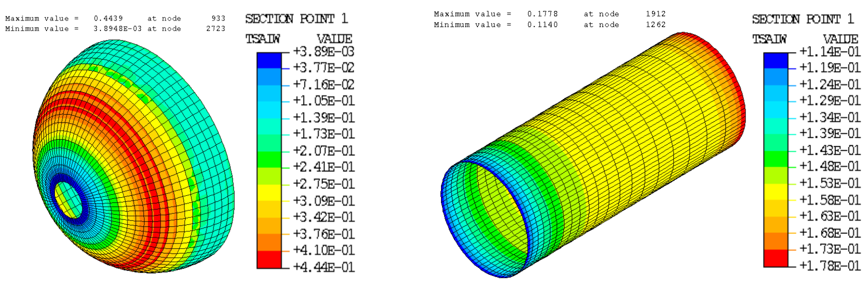


Figure 9: Influence of the number of helical layers on Tsai – Wu coefficient.



(a) (b)

Figure 10: TW coefficient behavior. 163 helical layers. (a) Sphere (b) Cylinder.

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4 Conclusion

Mechanical behavior of a filament winding vessel subject to internal pressure was studied considering the manufacturing process variables. For several design parameters such as winding angle and laminate sequence, Tsai – Wu failure coefficient was calculate as the limit state function of the laminate. Numerical evaluation, by means of the finite element method using ABAQUS program, has indicated a significant influence of both the winding angle change and the thickness variation along the dome. On the other hand, simulation reveals that the stress component in the perpendicular direction to the fiber, S22, rules the vessel failure response. Furthermore, the analysis indicates that the spherical dome is the vessel critical zone, mainly around central zone where polar angle takes values between 35° and 50°.

Although the methods used in this study are theoretical, their accuracy must be verified by experimental data. The experimental data can be evaluated by means of strain gages. Furthermore, to study the composite vessel failure behavior a burst pressure test as well as a cycling pressurization test should be considered.

References

[1] American National Standards Institute/American Gas Association, *American National Standard for Basic Requirements for Compressed Natural Gas Vehicle Fuel Containers*, ANSI/AGA: New York and Cleveland, 33 p., 1992.

[2] American Society of Materials, *Engineered Materials Handbook*. Volume 1. Composites, ASM International: Ohio, pp. 503-504, 1998.

[3] Miravete, A., *Materiales Compuestos*. Volumen I, INO: Zaragoza, pp. 181-194, 2000.

[4] Tsai S., *Theory of Composites Design*, Think Composites: Dayton, Section 8, 1992.

[5] MSC / Patran. *Reference manual*.

[6] ABAQUS/Standard. *User's manual*. Vol. II.

[7] Baldwin, D., Newhouse, N. & Him Lo, K., High pressure composite accumulator bottles. *Proc. of the 2nd Int. Conf. On Composite Materials for Offshore Operations*, University of Houston: Houston, 1997.

[8] Chang, R.R., Experimental and theoretical analyses of first-ply failure of laminated composite pressure vessels. *Composite Structures*, **49**, pp. 237-243, 2000.

[9] Zienkiewicz, O.C. & Morgan, K., *Finite Elements and Approximation*, Wiley: Chichester, pp. 33-34, 1982.

[10] Ferziger, J.H. & Peric, M. Computational Methods for Fluid Dynamics, Springer: Heidelberg, pp. 32-33, 1997.

[11] Kabir, M.Z., Finite element analysis of composite pressure vessels with a load sharing metallic liner. *Composite Structures*, **49**, pp. 247-255, 2000.

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