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Analysis of Failure Pressures of Composite Cylinders with a Polymer Liner of Type IV CNG Vessels

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***Abstract*—**The present study deals with the analysis of the cylindrical part of a CNG storage vessel, combining a plastic liner and an over wrapped filament wound composite. Three kind of polymer are used in the present analysis: High density Polyethylene HDPE, Light low density Polyethylene LLDPE and finally blend of LLDPE/HDPE. The effect of the mechanical properties on the behavior of type IV vessel may be then investigated. In the present paper, the effect of the order of the circumferential winding on the stacking sequence may be then investigated. Based on mechanical considerations, the present model provides an exact solution for stresses and deformations on the cylindrical section of the vessel under thermo-mechanical static loading. The result show a good behavior of HDPE liner compared to the other plastic materials. The presence of circumferential winding angle in the stacking improves the rigidity of vessel by improving the burst pressure.

***Keywords*—**CNG; Cylindrical vessel; Filament winding; Liner; Polymer; LLDPE; HDPE; Burst pressure.

I. Introduction

THE CNG is considered as one of the more promising energy vectors of the future. It can be used as a fuel in many applications. However, this requires several technological hurdles to be cleared, especially the one concerning its storage. Storage must offer a high degree of safety as well as allowing ease of use in terms of energy density and dynamics of fuel storage and controlled release.

The use of composite materials is an extremely interesting alternative to metallic materials in the construction of vessels. Indeed, these materials are characterized by their lightness, rigidity, good fatigue strength, and corrosion resistance when their components are not metallic [1]. Thin or thick walled tanks are widely used in several branches of engineering, such as the storage of compressed hydrogen, liquefied and compressed natural gas [1].

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Gas storage consists of keeping the gas at room temperature under pressure in a cylinder. The first tanks were type I, entirely of metal would be too heavy for storage of CNG. Storage cylinders for compressed natural gas (CNG) used in vehicles are pressure vessels that have been traditionally produced using isotropic materials, such as steel and aluminum [2].

A notable improvement of this first technology is to reinforce the cylinder by filament winding composite just on the cylindrical section (type II). Currently, two solutions have given good satisfaction tanks type III metallic liner - composite reinforcing and type IV tanks: plastic liner - composite reinforcement [3]. The polymer composites have recently been introduced for that purpose [2], usually relying on the composite manufacturing technique of filament winding (FW). The composite materials rolled on plastic liners offer several advantages, including: high strength, low thermal conductivity and a non-magnetic behavior [4-5-6]. And they can minimise the weight, improving the aesthetic and also increasing the pressure vessel mechanical, impact and corrosion behavior. The Compressed hydrogen storage at 350 - 700 bar in Type III (metal-lined) and Type IV (polymer lined) vessels has been demonstrated in a number of prototype fuel cell vehicles [7].

These are important attributes in many present and future industrial and non-industrial large scale applications, such as, for example, liquid filters and accumulators, hydrogen cell storage vessels, oxygen bottles, GNC, pipe transportation, etc [8].

Velosa and al has studied a new generation of composite pressure vessels, where the vessels consist on a thermoplastic liner wrapped with a filament winding glass fibre reinforced polymer HDPE liner [9]. A high density polyethylene (HDPE) was selected as liner and a thermosetting resin used as matrix in the glass and carbon reinforced filament wound laminate of hydrogen vessel storage subjected to localized fire [10].

Barboza and al. investigates the behavior under burst pressure testing of a pressure vessel liner, produced with a polymer blend of 95 wt.% low linear density polyethylene (LLDPE) and 5 wt.% of high density polyethylene (HDPE) [2].

Weon and al attempts to study how the thermal ageing has an effect on the mechanical and thermal behaviors and to gain fundamental understanding on the degradation mechanism of linear low density polyethylene (LLDPE) pipe. It is expected that approaches for improving the durability and reliability of LLDPE pipe at operating conditions [11].

The present paper focalizes on the analysis of cylindrical vessels polymers reinforced by composite filaments under internal pressure with end effect. Three polymers are covered by this analysis, namely, LLDPE, HDPE and mixing LLDPE / HDPE. The effects of winding angle fiber composites and composite sequences on the burst pressure are the subject of this work.

II. Mathematical Formulation

Considering a vessel storage type IV consisting of a polymer plastic liner and a multilayered composite made of a polymer resin reinforced with long fibers (see Fig. 1), the general stress-strain relationship for each k-th component submitted to an axisymmetric mechanical loading is given by [3]:

$$\begin{Bmatrix}\sigma_z\\ \sigma_\theta\\ \sigma_r\\ \tau_{\theta r}\\ \tau_{zr}\\ \tau_{z\theta}\end{Bmatrix}^{(k)} = \begin{bmatrix}\mathbf{C}_{11} & \mathbf{C}_{12} & \mathbf{C}_{13} & 0 & 0 & \mathbf{C}_{16}\\ \mathbf{C}_{12} & \mathbf{C}_{22} & \mathbf{C}_{23} & 0 & 0 & \mathbf{C}_{26}\\ \mathbf{C}_{13} & \mathbf{C}_{23} & \mathbf{C}_{33} & 0 & 0 & \mathbf{C}_{36}\\ 0 & 0 & 0 & \mathbf{C}_{44} & \mathbf{C}_{45} & 0\\ 0 & 0 & 0 & \mathbf{C}_{45} & \mathbf{C}_{55} & 0\\ \mathbf{C}_{16} & \mathbf{C}_{26} & \mathbf{C}_{36} & 0 & 0 & \mathbf{C}_{66}\end{bmatrix}^{(k)} \begin{Bmatrix}\varepsilon_z\\ \varepsilon_\theta\\ \varepsilon_r\\ \gamma_{\theta r}\\ \gamma_{zr}\\ \gamma_{z\theta}\end{Bmatrix}^{(k)} \qquad (1)$$

Where z , θ , r represent a cylindrical coordinate system.

In the particular case of an axisymmetric loading, the local balance equations becomes in each k-th component [3]:

$$\frac{d\sigma_r^{(k)}}{dr} + \frac{\sigma_r^{(k)} - \sigma_\theta^{(k)}}{r} = 0 \qquad (2)$$

The radius r is such as $r_0 \le r \le r_a$, where r_0 and r_a are the structure inner and outer radius respectively (see Fig. 2). The strain-displacement relationships are [3]:

$$\begin{cases}\varepsilon_r^{(k)} = \dfrac{dU_r^{(k)}}{dr}, \quad \varepsilon_\theta^{(k)} = \dfrac{U_r^{(k)}}{r}, \quad \varepsilon_z^{(k)} = \dfrac{dU_z^{(k)}}{dz} = \varepsilon_0\\ \gamma_{z\theta}^{(k)} = \dfrac{dU_\theta^{(k)}}{dz} = \gamma_0\, r, \quad \gamma_{zr}^{(k)} = 0, \quad \gamma_{\theta r}^{(k)} = \dfrac{dU_\theta^{(k)}}{dr} - \dfrac{U_\theta^{(k)}}{r}\end{cases} \qquad (3)$$

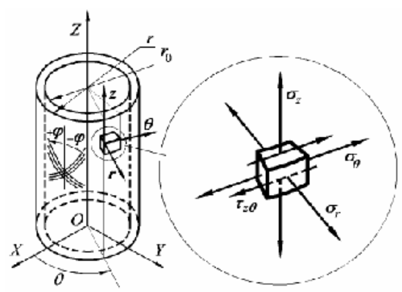

Fig. 1 Stress state in cylindrical part of type IV vessel [3]

The considered composite material is composed of an organic resin reinforced with long fibers. With respect to the local cylindrical co-ordinates system (see Fig. 3), the fourth order compliance tensor of composite S^c is reduced at the following form [3]:

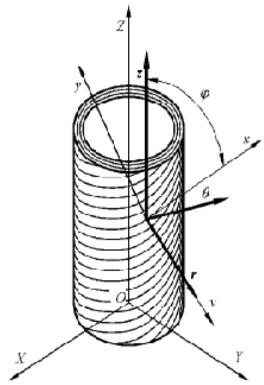

Fig. 2 Coordinate relation between cylindrical reference and the reference mark of the fiber [3]

$$S^c = \begin{bmatrix} S^c_{11} & S^c_{12} & S^c_{13} & 0 & 0 & 0\\ S^c_{12} & S^c_{22} & S^c_{23} & 0 & 0 & 0\\ S^c_{13} & S^c_{23} & S^c_{33} & 0 & 0 & 0\\ 0 & 0 & 0 & S^c_{44} & S^c_{45} & 0\\ 0 & 0 & 0 & S^c_{45} & S^c_{55} & 0\\ 0 & 0 & 0 & 0 & 0 & S^c_{66}\end{bmatrix} \qquad (4)$$

The damage seen in this work is related to the cracking of the resin along the direction of parallel fibers.

This type of cracking, assumed to change the compliance tensor components and to be more or less affected. In this context, three parameters of damage D_I, D_{II} and D_{III} respectively are defined and they characterize the lower transverse modulus E_{22} and shear modulus G_{12} and G_{23} [12].

The damage will be introduced by adding the damage contribution tensor H to the compliance tensor of composite S^c. In the present analysis, there is only the difference in behavior between transverse stress and compression is taken into account.

The elements of the compliance tensor damage can be expressed in terms of the internal variable D_I and only the sign of the hoop stress [12].

$$\tilde{S}^c = S^c + H(S, D_I, \sigma_2) \qquad (5)$$

Where, the damage contribution tensor H is given by:

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$$H=\begin{bmatrix}0&0&0&0&0&0\\0&H_{22}\,h(\sigma_2)&0&0&0&0\\0&0&0&0&0&0\\0&0&0&H_{44}&0&0\\0&0&0&0&0&0\\0&0&0&0&0&H_{66}\end{bmatrix}$$

In this present analysis, considering the polymer liner as an anisotropic elastic material, the fourth order compliance tensor S_e^L is of the following form:

$$S_e^L=\begin{pmatrix}S_{11}^L&S_{12}^L&S_{13}^L&0&0&0\\S_{21}^L&S_{22}^L&S_{23}^L&0&0&0\\S_{31}^L&S_{32}^L&S_{33}^L&0&0&0\\0&0&0&S_{44}^L&0&0\\0&0&0&0&S_{55}^L&0\\0&0&0&0&0&S_{66}^L\end{pmatrix}$$

Substituting the expression of radial and hoop stresses derived from equation (1) into equation (2) and using equation (3), the following differential equation is obtained [1-3]:

$$\frac{d^2U_r^{(k)}}{dr^2}+\frac{1}{r}\frac{dU_r^{(k)}}{dr}-\frac{N_1^{(k)}}{r^2}U_r^{(k)}=[N_2^{(k)}\varepsilon_0+N_3^{(k)}\Delta T]\frac{1}{r}+N_4^{(k)}\gamma_0 \quad (6)$$

Where

$$N_1^{(k)}=\frac{C_{22}^{(k)}}{C_{33}^{(k)}}\quad N_2^{(k)}=\frac{C_{12}^{(k)}-C_{13}^{(k)}}{C_{33}^{(k)}}\quad N_3^{(k)}=\frac{K_3^{(k)}-K_2^{(k)}}{C_{33}^{(k)}}$$
$$N_4^{(k)}=\frac{C_{26}^{(k)}-2C_{36}^{(k)}}{C_{33}^{(k)}}\quad \alpha_2^{(k)}=\frac{N_2^{(k)}}{1-N_1^{(k)}}\quad \alpha_3^{(k)}=\frac{N_3^{(k)}}{1-N_1^{(k)}}\quad (7)$$
$$\alpha_4^{(k)}=\frac{N_4^{(k)}}{4-N_1^{(k)}}$$

The solution of equation (16) depends on the value $\beta^{(k)}=\sqrt{N_1^{(k)}}$.

For $\beta^{(k)}=1$:

$$U_r^{(k)}=D^{(k)}r+E^{(k)}/r+r\ln(r)\left(N_2^{(k)}\varepsilon_0+N_3^{(k)}\Delta T\right)+\alpha_4^{(k)}\gamma_0 r^2 \quad (8)$$

For $\beta^{(k)}=2$:

$$U_r^{(k)}=D^{(k)}r^{\beta^{(k)}}+E^{(k)}r^{-\beta^{(k)}}+\left(\alpha_2^{(k)}\varepsilon_0+\alpha_3^{(k)}\Delta T\right)r+\frac{N_4^{(k)}}{2}\gamma_0 r^2\ln(r) \quad (9)$$

For $\beta^{(k)}\neq 1$ (or 2):

$$U_r^{(k)}=D^{(k)}r^{\beta^{(k)}}+E^{(k)}r^{-\beta^{(k)}}+\left(\alpha_2^{(k)}\varepsilon_0+\alpha_3^{(k)}\Delta T\right)r+\alpha_4^{(k)}\gamma_0 r^2 \quad (10)$$

$D^{(k)}, E^{(k)}$, γ_0 and ε_0 being integration constants. The superscript k is such as $k\in[1,w]$, where $w=n_L+n_C+1$. The integration constants are calculated by using the boundary conditions, given by [1-3-12].

The type IV CNG storage tank is submitted to maximum 40 MPa internal pressure to keep the behavior of the liner purely elastic. The internal radius of the liner is 33 mm and its thickness is 2 mm. for this study, the thickness of each composite layer is 0.27 mm. the solutions are obtained by using the Matlab numerical code. Table I present the material properties of polymer plastic liner LLDPE, HDPE and LLDPE/HDPE and Table II present the properties of carbon/epoxy composite.

During this work, four types of stacking sequences reinforcing HDPE liners were analyzed (Table III) .

TABLE I
POLYMER PLASTIC LINER PROPERTIES

	Tensil Modulus [MPa]	Yield stress [MPa]
LLDPE [13]	64	10
HDPE[2]	1050	25
LLDPE/HDPE[2]	171.5	15

TABLE II
ELASTIC PROPERTIES AND RUPTURE PARAMETERS [3]

	E_x [GPa]	E_y [GPa]	G_{xy} [GPa]	ν_{yx}
C/E	151	11	4	0,3

TABLE III
STACKING SEQUENCES REINFORCING

Sequence	Type
Seq1	$[\pm\varphi]_8$
Seq2	$[[+\varphi]_7+90_2]$
Seq3	$[90_2+[\pm\varphi]_7]$
Seq4	$[90+[\pm\varphi]_7+90]$

III. RESULTS AND DISCUSSION

The Fig. 3 show the variation the variation of TSAI HILL criterion according to the increasing of internal pressure for type the three polymer plastic liner reinforced by $[\pm 60]_8$ sequence.

The yield stress is quickly achieved for the LLDPE polymer, to a pressure of 20 MPa, the blend LLDPE / HDPE has allowed to increase the pressure up to 30 MPa. For the HDPE polymer, the yield stress is reached only for a pressure of 40 MPa. This concluded that in the elastic domain, the polymer HDPE has best characteristics for storage and transport at high pressure. According to the using pressure vessels, the choice of polymer can be made on the basis of the results obtained.

The results obtained show that increasing the pressure from 0 to 40 MPa did not affect the strength of the composite layers, where the results of the criterion TSAI HILL are still below 1 (Fig. 4).

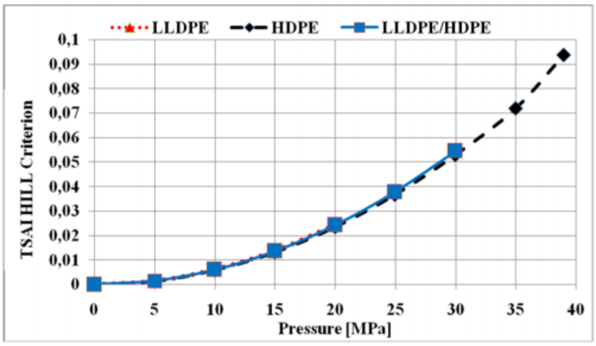

Fig. 3 Variation of Tsai Hill criterion with increasing internal pressure for first layered composite

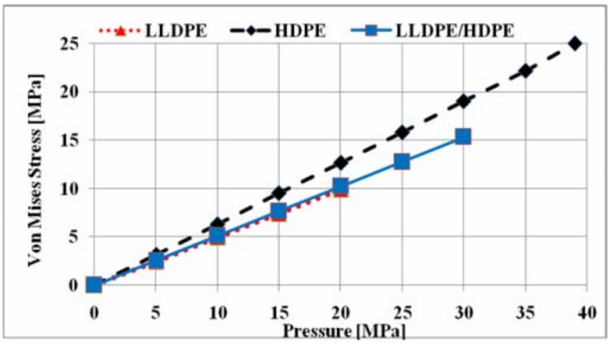

Fig. 4 Variation of Von Mises stress with increasing internal pressure for polymer liner

The effect of variation of the fiber orientation from 0 to 90° and stacking sequences of burst pressure is shown in Fig. 5. The figure shows clearly that the reinforcement of the composite layers by 90° circumferential winding has enabled increase the burst pressure tanks, mainly for winding angles of from 0 to 55°. The order of appearance 90° fibers also helped to improve the burst pressure, especially when it appears as first layer in the stacking sequence that will have a positive fact on the fracture behavior of pressure vessels.

IV. Conclusion

The focus to the analysis of the cylindrical part of a GNC storage vessel, combining a plastic liner and an over wrapped filament wound composite. Three kind of polymer are used in the present analysis: High density Polyethylene HDPE, Light low density Polyethylene LLDPE and finally blend of LLDPE/HDPE. The effect of the order of the circumferential winding on the stacking sequence has been investigated. The plastic liner is supposed to be an elastic material and for the composite is supposed to be an elastic –damageable material.

The results show the good behavior of HDPE, according to the other plastic materials tested in this analysis. The HDPE liner can resist to high pressure.

The reinforcement of stacking sequence by circumferential winding improves the rigidity of composite structure. The first appearance of 90° winding in stacking sequence, facts positively the burst pressure of cylindrical vessel.

In forthcoming paper, we also take into account, the elastoplastic behavior of HDPE liner, in order to improve the analytical model and to compare it with experimental test. An other hand, using commercial Finite Element Analysis (FEA) software is important in order to define adequate production parameters for the polymeric liner so that it could be successfully used in a composite pressure vessel.

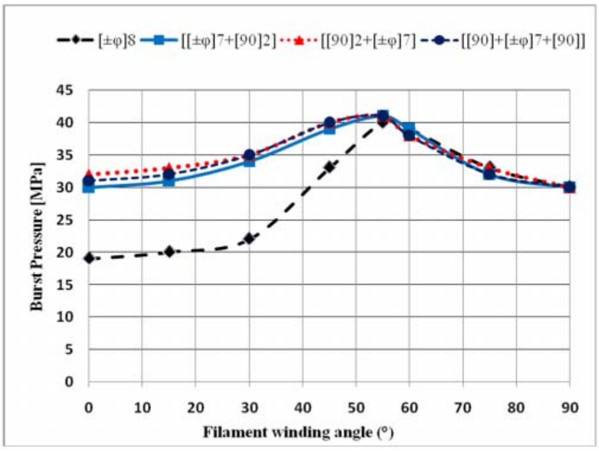

Fig. 5 Variation of burst pressure with increasing winding angle for different sequences

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