EFFECT OF ENVIRONMENTAL CONDITIONING ON BURST PRESSURE OF CARBON/EPOXY FILAMENT WOUND COMPOSITE PIPES

J. H. S. Almeida Júnior[a,c*], M. L. P. Tonatto[a], H. Faria[b], A. T. Marques[c], S. C. Amico[a]

[a]LAPOL/PPGE3M, UFRGS - Federal University of Rio Grande do Sul, Av. Agronomia 9500, 91501-970, Porto Alegre/RS, Brazil.
[b]INEGI - Institute of Mechanical Engineering and Industrial Management, Rua Dr. Roberto Frias 400, 4200-465, Porto, Portugal
[c]FEUP - Faculty of Engineering of the University of Porto, Rua Dr. Roberto Frias s/n, 4200-465, Porto, Portugal
[*]jhsajunior@globomail.com

Keywords: Filament winding; finite element analysis (FEA); burst pressure; hygrothermal coefficients.

Abstract

This research aims to study the burst pressure and mechanical behavior of filament wound composite pipes. Also, it was determined the thermal and expansion coefficients for evaluate their effect on the burst pressure of the composite pipes. The filament wound composites were manufactured with different winding angles, from ±35° to ±75°. The mechanical properties was obtained through accurate numerical models based on finite element method (FEM) and the hygrothermal coefficients via analytical approach. The results pointed an increase in the burst pressure up to ±55°, and an abrupt drop after it, for all failure criteria studied. The environmental conditioning reduced the maximum internal pressure strength in 2-3% of the composite pipes.

1. Introduction

Carbon fiber reinforced epoxy composites are steadily used in structural applications, such as in high performance vehicles, marine and in space sectors. Among the manufacturing systems for processing polymer composites, filament winding stands out due to factors like high accuracy in fiber positioning, fiber continuity, high fiber volume fraction and automated process. There are two possible configurations: in wet winding, the fibers pass through a resin bath for local impregnation and are then wound onto the rotating mandrel; in dry winding, the fiber tows previously impregnated with the resin (known as towpregs) are wound onto the mandrel. Filament wound is generally the best processing technique to produce cylindrical (axisymmetric) and elliptical parts with high structural performance.

Actually, through modern software associated with a computer-controlled machine, it is possible to manufacture parts with almost any angle, from 0° (axial) to 90° (hoop), even helped by manually adjustments (e.g. for angles near 0°), such as metal shafts at the extremities for prevent the fiber slippage in the turnaround zone (extremities of the part). The winding angle affects directly on the mechanical response of a composite pipe, when subjected to uniaxial and biaxial forces. There are several ways to predict the influence of the winding angle on the burst pressure, such as by netting analysis [1], analytically [2], by finite element analysis (FEA) [3] and experimentally [1,2].

Pipes when subjected to combined loads such as internal pressure, a fulfil design constrains and boundary conditions are required for analyze a short-term hydrostatic pressure test, aiming to evaluate the burst strength, as well as hoop and axial strength stresses. Due to the anisotropic behavior of a composite pipe, hoop and axial tensile strength and stiffness must be taking account throughout their design development, mainly for estimate the wall thickness [4]. Another essential manufacturing step is the winding angle, when it varies according to the subjected load. In case of biaxial loads, although most of studies report that ±55° angle is the optimum, because the interlaced fibers are in equilibrium and providing that the hoop stress is twice the axial one. This concept are not fully applied for any pipe' geometry, where, for example Hocine et al. [2] found an optimum winding angle of ±60°, whereas Onder et al. [5] found the aforementioned ±55° as optimum.

Several researchers have been studied the influence of processing parameter on the overall mechanical behavior of composite pipes. For instance, Mertiny and Ellyin [6] studied the effect of tension in the tow on the physical, axial and hoop stress of filament wound composite pipes. Soden et al. [7] studied the influence of winding angle on the strength and deformation of composite tubes subjected to uniaxial and biaxial loads, and they reached better stress/strain relationship for the ±55° pipes. Xia et al. [8] developed multi-layered carbon/epoxy composite pipes by wet filament winding, subjected to internal pressure and modelled their behavior analytically.

In the present research, it was studied the effect of the winding angle in filament wound composite pipes on their burst pressure, via numerical approaches. Numerical investigation was performed through the development of an accurate numerical model based on finite element method (FEM) and subjected to internal pressure load. In addition, it was numerically evaluated the burst pressure after an environmental (water plus temperature) conditioning.

2. Materials and methods

2.1 Materials and manufacturing

The following materials were used in this work:
- Carbon/epoxy towpregs from TCR Composites, where the carbon fiber is Toray T700-12K-50C and the resin system is UF3369;
- Cylindrical mandrel made of 1020 steel, with length of 381 mm and diameter of 136 mm;
- Release agent WB 2700, from AXEL Plastics; and
- Shrink tape of polyester with thickness of 0,002″, from DUNSTONE.

The composite pipes were manufactured using a KUKA robot KR 140 L100 with control and peripheral devices from MFTech. The delivery eye is able to process up to four towpregs simultaneously. The design and manufacturing of the laminates were aided by CADWind2007, which is a CAD and CAM software for filament winding. It converts data input containing all the winding parameters into a simulated model, which can be used for designing and manufacturing optimization. This simulation is then post-processed into a KRL (Kuka Robot Language) code and transferred to the robot.

Figure 1. Manufacturing of a composite pipe by dry filament winding process.

2.2 Finite element modelling

The structural modelling was carried out based on finite element method (FEM) and was conducted with the software Abaqus/CAE® 6.13. Non-linear geometry was considered in all cases since large and unbalanced deformations were foreseen.

The composite pipes were modelled by using 3D solid elements. The comprehensive material properties of the carbon/epoxy composites (Table 1) were collected by another research [9], which it was used the same raw material in the same storage conditions. The composite layers were made as continuum shell, all considered as orthotropic, as can be seen in Table 1. It was modeled 5 different pipes, varying their winding angle in: ±35°, ±45°, ±55°, ±65° and ±75°, all with 8 symmetric layers. In addition, the pipes were manufactured with 2 hoop layers, the outermost and innermost ones. Therefore, in accordance with the nomenclature, the following pipes were studied: $[90/\pm35_8/90]$, $[90/\pm45_8/90]$, $[90/\pm55_8/90]$, $[90/\pm65_8/90]$, $[90/\pm75_8/90]$. Figure 2 shows a schematic representation of one composite layup.

Elastic constants					
E_1 (GPa)	$E_2 = E_3$ (GPa)	$\nu_{12} = \nu_{13}$	ν_{23}	$G_{12} = G_{13}$ (GPa)	G_{23} (GPa)
129.7	9.1	0.31	0.32	3.16	2.05
Strength					
$\sigma_{1,t}$ (MPa)	$\sigma_{1,c}$ (MPa)	$\sigma_{2,t}$ (MPa)	$\sigma_{2,c}$ (MPa)	τ_{12} (MPa)	
1409.9	–520	42.5	–103.3	74.6	

Table 1. Mechanical properties of the carbon/epoxy lamina.

The models were developed using hexahedral elements, with C3D8R (solid linear element with reduced integration) with 3 integration points at each layer. The model has a mesh with 9000 elements and 18200 nodes. It was applied an internal pressure load with a magnitude of 30 MPa (300 bar), and the increment size was fixed in 0.1 of the total load step, aiming to analyze the structure at different pressure frames. The pipe was encastre in one extremity and all freedom degree were restricted. Also, was applied a concentrated load in one extremity representing the axial force in the flange areas. At least, it was applied four failure criteria aiming to estimate the burst pressure of the pipes: Maximum stress, maximum strain, Tsai-Hill and Tsai-Hu.

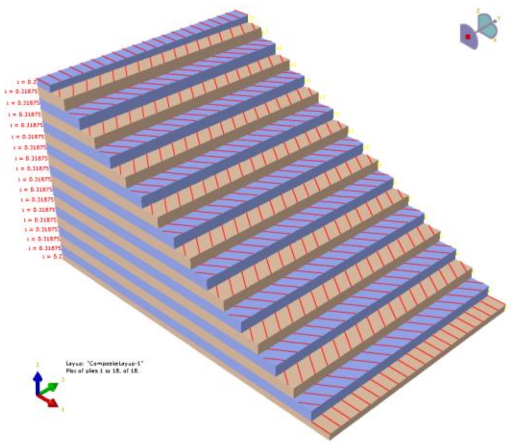

Figure 2. Composite layup description of the pipe [90/±35$_8$/90].

3.3 Environmental study

The composite pipes were immerged in a chamber containing “artificial” seawater (made in laboratory, following ASTM D-1141-03 standard) for 30 days. The system were submitted to a temperature of 80 °C, in an oven with air circulation. The density was measured based on the Archimedes principle and was conducted according to ASTM D792-08 standard. In addition, the fiber volume fraction was experimentally measured following ASTM D3171-11, by digestion with sulfuric acid. These two parameters, density and fiber content are necessary for calculate analytically α and β, which are linear thermal and expansions hygrothermal coefficients, respectively. The hygrothermal coefficients in the principal material directions α_1, α_2, β_1 and β_2 were determined by Equation (1) and (2), described as [10]:

$$\alpha_1 = \frac{\alpha_{1,f} E_{1,f} V_f + \alpha_{1,m} E_{1,m} V_m}{E_{1,f} V_f + E_{1,m} V_m} \text{ and } \alpha_2 = \alpha_3 = \alpha_{2,f}\sqrt{V_f} + \left(1-\sqrt{V_f}\right)\left(1 + V_f \nu_{12,m}\frac{E_{1,f}}{E_1}\right)\alpha_{1,m} \tag{1}$$

$$\beta_1 = \beta_{1,m} \times V_m \frac{E_{1,m}}{E_1} \quad \text{and} \quad \beta_2 = \beta_3 = \beta_{1,m}\left(1-\sqrt{V_f}\right)\left[1 + \frac{\sqrt{V_f}\left(1-\sqrt{V_f}\right)E_{1,m}}{\sqrt{V_f}E_2 + \left(1-\sqrt{V_f}\right)E_{1,m}}\right] \tag{2}$$

where, $\alpha_{1,f}$ and $\alpha_{1,m}$ are the longitudinal linear thermal coefficient of the fiber and resin and $\alpha_{2,f}$ in the transversal direction, $\beta_{1,m}$ is the linear expansion coefficient of the matrix, $E_{1,f}$ and $E_{1,m}$ are the fiber and matrix elastic modulus, V_f and V_m are the fiber and matrix volume fraction, and $\nu_{12,m}$ is the matrix Poisson’s ratio.

For measure the hygrothermal coefficients in the fiber (θ), axial (Z) and hoop (R) direction, it was applied the Equation (3), since $\alpha_R = \alpha_2$ and $\beta_R = \beta_2$.

$$\begin{aligned} \alpha_Z &= \alpha_1 \cos^2\varphi + \alpha_2 \sin^2\varphi \\ \alpha_\theta &= \alpha_1 \sin^2\varphi + \alpha_2 \cos^2\varphi \\ \beta_Z &= \beta_1 \cos^2\varphi + \beta_2 \sin^2\varphi \\ \beta_\theta &= \beta_1 \sin^2\varphi + \beta_2 \cos^2\varphi \end{aligned} \tag{3}$$

where, φ is the winding angle. Thus, the local hygrothermal coefficients were used as input for the simulations and was evaluated the effect of the hygrothermal conditioning on the pipes' burst pressure.

3. Results and discussion

The burst pressure of the 5 composite pipes is presented in Figure 3 presents the of the composite pipes studied by using the 5 failure criteria based on FEA. As can be seen, the maximum strain criterion shows the highest results, but it is not recommended for evaluate solids of revolution, because this independent criterion only evaluate the maximum strain of the fiber. Due to the high stiffness of the carbon fiber, it is expected that this criteria present highest values. Maximum stress is also an independent failure criterion, but presented milder results, comparing with the interactive failure criteria. Although would be not expected the maximum stress present reliable values, the use of comprehensive strength properties provide a good prediction by this criterion. Among the interactive criterion, Tsai-Wu presented more moderate results, which according to other researchers [5,7] it is ideal for predict the burst pressure of composite pipes and pressure vessels, because consider an interaction component on this formulation. In general, it is well know the increasing of the maximum internal pressure strength up to a winding angle of ±55°, followed by an abrupt drop for the subsequent angle. This "ideal" winding angle for composite cylinders is due to in this angle there is the ideal balance between the hoop and axial stresses, since the hoop is twice the axial one.

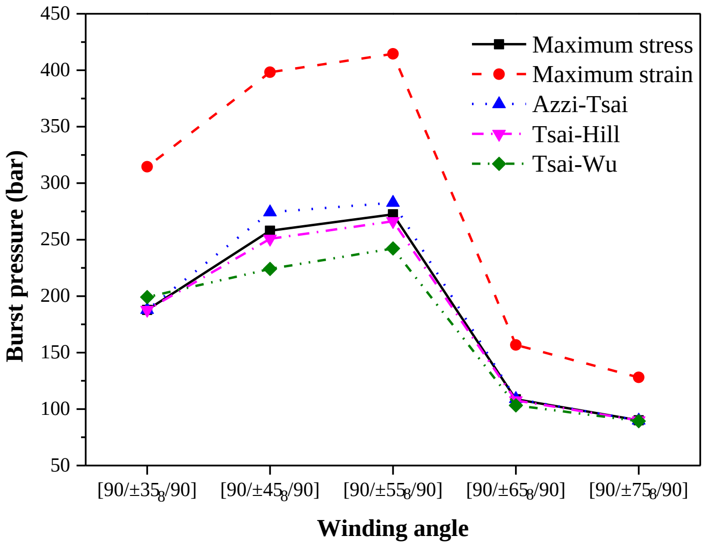

Figure 3. Variation of the burst pressure with winding angle by different failure criteria.

Figure 4 shows the variation of the Tsai-Wu failure index (*FI*) through the thickness for the different pipes in the step closer to *FI* = 1, when occurs the failure. It is noticed that the *FI* is higher in the hoop layers, clarifying the rupture firstly in the 90° layers. In this graph is clearer to see the best performance of the [90/±55$_8$/90] pipe, since for instance, its FI is almost the same for the sample [90/±75$_8$/90] in the helical layers, but for distinct pressure loads, 240 bar and 60 bar, respectively.

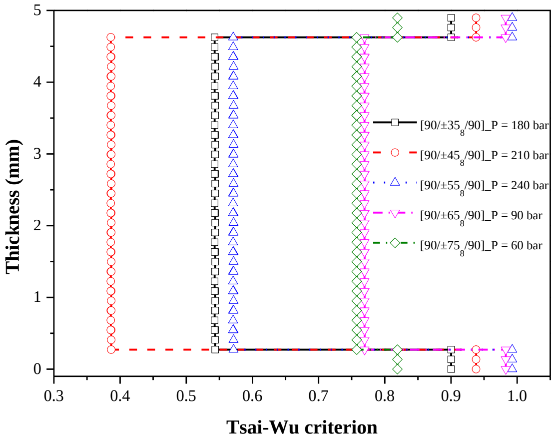

Figure 4. Scanning of the Tsai-Wu failure index through the thickness for the 5 pipes studied at different pressure loads.

Figure 5 presents the Mises stress and maximum principal logarithmic strain in the first ply, for all pressure frames. Stresses located in the center of the pipe (higher stress level in all pipes studied) was lower for the specimens oriented to ±35°, as well as for the strain, and the stress achieve a plateau for the pipes wound at ±55°. But the strain for the [90/±55$_8$/90] does not present the same behavior of the stress, because this angle prevents the axial and hoop deformations, due to the optimum balance of the interlaced fibers at this winding angle. Figure 6 shows an overall behavior of this pipe at 240 bar (nearest step of the burst pressure).

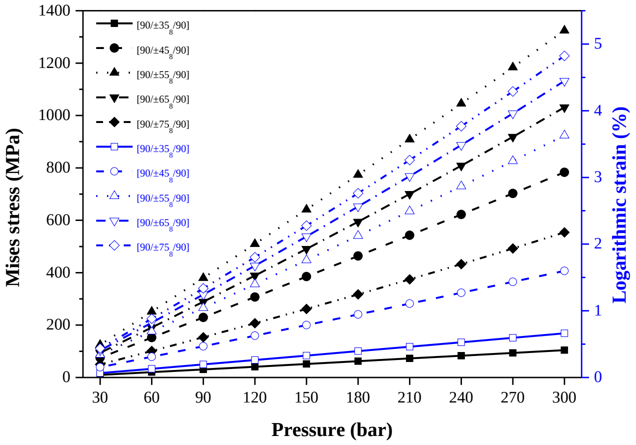

Figure 5. Von Mises stress and maximum principal logarithmic strain at the applied pressure loads.

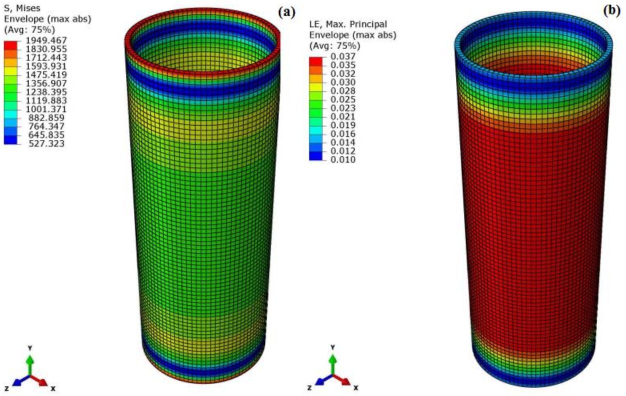

Figure 6. Envelope of the Mises stress (a) and logarithmic strain (b) of the [90/±55$_8$/90] composite pipe at a pressure of 240 bar.

3.1 Environmental conditioning results

In this section was analytically calculated the thermal and expansion hygrothermal coefficients in the principal directions, and after the coefficients in the fiber direction, as presented in Equation (3). As required in the cited equations, it was experimentally measured the composite density and fiber volume fraction ($\%V_f$), pointing 1.56 ± 0.02 and 72%, respectively. The moisture absorption of the composite pipes were 1.59-1.61%. The other fiber and matrix coefficients used were: $\alpha_{1,f}$ = −0.60 10^{-6}/°C, $\alpha_{2,f}$ = 15.0 10^{-6}/°C, $\alpha_{1,m}$ = 1.2 10^{-4}/°C, $\beta_{1,m}$ = 0.5 $E_{1,f}$ = 180.3 GPa, $E_{1,m}$ = 3.1 GPa $\nu_{12,m}$ = 0.30 [10,11]. Table 2 shows the calculated hygrothermal coefficients in the principal directions:

***a*₁ (1/°C)**	***a*₂ (1/°C)**	***β*₁**	***β*₂**
1.62E−7	3.56E−5	3.23E−3	7.87E−2

Table 2. Coefficients of thermal and expansion in the principal directions.

The effect of the hygrothermal conditioning, both thermal and expansion on the burst pressure of the composite pipes is presented in Figure 7. The results pointed a drop of 2-3% in the burst pressure of the pipes, which is a slightly decrease considering an immersion of 30 days in seawater at 80 °C. The composite is tensioned when immerged in water, due to the water absorption, which is ≈1.6% for the pipes, and due to this fact the composite support a lower load with the conditioning. Acting together with the water absorption, the temperature also contributes to this behavior, when thermal stresses influences directly on the decrease of the burst pressure.

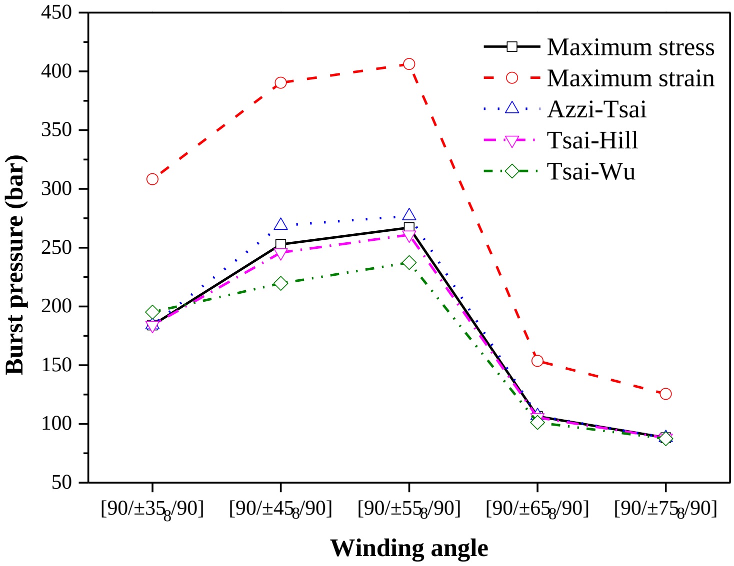

Figure 7. Variation of burst pressure after environmental conditioning of the pipes.

4. Conclusions

The effect of winding angle on the internal pressure strength of composite pipes with distinct winding angle was evaluated by using finite element method and using independent and interactive failure criteria. Also, the effect of environmental conditioning on the burst pressure was evaluated by calculating analytically the thermal and expansion coefficients and these parameters was inputted in the FEM model developed.

In all failure criteria used, the winding angle of ±55° was found as optimum for the cylinder studied, which was 22% and 172% higher than the $[90/\pm35_8/90]$ and $[90/\pm75_8/90]$, by the Tsai-Wu failure criteria. The environmental conditioning affects slightly the burst pressure of the composite pipes, reducing the maximum internal pressure supported in 2-3%.

Acknowledgements

The authors would like to thank AEB (Brazilian Space Agency) and CNPq for the financial support. The author Humberto Júnior acknowledges CAPES for its grant nº 9456-13-9.

References

---

[1] R. Rafiee. Experimental and theoretical investigations on the failure of filament wound GRP pipes. *Composites Part B*, 45:257-267, 2013.
[2] A. Hocine, D. Chapelle, M. L. Boubakar, A. Benamar, A. Bezazi. Experimental and analytical investigation of the cylindrical part of a metallic vessel reinforced by filament winding while submitted to internal pressure. *International Journal of Pressure Vessels and Piping*, 86:649-655, 2009.
[3] P. Mertiny, F. Ellyin, A. Hotan. An experimental investigation on the effect of multi-angle filament winding on the strength of tubular composite structures. *Composites Science and Technology*, 64:1-9, 2004.
[4] M. Xia, K. Takayanagi, K. Kemmochi. Analysis of multi-layered filament-wound composite pipes under internal pressure. *Composite Structures*, 53(4): 483-491, 2001.
[5] A. Onder, O. Sayman, T. Dogan, N. Tarakcioglu. Burst failure load of composite pressure vessels. *Composite Structures*, 89:159-166, 2009.
[6] P. Mertiny and F. Ellyin. Influence of the filament winding tension on physical and mechanical properties of reinforced composites. *Composites Part A*, 33(12):1615-1622, 2002.
[7] P. D. Soden, R. Kitching, P. C. Tse, Y Tsavalas. Influence of winding angle on the strength and deformation of filament-wound composite tubes subjected to uniaxial and biaxial loads. *Composites Science and Technology*, 46:363-378, 1993.
[8] M. Xia, H. Takayanagi, K. Kemmochi. Analysis of multi-layered filament-wound composite pipes under internal pressure. *Composite Structures*, 53:483–491.2001.
[9] J. H. S. Almeida Júnior, C. Staudigel, G. L. P. Caetano, S. C. Amico. Engineering properties of carbon/epoxy filament wound unidirectional composites. In *16th European Conference on Composite Materials*, volume 16, 1-8, 2014 (*Submitted*).
[10] E. J. Barbero. *Introduction to composite materials design*. CRC Press, USA, 2010.
[11] G. Korb, J. Koráb, G. Groboth. Thermal expansion behaviour of unidirectional carbon-fibre-reinforced copper-matrix composites. *Composites Part A*, 29(A):1563-1567, 1998.