COMPARATIVE PARAMETRIC MODELLING OF COMPOSITE TUBES AND COMPOSITE OVERWRAPPED PRESSURE VESSELS

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Abstract
In this work, the stress and strain levels of composite overwrapped pressure vessels and composite tube were evaluated, through an accurate numerical modelling based on finite element method (FEM). It was developed the models of the COPV and tubes with three aluminum liner thickness. Initially, the stress and displacement of the composite layers overwrapping the liner was analyzed and graphically represented. The parametric modelling for study the structural relationship between COPV and pipes were made by three new concepts developed in this work, liner stress and liner strain share fraction and thickness ratio. The results showed representative results at lower pressures, e.g. at 70 bar, where a composite tube can parametrically represent a COPV.

1. Introduction

Filament-wound composite tubes (pipes) and overwrapped pressure vessels (COPV) are being increasingly used in several infrastructural and industrial demanding applications. They present relatively high structural efficiency, due to the high stiffness-to- and strength-to-weight ratios. Also, the automated manufacturing process allows high productivity rates, thus economical competitiveness. Many fields are attended by filament-wound structures, such as automotive (i.e. natural gas storage), marine (i.e. fluids transport and storage) and aerospace (i.e. rocket motor or missiles).

In order to improve the understanding of the mechanical behavior of these structures, numerical modelling approaches have been developed by several researchers [1,2]. Namely, structural finite elements analysis (FEA) of composite laminates has been implemented with progressive complexity, seeking the detailed description of the specific features of such wound laminates. The final engineered solutions are typically achieved by structurally simulating the parts and iteratively validating such modelling through experimental characterization of their behavior. This wiser approach replaced the former fully empirical nature of product development used by the composites industry. Still, timely and costly manufacturing and testing of a number of specimens for the validation of the numerical models are needed, which inhibits faster development and wider utilization [3]. Therefore, all possible simplifications in the experimental part of the development are strongly aimed by the industry.

COPV and composite tubes are axisymmetric structures manufactured by filament winding and are composite parts, which can be optimized according to the loading service, since the geometric details and possibility of different winding angles throughout the layers, for instance. Composite tube and COPV differ themselves just without the cylindrical region, where in a tube the cylindrical-end region can be considered as an "extension" of this section, and in COPV there are several types of dome section, such as geodesic, spherical and elliptical, among others, further the polar boss. Figure 1 shows typical geometry of these parts.

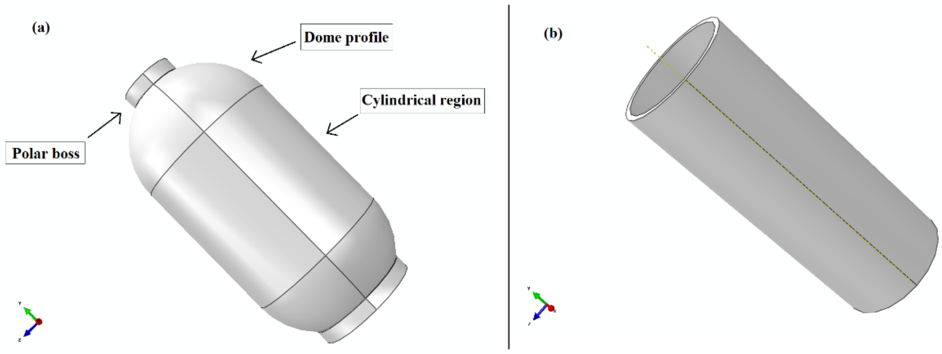

Figure 1. Typical geometry of a COPV (a) and a pipe (b).

In the way to keep the structural health of the part under service, the stresses and strains in different points of the COPV/tube are required. As well as experimentally is a hard and expensive assignment, a numerical model before a possible experimental validation is essential for the part design. Sun et al. [4] studied numerically the bursting failure in COPV rocket motor case, based FEA and using axisymmetric geometry in their model. Onder [5] produced glass fiber reinforced epoxy pipes and studied the burst failure by FEA, analytical and experimental approaches, once the analytical one presented closer results compared to the experimental ones.

Taking account the missing in the literature a parametric study between composite overwrapped pressure vessel and a composite tube, this is the motivation of this work. Accurate numerical models were developed using the Abaqus® FEA software platform, of COPV and tubes with different liner thickness, and linerless, and was evaluated the stress and strain levels in different points of the structure, keeping the same geometrical specifications.

2. Finite element modelling

The COPV and composite pipes were modeled by using aluminum liner, fully overwrapped by a carbon/epoxy towpreg (T700). For the development of an accurate model of the COPV and pipe, adequate material properties for the liner and composite layers are required. The elastic properties and the plasticity hardening data (aluminum liner) of the selected raw materials are presented in Table 1 and Table 2.

Property	E_{11} (GPa)	E_{22}, E_{33} (GPa)	υ_{12}, υ_{13}	G_{12}, G_{13} (GPa)	G_{23} (GPa)	υ_{23}
Aluminum	73.77	73.77	0.33	27.73	--	0.33
T700	148.24	1.56	0.28	1.46	0.56	0.31

Table 1. Elastic properties of the liners and composite [6].

The structural modelling was realized based on finite element method (FEM) and was conducted through the software Abaqus/CAE® 6.13. Non-linear geometry was assumed for all cases, since large and unbalanced deformations are expected.

The composite lay-up was kept constant for all COPVs and pipes, with 20 layers defined as in Table 3. The outer dimensions of the liners was kept constant for all vessels, with a length of 540 mm and outer diameter of 572 mm in the cylindrical region. These was the pipes' dimensions, once its dimensions was defined based on the cylindrical region of the COPV, aiming to compare these behaviors keeping the same geometrical relationships. These dimensions are showed in Figure 2.

Data point	*Aluminum*	
	Yield Stress (MPa)	*Plastic Strain*
1	300	0.0
2	320	0.00016
3	340	0.00047
4	355	0.00119
5	375	0.00449
6	390	0.01036
7	410	0.0213
8	430	0.03439
9	450	0.05133
10	470	0.08
11	484	0.1471

Table 2. Hardening data for the different liners.

Layer	*Pattern*	*Friction*	*Winding angle*	*Thickness (mm)*	*Band width (mm)*
1-10	Hoop	Yes	90°	5.0	25
11-20	Helical	No	±20°	8.0	-

Table 3. Composite lay-up for the COPVs and composite tubes studied.

Regarding the COPV modelling, the thickness of the liner was varied in 3, 5 and 7 mm. The liners were meshed with linear CAX4R (four-node bilinear axisymmetric quadrilateral) elements with reduced integration. Due to the different liner thicknesses modeled, the meshes have not the same element size and number, beyond keeping 6 elements through-the-thickness in the cylindrical and dome sections. This mesh arrangement avoid the *hourglassing* effect, preventing convergence issues.

For the composite layers, the models were developed using quadratic elements, with CAX6 (six-node quadratic) and CAX8 (eight-node biquadratic) element types. For the sake of simplicity and comparability, the composite layup was kept constant for all COPV studied. The composite vessel was split in 50 partitions and 600 elements along the longitudinal profile and 4 elements through the thickness at each layer, amounting a mesh with 25128 elements.

It was applied an internal pressure load with a magnitude of 70 MPa (700 bar), and the increment size was fixed in 0.1 of the total load step, aiming to analyze the structure at different pressure levels. All the structures were analyzed in two points: in the mid-point and in the edge-point (for COPV is the last point at the cylindrical section). A constrained interaction was defined between the outer surface of the liner and the inner surface of the composite lay-up, aiming to tie them numerically. Thus, a perfect bonding between the liner and the composite was assumed.

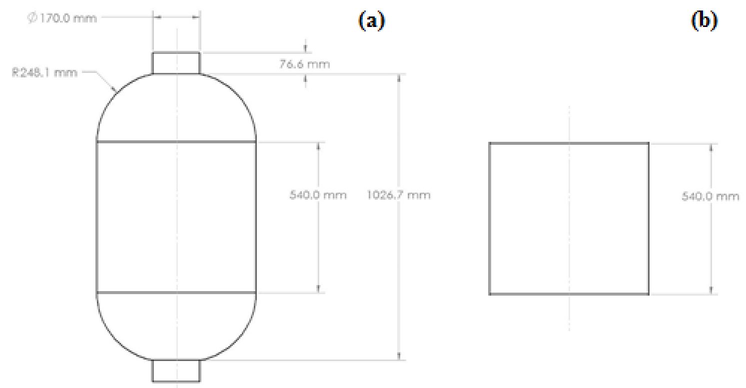

Figure 2. Geometrical specifications of the vessel (a) and tube (b) liners.

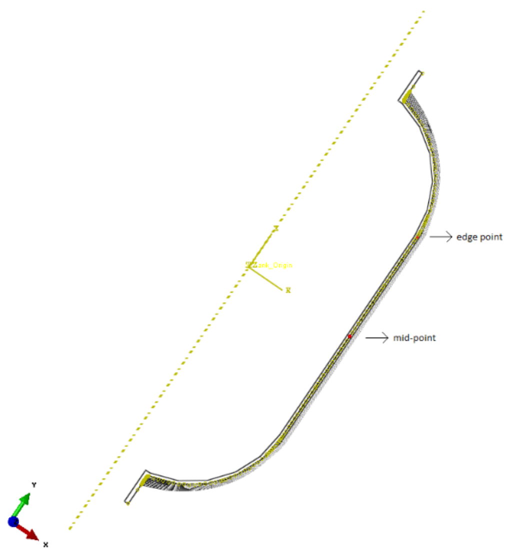

Figure 3. Points of the structure analyzed in this study.

3. Results and discussion

3.1 Analysis of the composite shell in the COPV

Figure 4 shows the stress level in each point along the composite shell, which overwrap a pressure vessel with aluminum liner of 7 mm. As mentioned in the experimental section, the first layer is hoop (90º) and the subsequent layers are helical oriented at ±20º. As can be seen the first layer support a high level of stress, once it is primarily in contact with the applied load. The hoop layer is essential for this COPV, since the length is twice (below than l/d = 10) the diameter of the COPV in the cylindrical region. The stress level in the cylindrical section is around 3 GPa, achieving more than 4 GPa in the extremities, where the cylindrical zone finishes and the stress level is higher due to be a turbulence zone.

In the helical layers, the Mises stress level is lower, because the hoop layers absorbed a large amount of the pressure applied. In the cylindrical zone the tension is constant, but the same does not happen in the other regions, such as in the dome. a different phenomenon occurs in the composite layers, once in the hoop the stress becomes decreasing up to an abrupt peak at the extremity, the helical layers presents an slowly increase in the same region, following an abrupt drop starting the dome section. As expected, the outer layers have a lower stress level. Another interest phenomena occurs at the polar boss region, where there is located the most stress level, achieving around 2.5 GPa in the second layer. this is expected because the polar boss region is a stress concentrator, due to the high number of force lines and a high stress gradient in the region, which is dominated by tensile forces, whereas in the cylindrical region the compressive one domain.

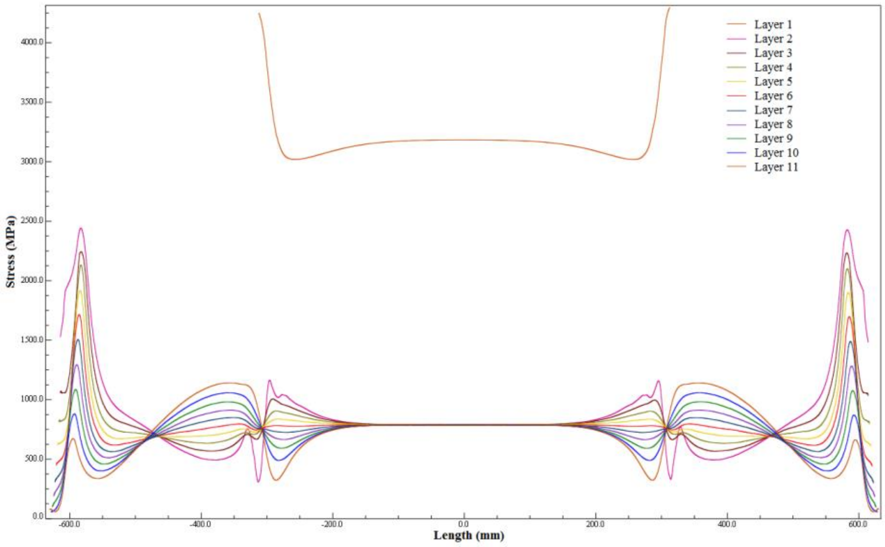

Figure 4. Variation of the Von Mises stress along the composite layers in the COPV.

As showed, the COPV structures exhibit a non-uniform distribution of stresses and strains owing to a number of factors. These include the shades of liner geometry and its interaction with the overwrap winding pattern, the relative stiffness of the liner to the overwrap, the liner-overwrap interface slip characteristics and the presence of incompatible curvature changes [7]. Also, it is valid to mention that the liner manufacturing is not so easy seeking a constant thickness along the vessel, and in areas where the liner thickness is uniform, the overwrap may be seen to act as an elastic foundation which cradles the liner. The polar boss areas are typically thickened and more rigid to support the port fixture, which is essential to provide an equilibrium due to the high stress level at the neck. In the elastic regime the boss support protections the overwrap from deforming uniformly with the membrane regions of the composite shell. Liner yielding generally initiates at the transition region between the boss and the membrane areas of the liner. Early boss failures were attributed to this stress concentration and new winding patterns increased the amount of fiber in the boss region to better support the boss fixture [8]. The nature of the elastic-plastic behavior of the liner is also prominent in determining the stress state of the overwrap.

Figure 5 presents the displacement of the composite overwrap in the COPV with liner thickness of 7 mm. It is valid to mention that the behavior showed is only of the composite layers. As well as for the stress analysis, the understanding of the displacement of composite layers along the length is hard to explain, due to the geometry complexity and the high number of forces which act simultaneously in the structure at the same time, and acting non-uniformly in different zones of the COPV, as can be seen in the plot below. The cylindrical section is dominated by compressive forces, once is viewed that the structure compressed in this section and expanded in the dome section and especially in the polar boss region, since the tensile forces is dominant in this region. The uniformity of the displacement in the hoop and helical pattern must be highlighted, once the composite layers displaces homogeneously along the tank length, once the same behavior would not expected if was analyzed the strain.

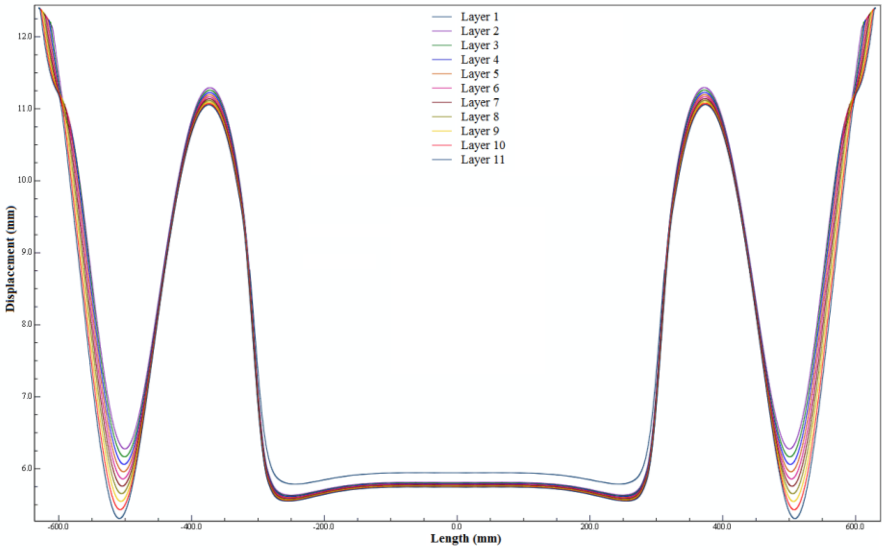

Figure 5. Variation of the spatial displacement (U) along the composite layers in the COPV.

3.2 Analysis of the COPV and composite tubes

In view of setting a means of comparison between different configurations of the COPV and tube structure, three new concepts were developed for this work. Namely, the liner stress share fraction (σ_{lsf}), liner strain share fraction (δ_{lsf}) and the thickness ratio (t_r) were set as main parameters for the analysis and are defined as:

$$\sigma_{lsf} = \frac{\sigma_l}{\sigma_l + \sigma_c} \qquad \delta_{lsf} = \frac{\delta_l}{\delta_l + \delta_c} \tag{2}$$

and,

$$t_r = \frac{t_l}{t_c} \tag{3}$$

where σ_l and σ_c are the stresses in the corresponding points of the liner and the composite, respectively, and t_l and t_c are the thicknesses of the liner and composite, respectively.

Figure 6 shows σ_{lsf} and δ_{lsf} in function of t_r. It was analyzed the stress and strain in the mid-point and edge-point of the structures. It is viewed that σ_{lsf} presents relatively close values for the three liner thickness analyzed. For instance, for thickness ratio of 0.23, the liner stress share fraction presented a difference of 0.02 between the COPV and the tube, at the mid-point, whereas at the edge-point the difference was 0.017. For higher thickness ratio, the values are not too representative in the t_r of 0.23. In the other hand, the results of the liner strain share fraction were more representative than the stress results, once presented more close values in the three liner thickness studied.

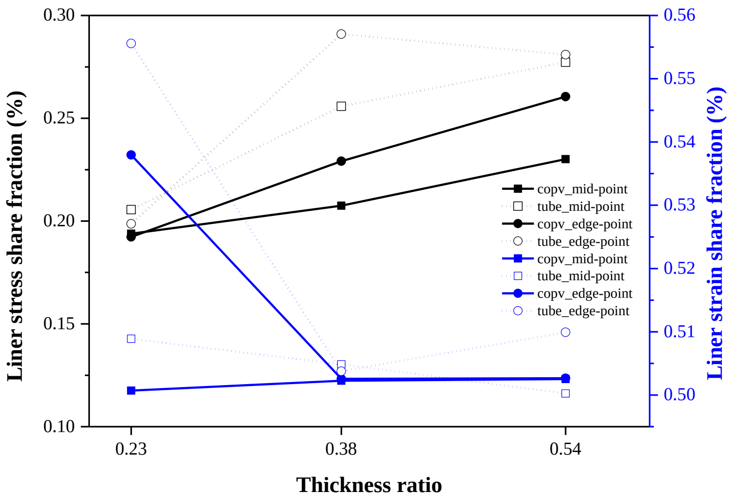

Figure 6. Liner stress and strain share fraction *vs.* thickness ratio for the COPV and composite tube studied at a pressure of 70 bar.

Figure 7 presents the results of the σ_{lsf} and δ_{lsf} for the three liner thickness analyzed along the applied internal pressure, where the total pressure was divided in ten frames, as can be seen in the graph. The results provided excellent results, where the results collected for the COPV and the composite tube were near and the trend was the same, analyzing the stress fraction. It is noticed that increasing the internal pressure load the liner share a smaller portion of the load, once the composite layers support the load installed, but in different frames for the three thickness ratio. After a pressure of 210 bar, only the liner of 7 mm share a representative fraction of the load, as well for the COPV and tube, at the mid-point (Figure 7 (a)). The liner strain share fraction showed a disordered behavior, being constant for the three thickness ratio studied.

Figure 7 (b) presents the same values, but analyzing the edge point in the two structures. As expected, the values was not liner and mainly for the composite tube was not representative. As mentioned, this behavior could be achieved, once the edge point is a turbulence zone, because is the interface between the cylindrical region and the dome section. Taking account that in a numerical modelling some manufacturing issues are not related, such as welding and thickness variations, an experimental approach could present more distinct results in the edge point of these structures.

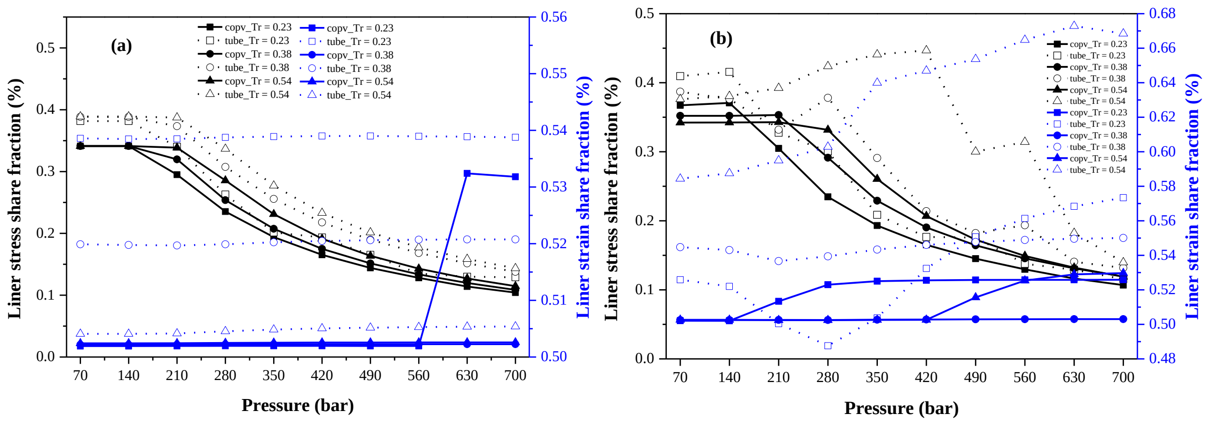

Figure 7. Liner stress and strain share fraction along the applied internal pressure for the COPV and composite tube in the mid-point (a) and edge-point (b).

4. Conclusions

In this work was developed accurate numerical models of a composite overwrapped pressure vessels and composite tubes, both with an aluminum liner with different thickness, both under internal pressure. It was analyzed the stresses and strain levels at the mid-point and the edge point, considering only the cylindrical region for the COPV. The geometry of these structures, mainly the COPV, becomes too hard to analyze deeply their behavior in specific points, as in this work. The Mises stress and the displacement of the composite layers were well represented and was clear that the polar boss region is critical for the COPV, being a stress concentrator, due to the high gradient of stress in this section.

Regarding the parametric modelling between the COPV and the composite tubes, the results showed that the COPV is more stable than the composite tube, presenting more representative values. Perhaps, the stress and strain at low pressures, such as 70 bar presented representative values for the COPV and tube, but for higher pressures, the behavior was not regular, mainly for the tubes, because their structures have more free length zones and is not so stable than a COPV.

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