FIBRE REINFORCED THERMOSETTING AND THERMOPLASTIC MATRIX FILAMENT WOUND PRESSURE VESSELS

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KEYWORDS: Filament winding, composite vessel, thermoplastic matrix composite, thermoplastic line

ABSTRACT

Fibre reinforced thermosetting and thermoplastic matrix filament wound pressure vessels for large scale market applications have been studied in this work. The vessels consist on a thermoplastic liner wrapped with a filament winding glass fibre reinforced polymer matrix structure [1]. The present paper covers the manufacture, simulation and pressure vessel prototypes testing. A high density polyethylene (HDPE) was selected as liner and thermosetting and thermoplastic polymers were used as matrices in the glass reinforced filament wound laminate. A conventional 6-axis CNC controlled filament winding equipment was used to manufacture the thermosetting matrix composite vessels and adapted for production of thermoplastic matrix based composite vessels. The Abaqus 6.4.2 FEM package was used to predict the mechanical behaviour of pressure vessels with capacity of approximately of 0,068 m^3 (68 l) for a 0.6 MPa (6 bar) pressure service condition according to the requirements of the EN 13923 standard, namely, the minimum internal burst pressure. The Tsai-Wu and von-Mises criteria were used to predict composite laminate and thermoplastic liner failures, respectively, considering the elasto-plastic behaviour of the HDPE liner and the lamina properties deducted from the micromechanical models for composite laminates.

1. INTRODUCTION

Traditional materials, such as, steel, are successfully being replaced by polymer matrix composites materials in the construction of pressure cylinders for many common applications. Multi-axial filament winding is the best adequate processing technology to be use in the production of composite vessels for medium to high internal pressures [2, 3]. Such technology allows processing simultaneously the vessel cylinder and domes and use non-geodesic optimised fibre patterns that permit withstand the higher mechanical efforts involved with lower vessel-wall thicknesses.

The present paper covers the production and testing of pressure vessels made from fibre reinforced thermosetting and thermoplastic matrix composites.

A vessel consisting in a thermoplastic liner wrapped with a filament winding glass fibre reinforced thermosetting and thermoplastic polymer structure has been studied. Finite element analysis (FEM) was used to predict the pressure vessel mechanical behaviour according to the requirements of the EN 13923 standard, namely, the minimum internal burst pressure.

2. RAW MATERIALS AND PRESSURE VESSEL DESCRIPTION

A pressure vessel, with the dimensions shown in Figure 1, having the capacity and internal diameter of 0.068 m^3 and 205 mm, respectively, was chosen to be studied in this work.

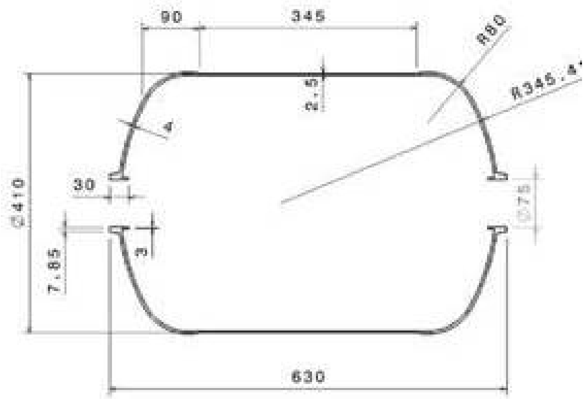


Figure 1. Dimensions of the pressure vessel under studied

A thermosetting orthophthalic unsaturated polyester resin matrix reinforced with a weight percentage of 70% of 2400 Tex type E continuous glass fibres was selected to be used in the pressure vessel laminate. Table 1 summarises the mechanical properties of structural wall glass reinforced unsaturated polyester (GF/UP) laminae. The values under the column “Calculated Values” were predicted from the manufacturer data sheets using well-know micromechanical models for composite materials [4-7].

A high density polyethylene (HDPE), Rigidex® HD3840UR from INEOS, has been selected to produce the thermoplastic liner by rotational moulding. Table 2 shows the main experimental properties determined in this HDPE.

Table 1: Properties of the GF/UP laminae

Property	Unit	Values	
		Data sheet	Calculated
Longitudinal Strength	MPa	800	-
Longitudinal Modulus	GPa	40	-
Transversal Strength	MPa	-	40
Transversal Modulus	GPa	-	10
Shear Strength	MPa	-	35
Shear Modulus	GPa	-	0.5
Poisson’s Ratio	-	-	0.35
Density	g/cm^3	-	1.9
Glass mass content	%	70	-
Glass volume content	%	-	52

Table 1: HDPE liner properties

Property	Unit	Value
Tensile modulus	MPa	270 ± 8
Yield stress	MPa	13.8 ± 0.4
Yield strain	%	14.36 ± 0.4
Elongation at break	%	> 40
Density	g/cm^3	0.94

Glass/polypropylene commingled fibre tows (TWINTEX PP75 UD) supplied by Saint-Gobain was also chosen to produce the alternative thermoplastic matrix composite gas vessels studied in this work. Table 3 summarises the mechanical properties of the used tapes. Also, values under the column “Calculated Values” were predicted from the manufacturer data shown in Table 4 using well-known equations from the micromechanical theory of composite materials.

Table 3: Properties of TWINTEX®

Property	Unit	Data Sheet Values	Calculated Values
Longitudinal Strength	MPa	700	-
Longitudinal Modulus	GPa	38	-
Transversal Strength	MPa	-	30
Transversal Modulus	GPa	-	1.9
Shear Strength	MPa	-	17
Shear Modulus	GPa	-	0.7
Poisson's Ratio	-	-	0.35
Thermal conductivity	W/mK	-	0.19-0.38
Electrical resistivity	Ωm	-	$2x10^{10}$
Density	g/cm^3	1.75	-
Glass mass content	Wt%	75	-
Glass volume content	Vol%	50	-

Table 4: Raw materials properties

Property	Unit	Glass fibres (GF)	Polypropylene (PP)
Strength [a)]	MPa	1450	37
Tensile modulus	GPa	76	0.96
Poisson´s Ratio	MPa	0.27	0.35
Density	g/cm^3	2.6	0.9

a) in the case of PP the value shall be considered as the yield strength

Figure 2 depicts the HDPE liner produced by rotational moulding in the company ROTOPORT that is being used in the present work. For testing and evaluate their performance, two different types of threads were used in end-domes liner fittings: a HDPE thread directly manufactured in the liner during the rotational moulding process and a metallic thread insert that was incorporated in the HDPE liner wall.

Figure 2. Rotational moulding HDPE liner

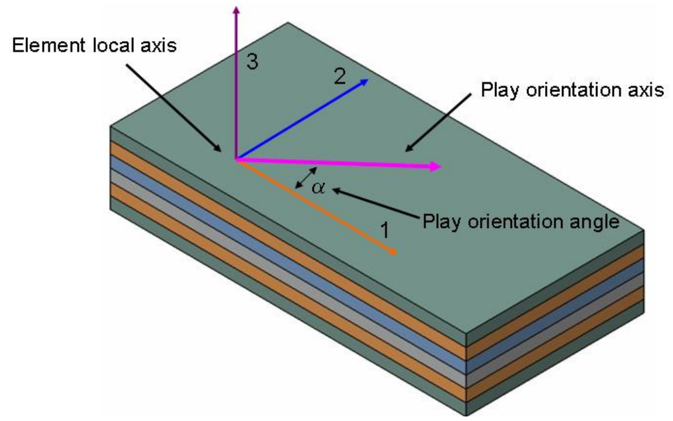


Figure 3. Cylinder ply stacking sequence and orientation

3. FEM analysis

Abaqus 6.5 FEM packages [8] were used to predict the mechanical behaviour of the pressure vessel cylinder by finite element analysis. Non-linear analyses were used in the mechanical behaviour simulations, first on the HDPE liner alone and after on the overall composite pressure vessel (HDPE liner wrapped by GF/UP laminate). The properties previously presented in Tables 1 and 2 for the GF/UP lamina and HDPE liner, respectively, were used in the simulations. Furthermore, the properties in Table 3 were also used in the simulations of the vessels made using the commingled TWINTEX® tows.

The HDPE liner was considered to have elasto-plastic behaviour and the von-Mises and Tsai-Wu criteria were used to predict the failure in the HDPE liner, GF/UP and TWINTEX laminates, respectively.

Fibre orientation, thickness distribution, stacking sequence and number of layers were the parameters used to describe the laminate composite structure using shell composite linear elements. Figure 4 shows the ply stacking sequence and the material orientation angles used in the cylindrical vessel zone FEM simulations for the case of the GF/UP laminate. The Simpson's integration rule (three points through thickness) was used to calculate the cross-sectional behaviour of the shell. Reduced integration formulation was applied in the stiffness matrix shear components and the full integration in other matrix terms.

As Figure 4 shows, the variation of the thickness in different zones along the vessel was taken into account in the FEM model.

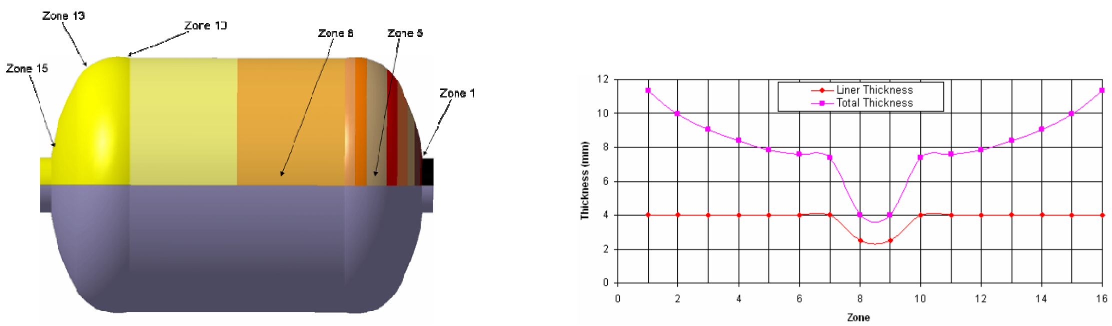
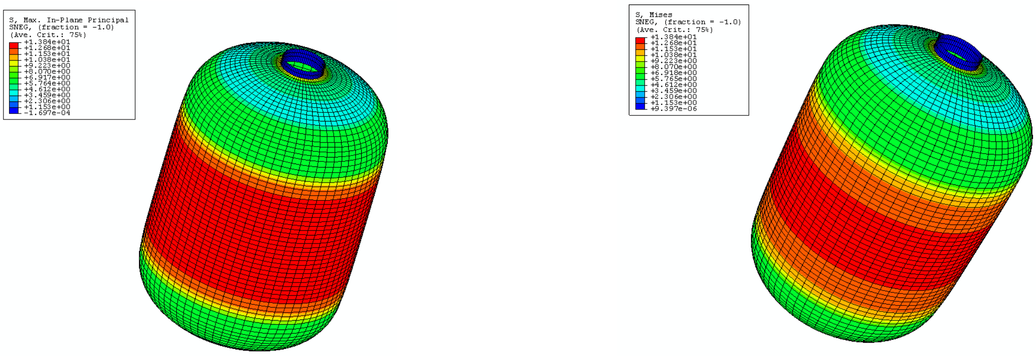


Figure 4. Variation of the thickness along the composite vessel

As it may be seen in Figure 4, the composite thickness varies along the vessel length reaching maxima values near the end-dome fittings due to the filament winding stacking process. The increase of thickness due to the central HDPE welding line was also taken in consideration.

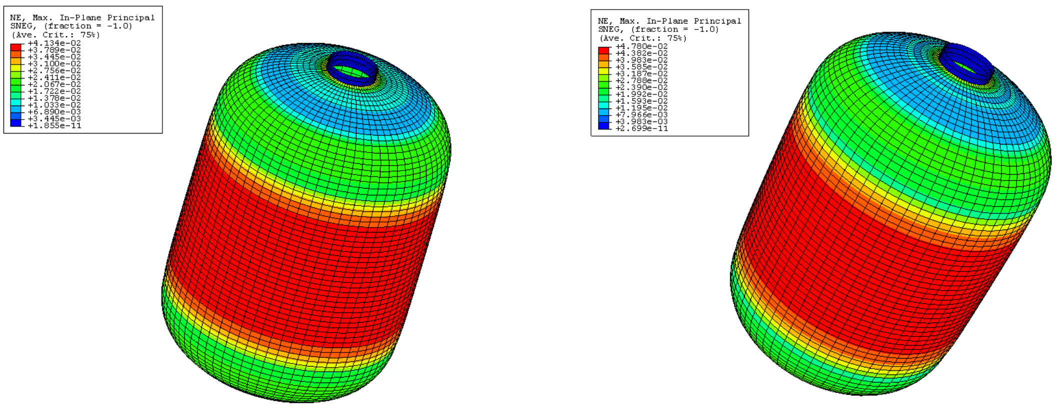
4. RESULTS AND DISCUSSION

To predict the HDPE liner burst pressure, it was submitted alone to a constant internal pressure increase in the FEA model. The von-Mises stresses and strains fields obtained from the simulations conducted in the HDPE liner are shown in Figures 5 and 6.



a) at the pressure of 1.56 bar *b) at the pressure of 1.68 bar*

Figure 5. von-Mises field stresses determined in the HDPE liner



a) at the pressure of 1.58 bar *b) at the pressure of 1.68 bar*

Figure 6. von-Mises field strains determined in the HDPE liner

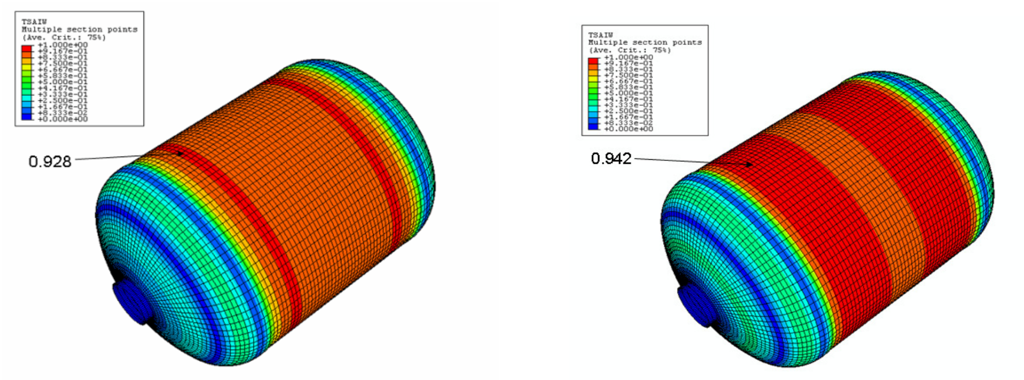
As it may be seen in above figures, the results allowed predicting that HDPE liner begins to exhibit creep behaviour at a internal pressure around 1.56 bar. When the pressure was increased from 1.56 bar to 1.68 bar a stress level in the liner wall was maintained around the yield stress. For similar levels of internal pressure, Fig 6 shows that a deep increase on liner wall strain was obtained at that constant yield stress value.

FEM simulations were then conducted on the overall composite pressure vessel considering the elasto-plastic and elastic behaviours in the HDPE liner and GF/UP laminate, respectively. The objective was to find a GF/UP composite laminate able to withstand a maximum internal initial burst pressure 18 bar. According to the requirements of the EN 13923 standard, for such burst pressure the vessel could be commercialised to withstand a standard 6 bar service pressure.

To regularise the HDPE liner surface and obtain better finishing in the outside vessel surface, it was decided to use circumferential (90º) layers in the initial and final laminae of the GF/UP composite laminate. It was also chosen to built the remaining GF/UP laminate using cross-ply layers with fibres oriented at $\pm\alpha$. A deep research has been conducted in order to optimise the cross-ply angle between 20º and 30º. Finally, a ±20º cross-ply laminate was chosen because obtained results have shown that this kind of laminate was able to withstand higher internal pressures in the vessel.

However, as Figure 7 depicts, it was found that failure was near to occur in some cross-ply internal layers having fibres oriented at ±20º at lower vessel internal pressures. From this figure, it is possible to conclude that the FEM analysis predicted failure in the cross-ply layer number 15 of the GF/UP laminate at an internal pressure around 19 bar. Thus, the selected GF/UP composite laminate was considered appropriate to manufacture composite vessels for withstand the 6 bar standard service pressure.

A deep analysis allowed also to find that the high interlaminar shear stresses developed in the cross-ply layer number 15 were mainly responsible for the failure observed.



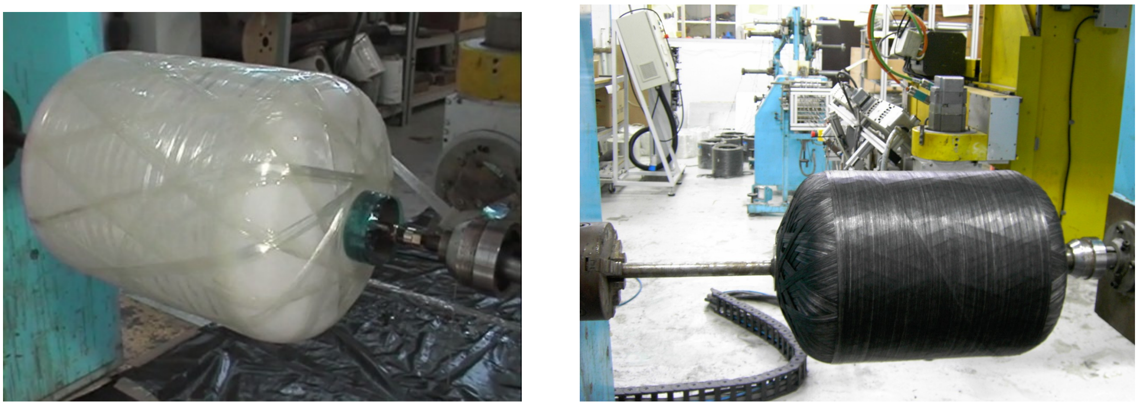
a) layer #12 at pressure of 18.72 bar *b) layer #15 at pressure of 19.68 bar*

Figure 7. Tsai-Wu field stresses in the internal composite ±20º cross-ply layers

As very similar results were obtained from the FEM simulations of the vessels made in commingled TWINTEX® thermoplastic matrix tows it was not considered relevant to present them in this text.

5. PRODUCTION OF PROTOTYPE VESSELS

Prototype composite vessels were manufactured in the conditions used in the FEM simulations using a 6 axes CNC controlled filament winding machine from Institute of Mechanical Engineering and Industrial Management (INEGI) and submitted to hydraulic burst pressure tests (Figures 8 and 9).



a) production of a GF/UP vessel *b) production of a TWINTEX® vessel*

Figure 8. Production of the thermosetting and thermoplastic matrix pressure vessels

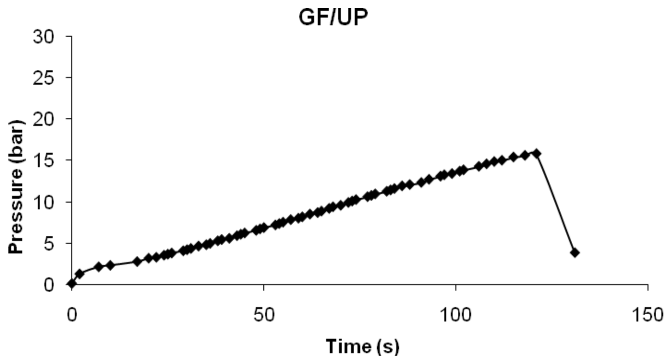
a) GF/UP vessel *b) TWINTEX® vessel*

Figure 9. Thermosetting and thermoplastic matrix composite pressure vessels

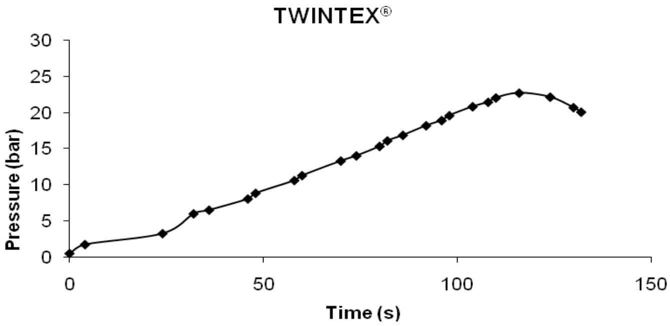
6. VESSELS BURST TESTING

Figure 10 shows typical pressure/time curves obtained from a burst test made in INEGI according to EN 12245 European standard. The obtained results have shown that burst occurred for the thermosetting and thermoplastic matrix vessel at pressures of 16 bar and 22 bar, respectively. Such results demonstrated that the structural container fully accomplished the requirements of the EN 13923 European standard to withstand a working pressure of 6 bar.

As may be seen from Figure 10 higher burst internal pressures were obtained on the thermoplastic matrix prototype vessels made with TWINTEX® tows. In this last case, slightly higher experimental burst pressures than the values predicted by FEM were found. The lower burst pressure obtained from FEM simulations is probably due to failure do not occur by interlaminar shear in the experimental pressure test. After interlaminar shear failure occurs, the laminate layers seem to suffer slippage, which makes the commingled reinforced fibres to become re-oriented in the direction of the efforts and withstand an additional internal pressure. In fact, other authors have demonstrated that, as simplified models (netting theory, for example) may predict, vessels only made by overwrapping dry fibres on a liner may withstand large internal pressures [9].



a) GF/UP vessel



b) TWINTEX® vessel

Figure 10. Composite pressure vessels burst tests

7. CONCLUSIONS

This work shows that the FEM analyses is a powerful tool to optimise composite pressure vessels lay-up. The FEM simulations made allowed predict a high creep behaviour on the HDPE liner alone above internal pressures of 1.56 bar. It was also possible to define the laminate to be used in the production of pressure composite vessels able to withstand the minimum standard service pressure of 6 bar, which according to the requirements of the EN 13923 standard enable to support burst pressure of 18 bar. Because the cross-ply laminate layers have shown to fail at this last pressure due to high interlaminar shear stresses, it is expectable that prototype vessels will be able to withstand higher burst pressures. In fact, previous works proven [9, 10] that the interlaminar shear stresses are probably not the main cause for overall failure of pressure vessels structural laminates. Furthermore, slight better experimental burst pressure results were found in the case of the thermoplastic matrix vessels.

ACKNOWLEDGEMENTS

Authors wish to acknowledge the financial support given to this work through the project RESCOMPRE by the Portuguese Agency for the Development (ADI).

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