STUDYING THE PRODUCTION OF FILAMENT WOUND COMPOSITE PRESSURE VESSELS

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Abstarct

A new generation of composite pressure vessels for large scale market applications has been studied in this work. The vessels consist on a thermoplastic liner wrapped with a filament winding glass fibre reinforced polymer matrix structure. A high density polyethylene (HDPE) was selected as liner and a thermosetting resin was used as matrices in the glass reinforced filament wound laminate.

The Abaqus 6.5.1 FEM package was used to predict the mechanical behaviour of pressure vessels according to the requirements of the EN 13923:2005 standard. The composite laminate and thermoplastic liner failures were predicted, considering the elasto-plastic behaviour of the HDPE liner and the laminae properties, respectively.

Finally, prototype pressure vessels were produced in the defined conditions to be submitted to pressure tests. The comparison between the FEM simulations and experimental results are discussed in the present paper.

1 Introduction

Polymer matrix composites are replacing materials traditional materials in the construction of pressure cylinders for many common applications. The use of polymer composites allows reducing weight, improving the aesthetic and increasing the pressure vessel mechanical, impact and corrosion behaviour [1].

These are relevant pressure vessel characteristics for many present and future large scale applications, such as, liquid filters and accumulators, hydrogen cell storage vessels, oxygen bottles, etc.

Multi-axial filament winding is the most promising processing technology to be used in the serial production of vessels able to withstand medium to high internal pressures [2, 3]. Such technology allows processing simultaneously the vessel cylinder and domes and use non-geodesic optimised fibre patterns in the composite laminate layers and permit withstand higher mechanical efforts.

The present paper covers the manufacture and simulation of pressure vessels made from fibre reinforced matrix composites.

The vessel consists in a thermoplastic liner wrapped with a filament winding glass fibre reinforced structure. 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 Experimental

2.1 Pressure Vessel Characteristics

Figure 1 depicts the HDPE liner used to produce the pressure vessels studied in this work. It has the capacity and internal diameter of 0.068 m^3 and 205 mm, respectively.

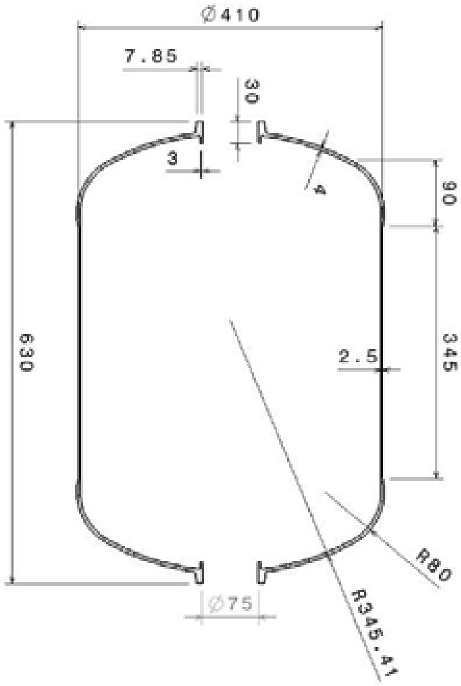

Figure 1. HDPE liner dimensions

The HDPE liners were produced by rotational moulding in the Portuguese company ROTOPORT. Figure 2 depicts one liner that was used for testing and evaluate their performance.

Fig. 2. Rotational moulding HDPE liner

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.

2.2 Raw Materials

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 structural wall 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 composites [4-7].

Table 1. Properties of the GF/UP laminae

Property	Unit	Data Sheet values	Calculated Values
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

A high density polyethylene, Rigidex® HD3840UR from INEOS, has been selected to produce the thermoplastic liner by rotational moulding. Table 2 shows the HDPE main mechanical properties determined experimentally and also those presented in the manufacturer data sheets.

Table 2. Properties of the HDPE liner

Property	Unit	Value
Tensile modulus	MPa	650
Yield stress[a]	MPa	13,8 ± 0,4
Yield strain[a]	%	14,4 ± 0,8
Elongation at break	%	> 1000
Density	g/cm^3	0,94

[a] experimentally by tensile tests determined according ISO 527

2.3 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 of the HDPE liner alone and after of the overall composite pressure vessel consisting in the 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. 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 and GF/UP laminate, 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 3 and 4 show the plies stacking sequence and the material orientation angles used in the cylindrical vessel zone FEM simulations.

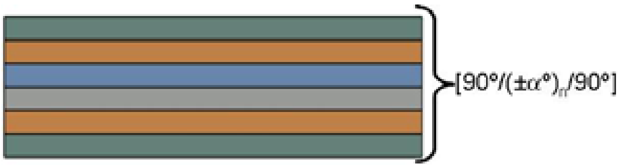

Figure 3. Plies stacking sequence

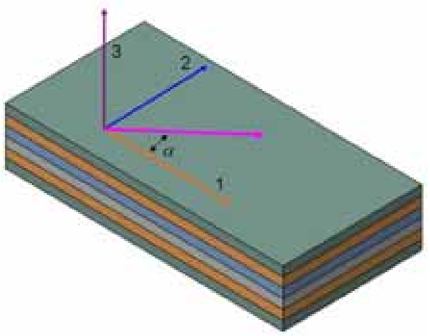

Figure 4. Material co-ordinate axis system

Simpson’s integration rule (three points though the 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. The elements were stabilized for spurious modes, enabling a correct discrete spatial description.

Figures 5 and 6 show the variation of the thickness in different zones along the vessel used in the FEM simulations The structural composite wall considered in this study was $[90°/(\pm 20°)_8/90°]$.

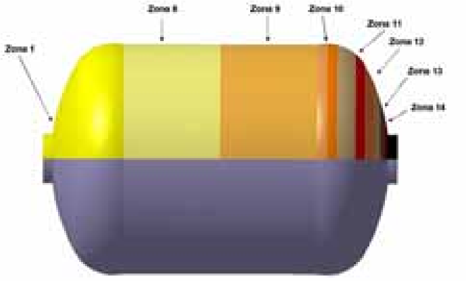

Figure 5. Composite vessel zones

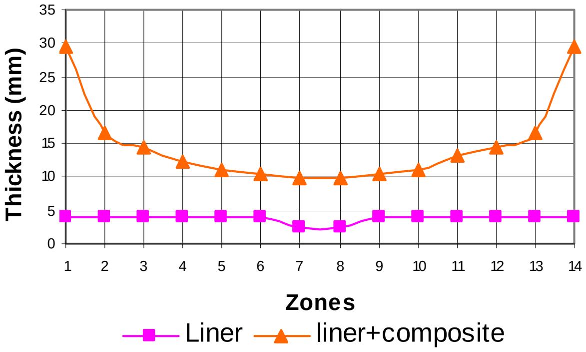

Figure 6. Thickness along the composite vessel

As it may be seen in the above Figures, the composite thickness varies along the vessel length reaching maximum values near the end-dome fittings due to the filament winding stacking process.

3. Results and Discussion

To predict the HDPE liner mechanical behaviour, it was submitted alone to a constant internal pressure increase in the elasto-plastic FEA model. The Von Mises stresses and strains fields obtained from the simulations conducted in the HDPE liner are shown in Figures 7 and 8

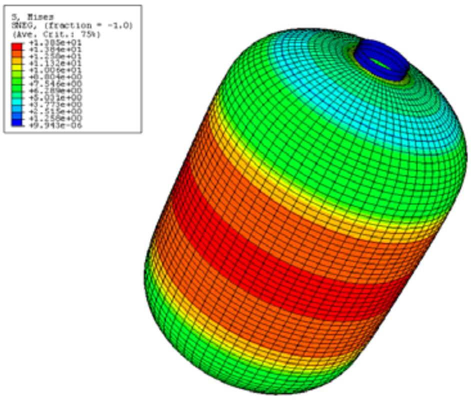

Figure 7. Von Mises field stresses in the HDPE liner at 1.8 bar

As it may be seen in Figure 7, the results determined allowed predicting that HDPE liner reaches the yield stress under an internal pressure around 1.8 bar.

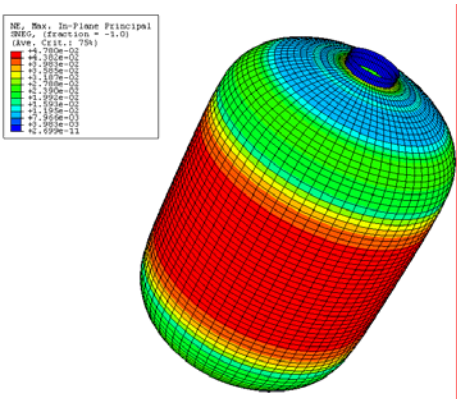

Figure 8. Strains obtained in the HDPE liner at 1.8 bar internal pressure

To validate the FEM simulations made, HDPE liners with four strain gauges conveniently bonded in their middle cylindrical body, oriented in both circumferential and longitudinal directions, were submitted to internal pressure tests (Figure 9). The measured strains and pressure values were recorded in a personal computer using a data acquisition system.

Figure 9. Instrumented HDPE liner

Figures 10 and 11 compare the experimental and FEM strain results obtained in longitudinal and circumferential directions of the liner.

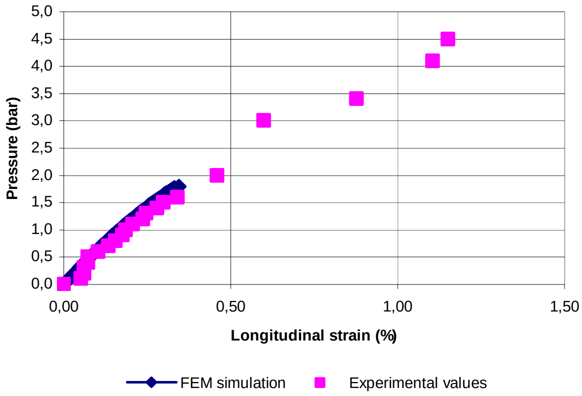

Figure 10. Comparison between longitudinal strains obtained in the pressure tests and FEM analysis

As can be seen in Figures 10 and 11 a very good correlation was obtained between the experimental and FEM simulation results.

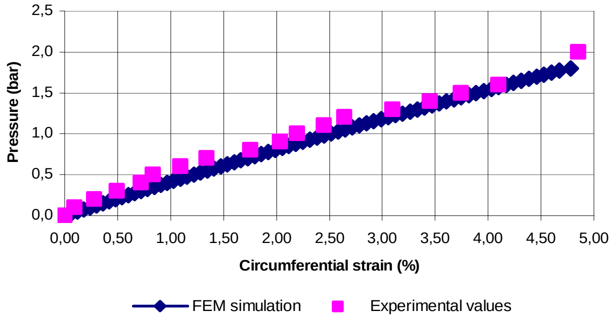

Figure 11. Comparison between circumferential strains obtained by pressure tests and FEM analysis

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 in the Abaqus 6.5 software package, respectively.

Figure 12 shows the Tsai-Wu field stresses obtained in the #12 composite layer, with fibres oriented at 20º, when the composite vessel was submitted to a 18.5 bar internal pressure.

As may be seen in Figure12, it was found that failure should occur in referred cross-ply internal layer at 18.5 bar. Thus, the selected GF/UP composite laminate was considered appropriate to manufacture composite vessels for withstand the 6 bar service pressure class according to EN 13923 standard.

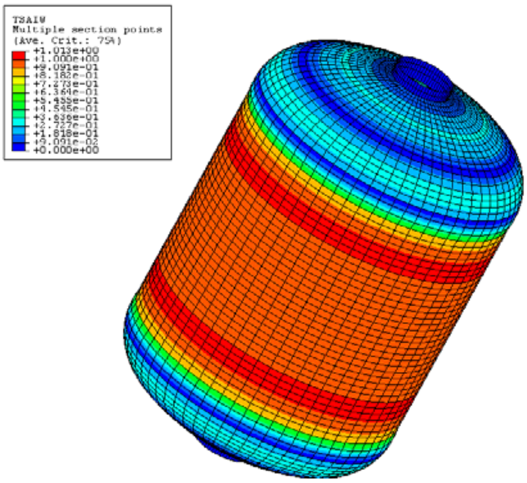

Figure 12. #12 composite layer Tsai-Wu field stresses at the internal pressure of 18.5 bar

From a deep analysis it was found that the high interlaminar shear stresses developed in the vessel structural composite layers were mainly responsible for the failure observed. Then, as previous works [9] have shown the FEM analysis using the Tsai-Wu failure criterion seems to give conservative estimations of composite vessels burst in these conditions, it is expected that subsequent pressure testing experiments to be made in prototype vessels demonstrate that they could enable to withstand higher service pressures.

4. Production of Vessel Prototypes

Composite vessel prototypes were produced using the HDPE liner and GF/UP laminate used in the FEM simulations in a 6-axes PULTREX filament winding machine. Figure13 and 14 show a typical stage of the prototype filament winding and one of the produced composite vessels, respectively.

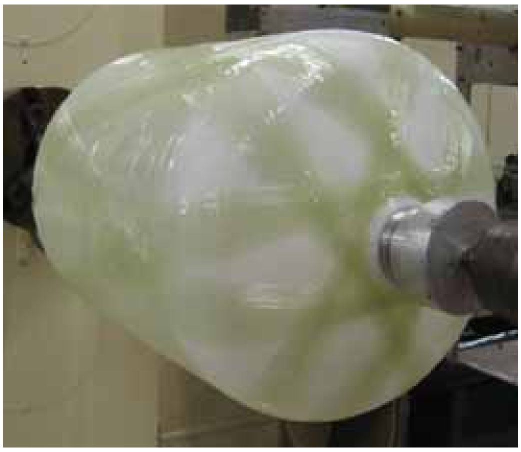

Figure 13 On-going prototype filament winding

Figure 14 Final composite prototype vessel

5. Conclusions

This work shows that the FEM analyses could be a powerful tool to optimise composite pressure vessels lay-up. The FEM simulations made allowed concluding that the HDPE liner could withstand an internal pressure around 1.8 bar.

A very good agreement was found between the experimental and elasto-plastic FEM simulation results of the HDPE liner mechanical behaviour under internal pressure. Worse agreements were found when elastic analyses were used in the FEM simulations.

From the FEM simulations it was also possible to define the laminate to be used in the production of pressure composite vessels able to withstand the minimum service pressure class of 6 bar according to the requirements of the EN 13923 standard.

Because the cross-ply laminate layers have shown to fail mainly due to high interlaminar shear stresses, it is expected that the prototype vessels should support higher burst pressures. In fact, previously works proven [9] that the interlaminar shear stresses are probably not main cause for overall failure of composite pressure vessels structural laminates.

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