COMPOSITE PRESSURE VESSELS FOR COMMERCIAL APPLICATIONS

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1 Introduction

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

For applications having higher service temperatures, such as, thermal accumulators and solar panel vessels, thermoplastics presenting greater temperature performance, for example, polypropylene (PP), polyamide (PA), polycarbonate (PC) Polyvinylidene difluoride (PVDF) or even thermosettings are being studied for application as vessel liners.

Traditional materials, such as, steel, are successfully being replaced by polymer matrix composites materials in the construction of pressure cylinders for many common applications. The use of polymer composites allows minimising the weight, improving the aesthetic and also increasing the pressure vessel mechanical, impact and corrosion behaviour [1]. 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, etc.

Multi-axial filament winding is the most adequate processing technology to produce composite vessels for medium to high internal pressures at serial industrial level [2, 3]. Such technology allows processing simultaneously the vessel cylinder and domes and use non-geodesic optimised fibre patterns in the composite laminate layers that permit withstand the higher mechanical efforts involved with lower vessel-wall thicknesses.

This work is part of a larger study concerning the development of a new generation of filament wound composite vessels to be applied on the storage of fluids under pressure. The present paper only covers an initial part of the work that concerns the manufacture and simulation of the behaviour of pressure vessels made from fibre reinforced thermosetting matrix composites.

A vessel consisting in a thermoplastic liner wrapped with a filament winding glass fibre reinforced thermosetting resin structure has been studied. The finite element analysis (FEM) was used to predict the pressure vessel mechanical behaviour according to the requirements of the EN 13923:2005 standard, namely, the minimum internal burst pressure.

The paper will present the design of a multi-axial filament winding prototype equipment that will be constructed for being used in the manufacture of the initial prototype vessels.

The paper will also present and discuss results obtained from internal pressure tests made in thermoplastic liners and will compare them with those ones obtained from the FEM simulations made.

2 Manufacturing the composite pressure vessels

2.1 Pressure vessel requirements

According to the market demands, three main groups of vessels with the following requirements were selected to be studied in this work:

i) Group I (expansion vessels and swimming pool filters):
- maximum pressure: 1 MPa
- maximum temperature: 40 ºC

ii) Group II (Electric water heaters and other thermal accumulators):
- ,maximum pressure: 1 MPa
- maximum temperature: 80 ° C

iii) Group III (expansion tanks using glycol as heat exchanger fluid):
- maximum pressure: 0.3 MPa
- maximum temperature: 130 ° C

Table 1 summarizes further requirements for the above mentioned pressure vessels.

2.2 Raw materials

As mentioned before, the pressure vessels will consist in an internal plastic liner (to be integral part of the final vessel) wrapped with a filament winding continuous glass fiber reinforced polymer matrix structure. Such vessels present as advantages over the existing ones much better price/performance ratio, mechanical strength and corrosion resistance.
Vessels from group I, which demand low service temperatures, require the use of cheap thermoplastic liners, such as, polyethylene (PE), and structural filament winding walls based on an orthophthalic polyester resin reinforced with continuous E type glass fibers.
The groups of pressure vessels requiring higher service temperature ranges must use liners made from much higher thermal performance polymers, such as, poly (vinylidene fluoride) (PVDF), polyamide (PA), polycarbonate (PC), polyacetal (POM) and/or thermosetting resins (isophthalic polyester / bisphenolic, vinyl ester).

2.3.1 Liners

To minimize costs, it was decided to start the study from group I vessels liners, requiring lower demanding service temperatures (room temperature). A liner made from cheap low density polyethylene (LDPE), ICORENE® 1613 from IcoPolymers, was produced by rotational molding to manufacture these vessels (Figures 1 and 2).
The following geometry/capacity was adopted for the initial vessels under study(Fig. 3):
- diameter: 400 mm (approx..)
- capacity: 0,07 m^3 (approxim.)
- vessels dished end geometry: torispherical decimal

It were already produced liners for the more demanding pressure vessels of group III in poly vinylidene fluoride (PVDF) manufactured by rotational molding and in glass reinforced isophthalic thermosetting polyester resin (Fig. 4) processed by hand-lay-up and vacuum infusion.
For pressure vessels of group II one aims to use a polypropylene (PP) liner processed by rotational or blow molding according to the required production rate.
Fig.5 shows the initial stainless steel fittings designed to be embedded by polymer in the vessel dished ends during rotational molding. As leaks were detected through the larger dished end fitting in the firsts hydraulic pressure tests made it was decided to redraw it. Thus, in order to obtain good sealing this larger fitting was made in two parts able to be fastening tight into each other with a sealant (see Fig. 6).

2.3.2 Filament winding structural wall

Glass fiber reinforced thermosetting polyester or thermoplastic matrices layers were selected to be used in the structural wall for all types of vessels.

2.3 Processing equipment

Figure 7 shows a schematic drawing of 6-axis filament winding equipment that was designed to manufacture initial prototype composite pressure vessels. The following major geometric specifications were considered for the equipment: 1500 mm of maximum vessel diameter, 3000 mm of maximum vessel length, longitudinal, transversal and vertical head courses of 3020 mm, 610 mm and 1135 mm, respectively, 300º as maximum rotational angle of head vertical axis and 800 mm as maximum height of the mandrel rotational axis.
Concerning to the filament winding equipment speeds the following major specifications were considered: 0-200 rpm of mandrel rotational speed, 0-1 m/s, 0-0.6 m/s and 0-0.3 m/s as longitudinal, transversal and vertical head speeds and, 0-110 rpm as rotational speed of the vertical and horizontal head axes. Finally, it was considered the possibility of using 15-20 fiber reinforcing strands simultaneously and the use of fiber strand bandwidth of 80 mm.

The CADWIND software from Material Company [4] was used to simulate the strand fiber path during the vessel filament winding, using different desired angles. Figure 8 shows simulations of the fiber strand trajectory paths for winding angles of 29 º and 89º, respectively.
An assembly comprising a robot Motoman HP-20 and a rotational drive axle was used to assess the feasibility of the previously defined trajectories (Figures 9 and 10). Such trajectories have been validated by the obtained results.

3 Testing

Samples from points 1 to 4 represented in Fig. 3 were cut from the LDPE and PVDF produced liners were submitted to tensile testing according to ISO 527 standard in a 50 kN Shimadzu universal testing machine at the crosshead speed of 5 mm/min.
Table 2 summarizes the obtained results. As expected the PVDF presented higher mechanical properties (strength an modulus) than the LDPE. Results also showed that LDPE exhibited a much more ductile behavior than PVDF.
LDPE liners were submitted to hydraulic pressure tests at six different pressure levels: 0.154, 0.209, 0.260, 0.304, 0.358 and 0.499 (MPa). Six strain gauges, three able to measure strains in the circumferential and the remaining ones in longitudinal directions, were bonded to the LDPE liner (Fig. 11) in the zones 1, 2 and 4 shown in Fig. 3.
Table 3 shows the experimental results obtained and also numerical ones obtained by FEM analysis. The ABAQUS® software was used in the FEM simulations by considering the linear elastic material approach, the LDPE properties shown in Table 2, a Poisson's ratio of 0.37 and the dimensions depicted in Fig. 3.
As may be seen from results shown in Table 3 substantial differences were obtained between experimental and FEM results probably due to the non-application of an elasto-plastic material model in the numerical simulations as it was demonstrated by previous studies [5].

4 Conclusions

In this work, concerning the development of glass fiber reinforced pressure vessels for large scale market usages, were defined the requirements for different types of applications. Accordingly to the defined requirements different raw-materials and processing technologies were selected to produce the composite pressure vessels.
A customized filament winding equipment is being developed by using computer simulations and robotic experiments and tests.
Liners made of LDPE, PVDF and glass fiber reinforced unsaturated polyester resin were already produced by rotational molding and hand-lay-up and vacuum infusion technologies.
Relevant mechanical properties were already experimentally determined on liner materials.
Furthermore, LDPE liners were submitted to hydraulic pressure tests and the obtained experimental strain results compared with FEM predictions using a linear elastic material model. The differences found between experimental and numerical data suggest the need of using an elasto-plastic material model in FEM analysis.

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Tables

Table 1. Pressure vessels requirements

Vessel Group	**Capacity** (m^3)	**Diameter** (mm)	**Length** (mm)	**Maximum Pressure** (MPa)	**Maximum Temperature** (ºC)
I	0,02-1,5	250-1000	350-2100	0,6/1,0	40
II	0,015-1,5	300-1000	300-2100	1,0	80
III	0,005-0,08	200-400	250-700	0,3	130

Table 2. Tensile properties obtained on the LDPE and PVDF

Material	**Tensile Strength** (MPa)	**Tensile Modulus**[b] (MPa)	**Strain at break** (%)
LDPE	19.6 ± 0.5 [a]	489 ± 36	285 ± 92
PVDF	32.3 ± 2.0	707 ± 56	12.3 ± 0.8

[a] Yield Strength
[b] Modulus at 0.25%

Table 3. Experimental and numerical pressure tests results on the LDPE liner

Zone		**Type of results**	**Pressure (MPa)**					
			0.154	0.209	0.260	0.304	0.358	0.499
Strain(%)	Circumferential zone 1	Experimental	0,007	0,020	0,035	0,051	0,076	0,171
		FEM	0,060	0,149	0,232	0,304	0,392	0,621
	Longitudinal zone 1	Experimental	0,114	0,289	0,461	0,631	0,846	1,463
		FEM	0,110	0,274	0,427	0,559	0,720	1,141
	Circumferential zone 2	Experimental	0,073	0,199	0,345	0,513	0,753	1,770
		FEM	0,295	0,734	1,141	1,494	1,925	3,052
	Longitudinal zone 2	Experimental	0,019	0,031	0,038	0,040	0,043	0,084
		FEM	0,048	0,120	0,187	0,245	0,316	0,501
	Circumferential zone 4	Experimental	0,020	0,049	0,079	0,116	0,163	0,376
		FEM	0,031	0,077	0,120	0,157	0,202	0,320
	Longitudinal zone 4	Experimental	0,104	0,257	0,412	0,549	0,711	1,145
		FEM	0,078	0,195	0,303	0,397	0,511	0,810

Figures

Figure 1. LDPE liner

a) Rotational mold b) opened mold

Figure 2. Rotational molding of the thermoplastic liner

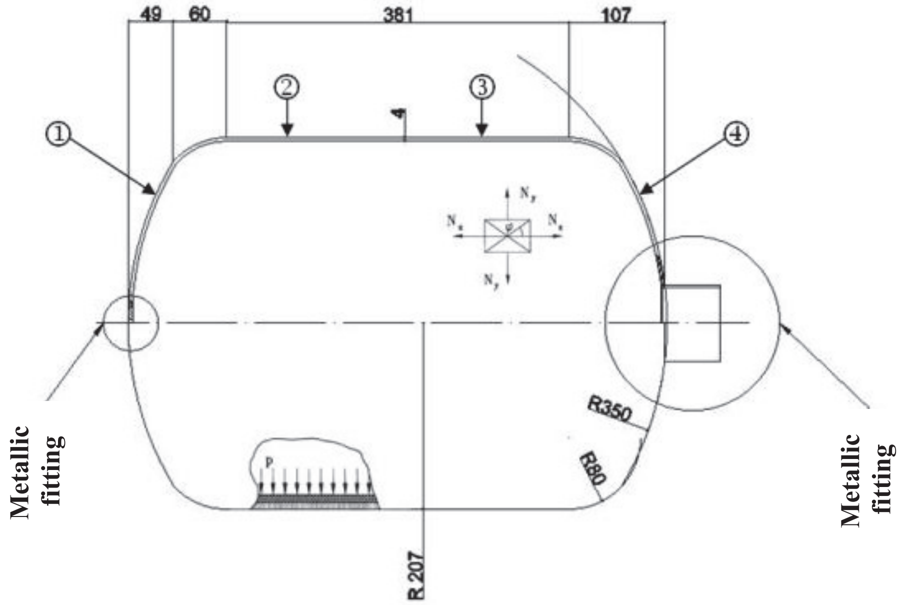
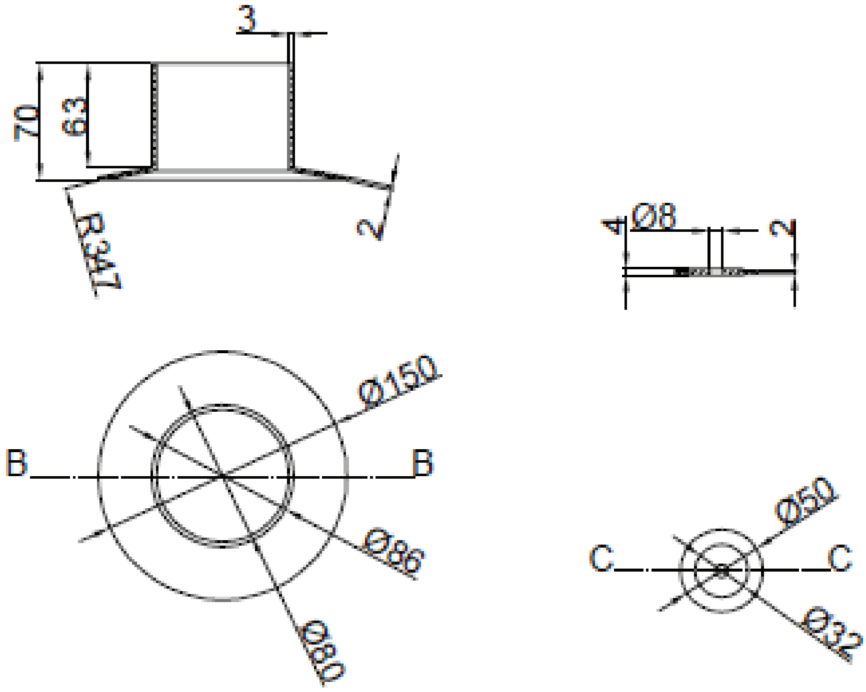


Figure 3. LDPE liner geometry

Figure 4. LDPE liner geometry



a) larger dished end fitting b) smaller dished end fitting

Figure 5. Initial stainless steel fittings

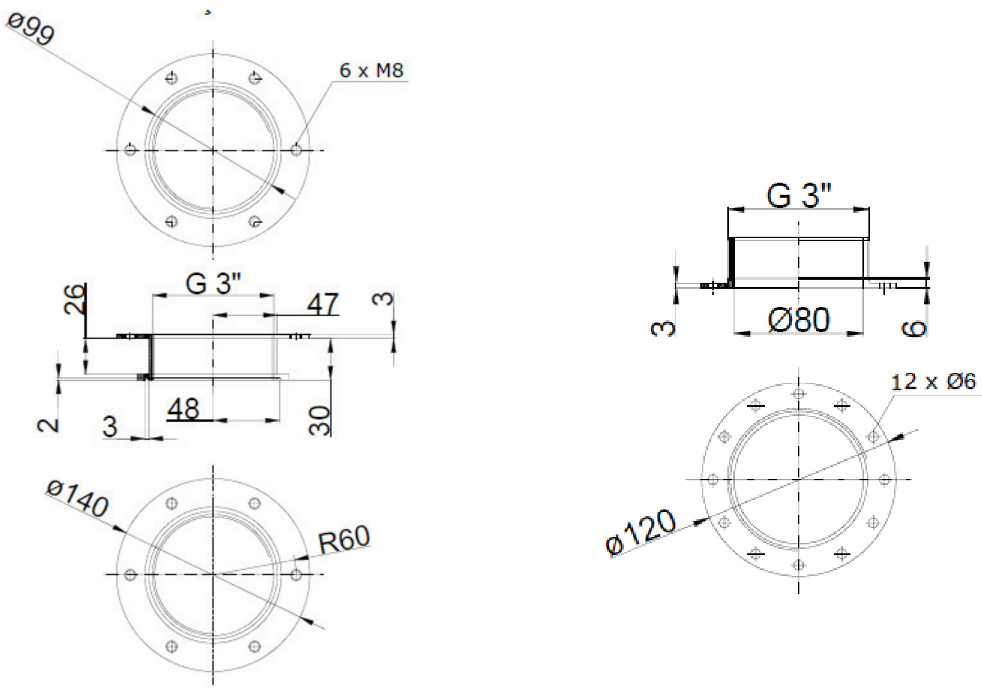


Figure 6. Final larger fitting adopted

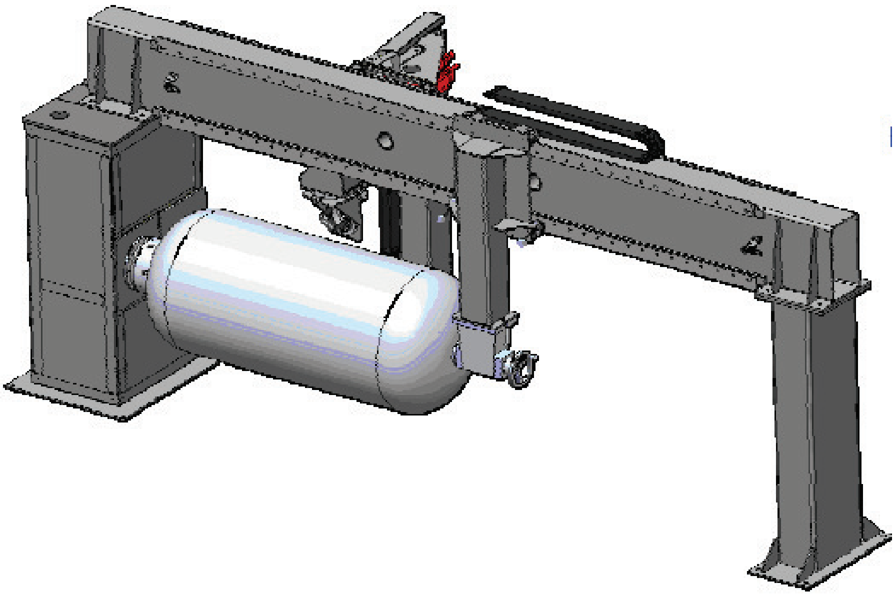
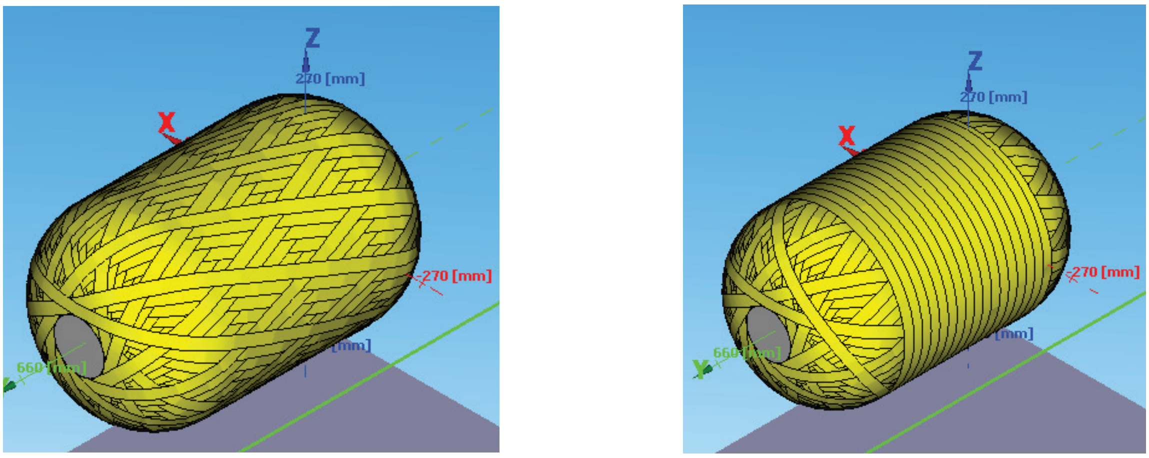


Figure 7. Schematic drawing of the designed multi-axial filament winding equipment



a) 29º angle b) 89º angle

Fig. 8. Simulation of trajectory fiber paths for different filament winding angles

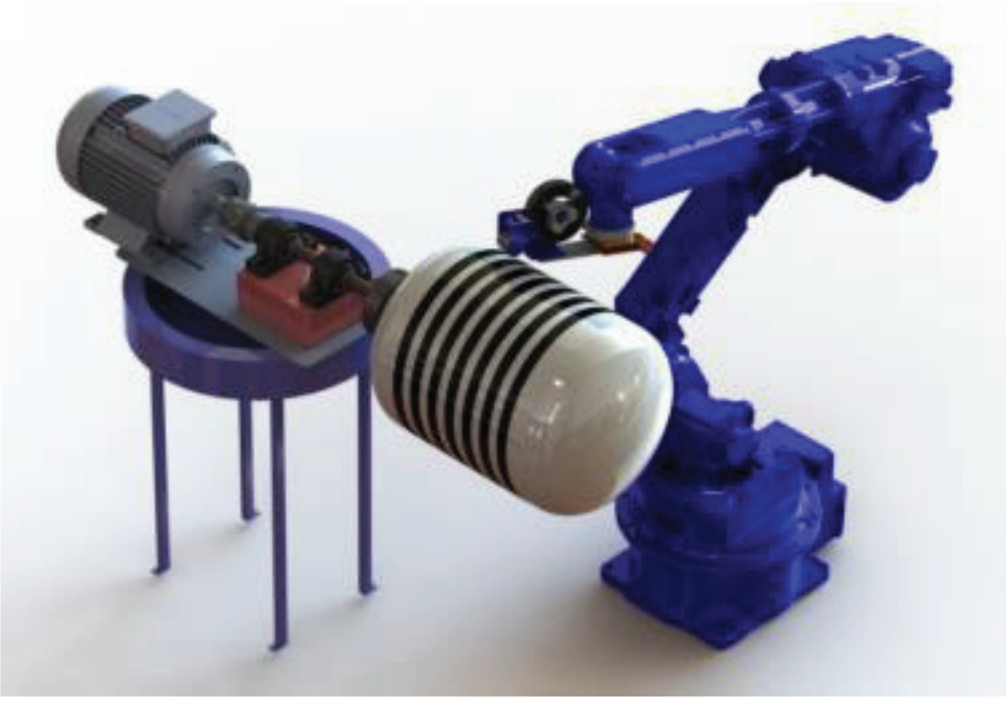


Figure 9.Schematic robotic assembly

Figure 10.Used robotic assembly

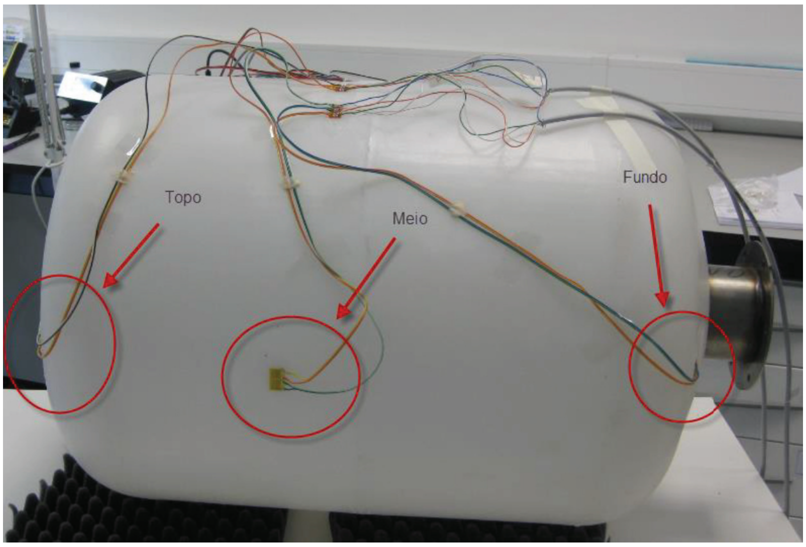


Figure 11. Strain gauges bonded to the LDPE liner.