TOWPREG-BASED DESIGN AND MANUFACTURE OF MULTI-SUPPLY FILAMENT-WOUND COMPOSITE PRESSURE VESSELS

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ABSTRACT

Hydrogen-powered vehicles enable an emission-free mobility. One of the main hindrances to a wide spread application of these systems, is the component costs, e.g. the hydrogen storage. In order to facilitate a broad deployment of hydrogen vehicles, emerging high-productive manufacturing technologies are preferred. In this paper, the design and manufacture of composite pressure vessels (CPV) based on pre-impregnated fibers, so-called towpregs, is investigated. For the manufacturing, the novel multi-supply filament winding (MFW) technology is used. MFW allows the processing of up to 48 towpregs simultaneously and is especially suited for towpregs. Initially, the influence of the winding parameters on the mechanical properties are analyzed. Suitable process parameters are selected for the calculation of the laminate layout through finite element analysis and as machine input parameters. After consolidation, the manufactured vessel is subjected to internal pressure to ascertain the failure pressure and failure mechanism. Samples of the dome and cylindrical part are analyzed via computer-tomography to determine the void content of the laminate. In summary, a novel and an effective manufacturing process for CPV is illustrated with emphasis on its process parameters for an industrial implementation. Further, a sufficient laminate layup for the processing of towpregs is developed.

Keywords: Composite Pressure Vessel, Towpreg, Multi-Supply Filament-Winding
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1. INTRODUCTION

1.1 Applications and markets

Emission-free mobility concepts are the key drivers in todays' automotive industry. Hydrogen fuel cell-powered vehicles enable a promising alternative in contrast to electrical vehicles due to their extended ranges and reduced refueling times. The hydrogen in fuel cell electrical vehicles (FCEV) is stored in composite pressure vessels (CPV). Due to the available assembly space, in passenger cars the storage is required at 700 bars, while CPV in long haul trucks are operated at 350 bars [1]. In hydrogen-powered passenger cars the CPV store around 5.6 kg hydrogen, which allows ranges above 500 km [2]. The annual sales volume for such cars in Europe is estimated to be up to 750,000 by 2030 [2]. Fuel cell trucks are very attractive, since they cover ranges of 1,000 km and the refueling time is kept below 10 minutes [2]. For the year 2030, the annual sales in Europe are forecasted to 10,000 [2]. Besides passenger cars, fuel cell trucks and busses, hydrogen fuel cell technology is emerging in other mobility markets as well. By 2030, the deployment of about 570 fuel cell trains in Europe is estimated [3]. In addition, hydrogen-powered ferries and civil aviation are also part of current research projects. Since the hydrogen storage in CPV covers around 15.2 %

of the total system costs, cost-effective and high-productive manufacturing processes become important for an industrial scale-up [4].

1.2 Composite Pressure Vessels

Pressure vessels are divided into five types. Full-metal pressure vessels are referred to as type I. In case of a composite reinforcement in hoop direction, the vessel is stated as type II. For mobile hydrogen storage the types III, IV and V are used. Type-III-vessels describe a load-sharing metal liner of steel or aluminum, which is reinforced by a composite in helical and hoop direction. These tanks are typically operated at 350 bars. For pressures up to 700 bars and an increased gravimetric density, type-IV-vessels are the common state of the art (Figure 1).

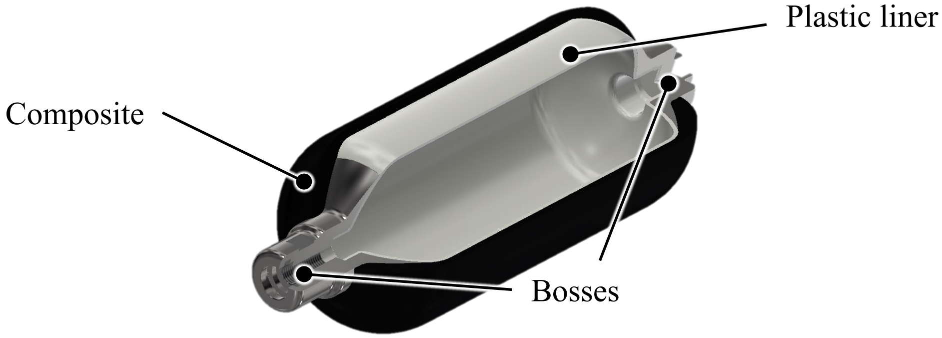

Figure 1. Illustration of a type IV composite pressure vessel.

Type-IV-vessels consist of an inner non-metallic liner, e.g. high-density polyethylene (HDPE) or polyamide (PA), which serves as an inner barrier for the stored fluid and as a mandrel during the manufacturing process. Due to the high stiffness of the composite, the liner is considered to be non-loadbearing. The domes include metallic components, so-called bosses, which allow the connection to a high-pressure system and the fixation during the manufacturing process. Liner and bosses are reinforced by a carbon fiber/epoxy composite in hoop and helical direction. The only difference to type-V-vessel is the complete absence of the liner. [5]

Oftentimes, the gravimetric storage density is used as a performance indicator for CPV. The gravimetric storage density describes the ratio between the amount of stored hydrogen per kilogram tank. While current CPV designs for industrial applications achieve gravimetric storage densities of 4.5 %, the ultimate target is at 6.5 % [6].

1.3 Manufacturing of Composite Pressure Vessels

The most common manufacturing method for CPV is the filament-winding process. This process allows the processing of either dry rovings, which are impregnated in a resin bath during manufacturing, or pre-impregnated rovings. In case of wet filament-winding, the bobbins are charged into a creel and guided through a resin bath towards the winding head. Afterwards, multiple rovings are combined to a band. By means of inducing a relative traverse movement between winding head and the rotating liner, the band is wound in a desired winding pattern. For the processing of pre-impregnated rovings, so-called towpregs, no further impregnation in the resin bath is necessary. As the fiber tension and fiber orientation induce an external pressure on the surface of the liner, the liners are typically pressurized during the winding process.

Another alternative winding process is the multi-supply filament winding (MFW). In contrast to filament-winding, up to 48 rovings can be processed simultaneously. Therefore, the rovings are supplied in an equal distribution in hoop direction around the liner. Due to the large number of rovings, less winding cycles are required for the deployment of a complete layer. MFW is especially suited for towpregs and the deployment of unidirectional layers is possible. The MFW process is displayed in the following Figure *2*.

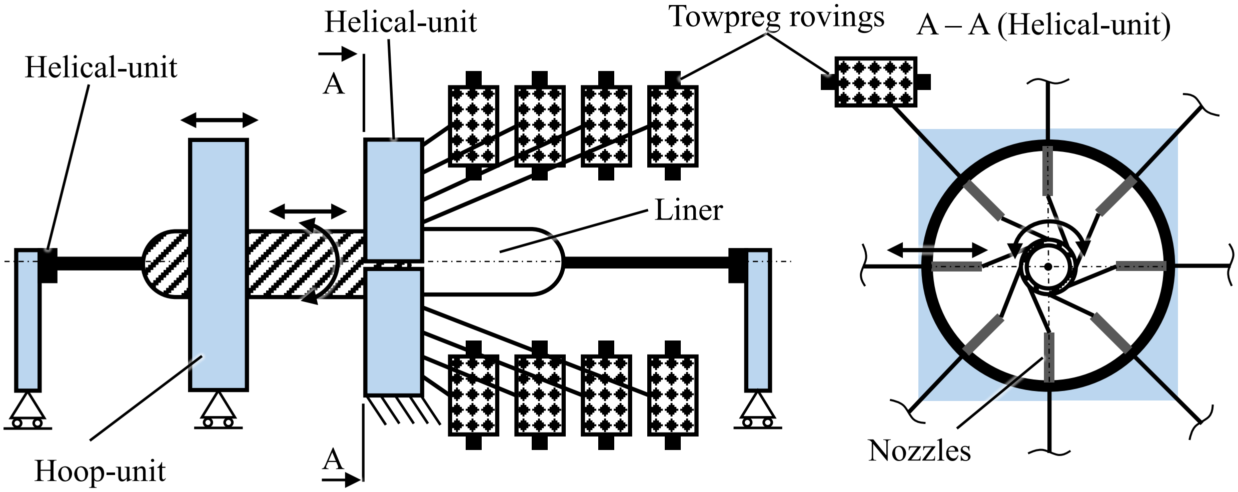

Figure 2. Illustration of the multi-supply filament-winding process.

After winding, the curing is conducted in an oven or autoclave at elevated temperatures for both, the wet-wound and towpreg-wound CPV. Based on experiments and expert interviews of the involved industry partners, the following Table 1 lists the main characteristics of both winding processes and the processed materials.

Table 1. Comparison between wet filament-winding and multi-supply filament-winding of towpregs based on expert interviews.

Parameter	**Wet filament-winding**	**Multi-supply filament-winding of towpregs**
Impregnation with resin	By resin bath during winding process	Prior to winding process
Winding speed	Up to 2 m/s	Up to 5 m/s
Band width	Band width approx. 10 % of winding core diameter	Up to 48 rovings with a width of 5 mm each
Material costs	18 USD per kg composite	37 USD per kg composite
Cleaning effort	Once per day	Once every few days

2. DESIGN AND MANUFACTURING

2.1 Assembly

In the following Figure 3, the assembly of liner and boss components is illustrated.

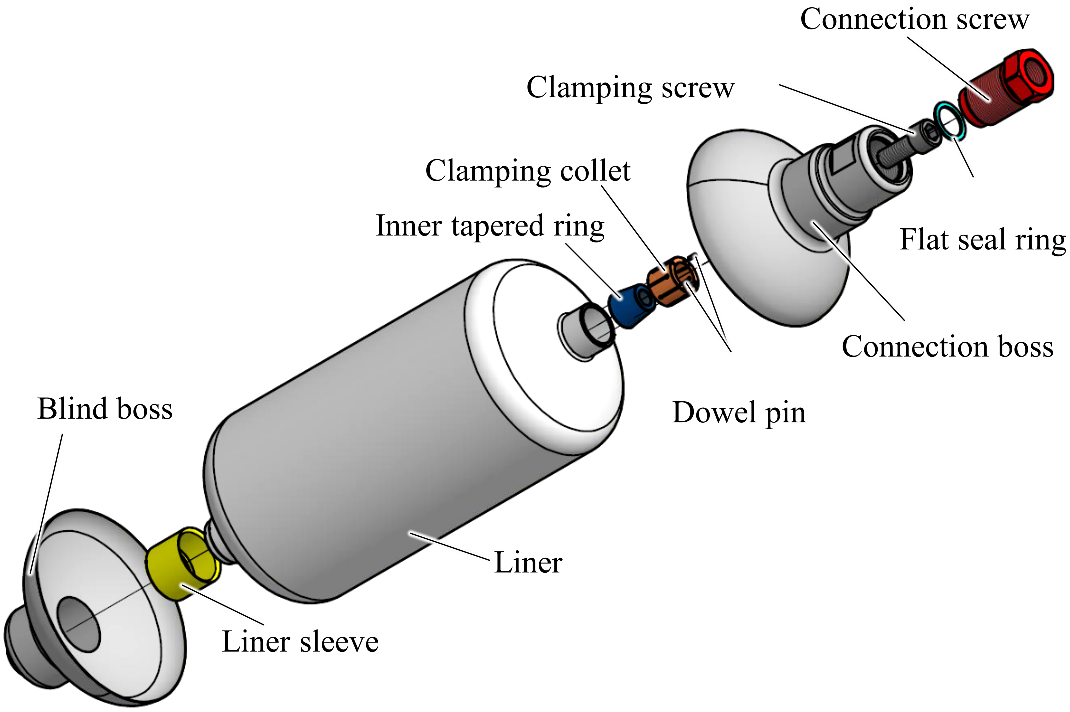

Figure 3. Exploded view of liner and boss assembly.

In this paper, a liner with an outer diameter of 130 mm is used. The liner consists of high-density polyethylene (HDPE) and provides a storage capacity of three liters. On the closed liner dome ending, the blind boss and liner sleeve are glued. For the connecting liner side, a sealing mechanism between boss and liner is used for the assembly. Therefore, a combination of a clamping collet, an inner tapered ring and a clamping screw induce a sealing and fixating pressure at the liners' bottle neck. In addition, a connecting screw is used for pressurization and sealed by a flat ring. In order to prevent a failure of the boss components in the following burst tests, a conservative material choice is made. All components consist of hardened steel (42CrMo4) despite the clamping collet, which is made of aluminum alloy 7075 T6, and result in an overall weight of 3,690 grams.

2.2 Composite Layup Design

Finite element solver Abaqus® from Dassault Systemes was used for the numerical analysis of the pressure vessel. The model of the pressure vessel was simplified for the analysis as shown in the Figure 4. Since the pressure vessel is rotationally-symmetric, an axisymmetric model was used for the analysis. Shell elements, CAX4R was used for liner and boss (with reduced integration) and CAX4 for the composite overlap. The winding angle increment on the dome was calculated using Clairaut relation [7]. The material properties and the laminate layout used for the analysis is provided in the Table 2 and Table 3 respectively.

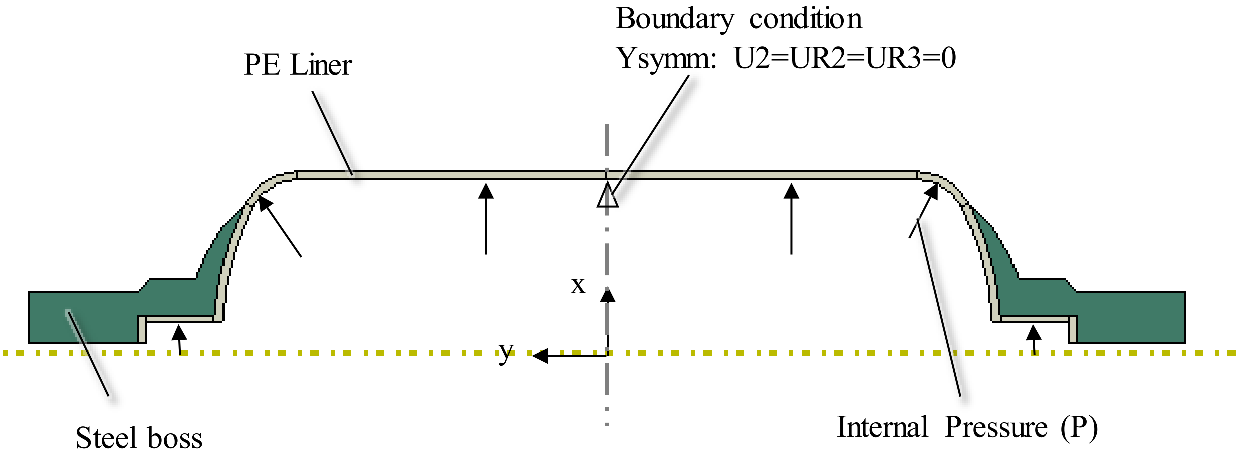

Figure 4: Boundary and loading conditions

Table 2. Mechanical properties of composite, liner and boss materials.

Symbol	**Parameter**	**Value**	**Unit**
Composite			
E_{11}	Young's Modulus in direction 1	125,588	N/mm²
E_{22}	Young's Modulus in direction 2	7,700	N/mm²
E_{33}	Young's Modulus in direction 3	7,700	N/mm²
G_{12}	Shear Modulus in-plane 1-2	5,600	N/mm²
G_{13}	Shear Modulus in-plane 1-3	3,700	N/mm²
G_{23}	Shear Modulus in-plane 2-3	3,700	N/mm²
υ_{12}	Poisson's ratio 1-2	0.30	-
υ_{13}	Poisson's ratio 1-3	0.21	-
υ_{23}	Poisson's ratio 2-3	0.21	-
$\sigma^{\perp}_{-}$	Tensile strength 90°	72	N/mm²
$\sigma^{\parallel}_{-}$	Tensile strength 0°	1,819	N/mm²
$\sigma^{\perp}_{+}$	Compression strength 90°	152	N/mm²
$\sigma^{\parallel}_{+}$	Compression strength 0°	1,150	N/mm²
τ_{12}^{m}	Maximum in-plane shear strength	90	N/mm²
T_{23}^{m}	Maximum out-of-plane shear strength	70	N/mm²
Liner			
E_{Liner}	Young's Modulus in all directions	1,500	N/mm²
υ_{Liner}	Poisson's ratio in all directions	0.43	N/mm²
Boss			
E_{Boss}	Young's Modulus in all directions	210,000	N/mm²
υ_{Boss}	Poisson's ratio in all directions	0.3	-
Directions: In fiber direction (1), perpendicular to fiber and inside layer (2), perpendicular to fiber and out of layer (3)			

Table 3. Composite lay-up for CPV simulation and manufacturing.

Layer	Orientation	Thickness
1	± 89°	1.0 mm
2	± 16°	1.5 mm
3	± 89°	1.0 mm
4	± 16°	1.5 mm
5	± 89°	1.0 mm
6	± 16°	1.5 mm
7	± 89°	2.0 mm
Total Thickness:		9.5 mm

2.3 Multi-Supply Filament-Winding

For the tank manufacturing the multi-supply filament-winding (MFW) machine MFW48-1200 by Murata Machinery, Ltd., Kyoto, Japan is used. Therefore, a total number of six towpreg rovings are processed at an ambient temperature of 20 °C. The towpreg rovings K-Preg 002-002-70-50 are provided by F.A. Kümpers GmbH & Co. KG, Rheine, Germany and consist of 1600 tex T700 carbon fibers and 70 weight percent of epoxy resin. All rovings have a width of 5 mm and are threaded into the MFW machine. Due to the tack and several guiding rolls, each roving provides a tension of 10 N. Two identical CPV are wound according to the mentioned composite layup. The helical layers are fully deployed after a number of 20 winding cycles, which results in a cross-wound pattern (Figure 5). By means of increasing the number of simultaneously processed rovings, the number of cycles can be reduced drastically. For instance, the maximum number of 48 rovings results in six cycles for the same orientation of the helical layers. For the hoop layers, one roving and one winding cycle are used only.

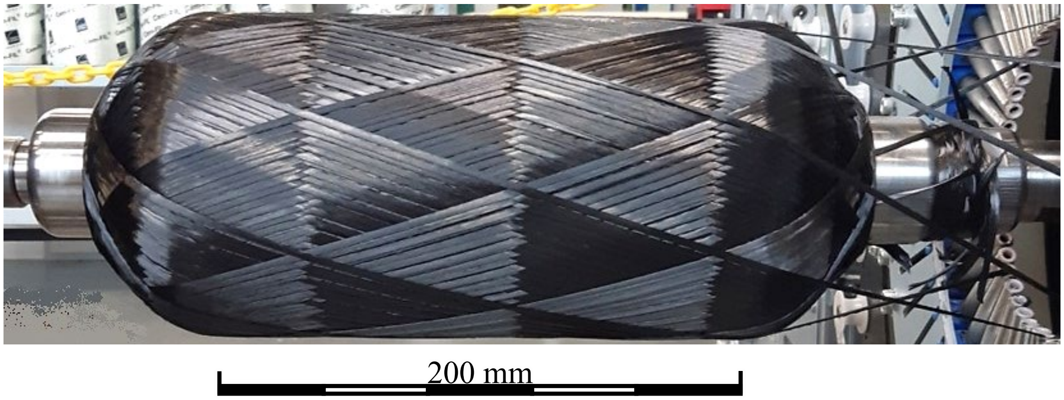

Figure 5. Helical winding pattern induced by multi-supply filament-winding of six rovings.

After winding the composite layup, a compaction tape is wound in hoop direction of the cylindrical part of the CPV with a tension of 20 N. Both CPV are consolidated with an internal pressure of 2.5 bars in order to stabilize during the consolidation process. The consolidation is carried out in an autoclave at an ambient pressure of 1 bar according to the following Figure 6. The cured CPV weigh 5,520 grams.

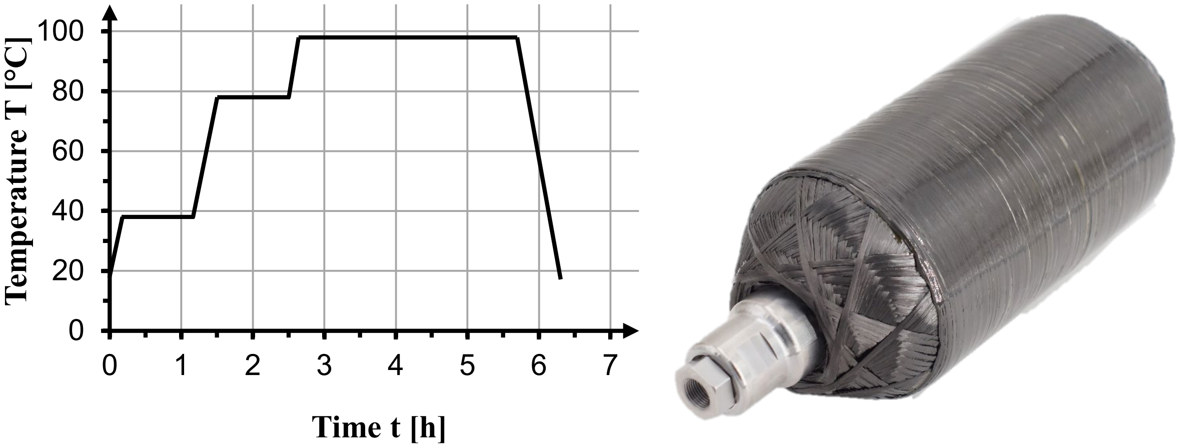

Figure 6. Curing cycle of MFW-tanks (left) and cured CPV (right).

3. RESULTS

In order to evaluate the CPV design and draw conclusions for the further development, the tanks are subjected to burst testing, failure analysis and computer tomography (CT). The two CPV weigh 5,520 grams each and have a laminate thickness of 9.5 mm in the cylindrical part.

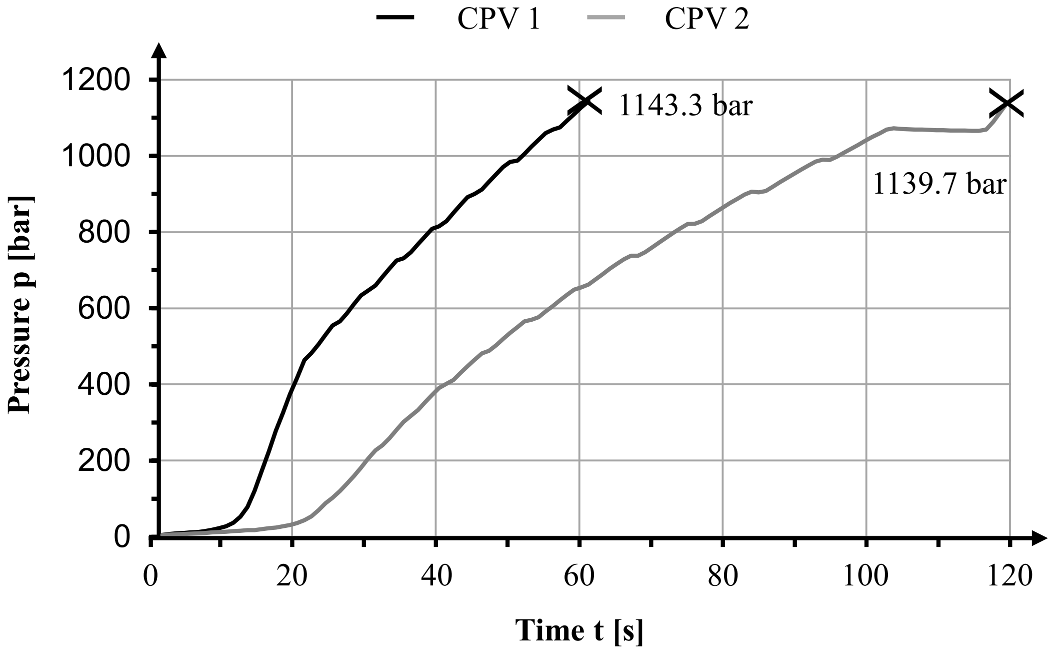

Figure 7. Burst testing curves of both tested CPV.

During burst testing, the achieved mean burst pressure of the two CPV is determined to 1,141.5 bars and can be obtained from the following Figure 7. Due to the low capacity of three liters per tank, the burst pressure of CPV 1 is achieved within 60 seconds only. Hence, the pressurization of CPV 2 is reduced for an extended testing time.

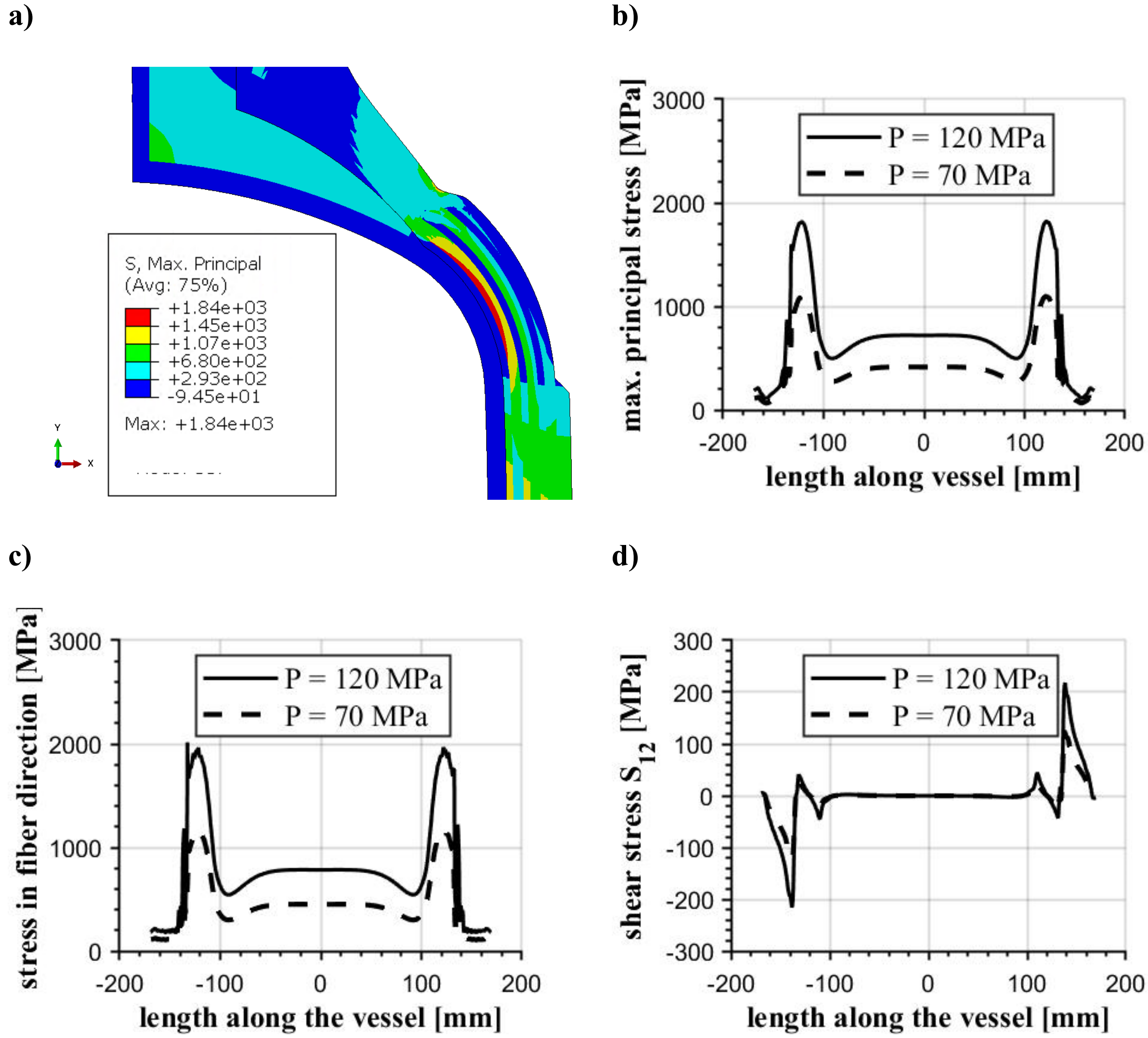

Figure 8. Stress distribution in the composite layer. Helical layer, layer 3, was considered. a) Contour plot of the maximum principal stress at the dome region, at P = 120 MPa. Max. stress is observed at the vicinity of the interface due to the secondary stress; b) Max. principal stress distribution along the length of the pressure vessel; c) Stress in the fiber direction in the layer 3. d) Shear stress distribution in the layer 3.

Analysis of the pressure vessel was conducted at two different pressures, 70 and 120 MPa. The results are presented in the Figure 8. The curves are for the layer 3 with 16° (see Table *3*). In this analysis, first ply failure is considered to be the failure in the pressure vessel, after the onset of failure, in conditions that the pressure is not reduced, it mostly results in a catastrophic failure. While even at 120 MPa the maximum principal stress is still within the experimentally determined laminate strength in fiber direction (1,819 MPa), a closer look at the stresses in the fiber direction shows that the laminate has already failed, since the stresses are over the laminate strength. A simple calculation of the pressure at failure gives 111.08 MPa (1,110.8 bar), which is very close to the experimental value.

Figure 8 shows a considerable shear and bending stress at the vicinity of the dome and the cylinder interface. One of the reason for this is the design of the liner and the boss, which results in a drastic change in the radius of curvature, which induces the bending moment. In addition, the hoop and helical winding results in a huge change (a variation of ca. 40 %) in the thickness at this junction, which results in the seen shear stresses.

The present failure mechanism of both tanks is identical. In both cases, the combination of radial elongation and stress concentration in the transition zone between dome and cylinder leads to a shearing of the liner along the boss edge. As a result, the connection boss is teared off the CPV (Figure 9).

Figure 9. Damaged CPV after burst testing (left) and sheared liner (right).

The void content of the CPV is determined via CT scanning of the structure. Therefore, samples of 10 x 10 mm are cut out of the laminate from various positions and subjected to CT scanning. This method allows the determination of void contents in cylinder and dome region through laminate thickness. As illustrated in Figure 10, the mean void content in the cylindrical portion of the CPV is around 5.3 %. Depending on the exact longitudinal position, the dome region features void contents up to 14.4 %.

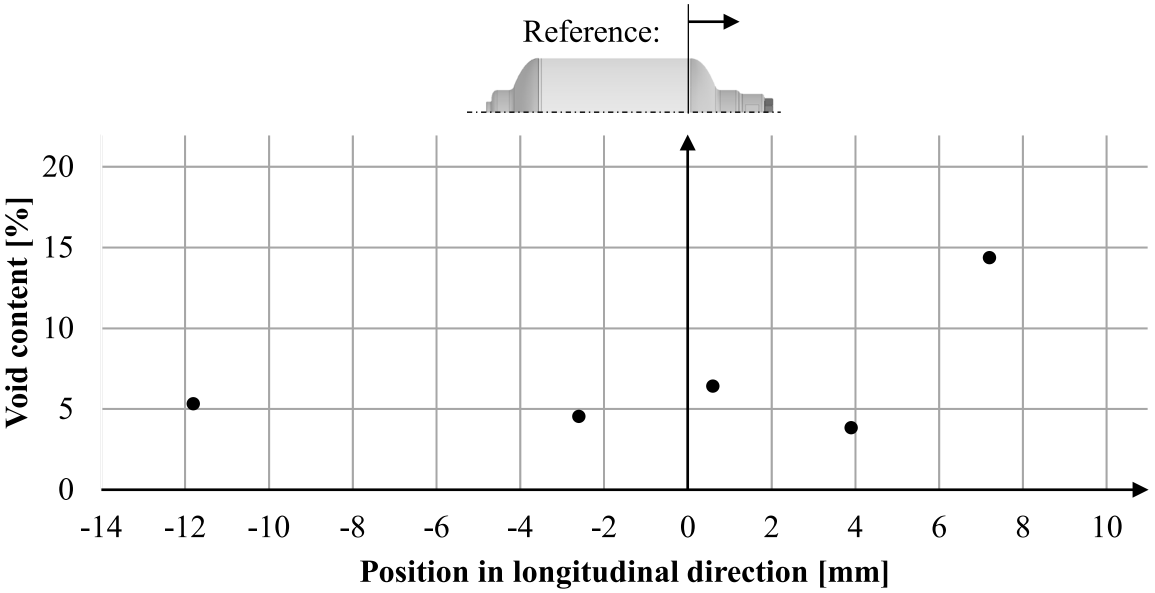

Figure 10. Mean void content of the CPV in longitudinal direction.

A closer analysis of the stress on the liner gives a better understanding of the failure mechanism, as seen in the Figure 9. Figure 11 shows the shear stress distribution (S_{12}) in the liner (note that the x-limit is at the boss ending). The polyethylene liner has a shear strength of 33.1 MPa at (at room temperature). One of the reasons for the failure of the tank is the contribution of this high shear stress at the interface. This is also observed in the experimental results.

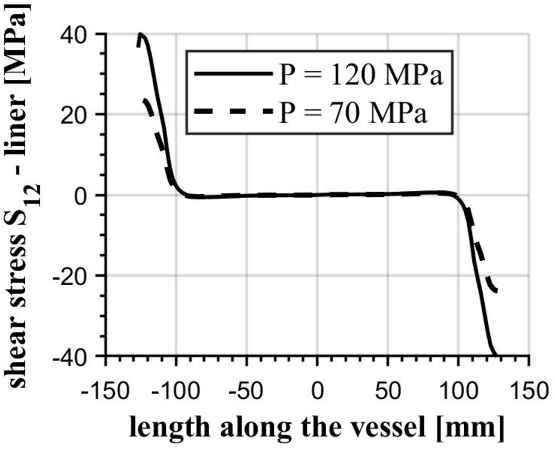

Figure 11: Shear stress distribution in the liner. In this case, the extreme points are the boss and the liner interface.

Finally, by applying a safety factor of 2.25 on the mean burst pressure, a fictional operating pressure of 508 bars can be derived. This fictional operating pressure is used to determine the gravimetric density of the CPV to 2.26 % kg hydrogen per kg CPV.

4. CONCLUSIONS

This paper illustrates the feasibility of an alternative manufacturing approach. Therefore, MFW and the processing of towpregs are combined to successfully demonstrate this approach. In conclusion, the developed CPV achieve a satisfactory burst test performance and the simulation yields to realistic results. These results will be used for future CPV designs. In order to decrease the total weight, the boss components can be significantly reduced in size. In addition, aluminum alloys can be selected for the bosses as well. By means of winding 48 rovings simultaneously, the winding time and the thickening of the dome region can be reduced. The overall performance can be enhanced by a more sophisticated laminate architecture and a reduced void content. For the void reduction, elevated roving tensions can be adjusted.

5. ACKNOWLEDGEMENTS

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