Pioneering a novel approach for H_2 tank production

Whitepaper

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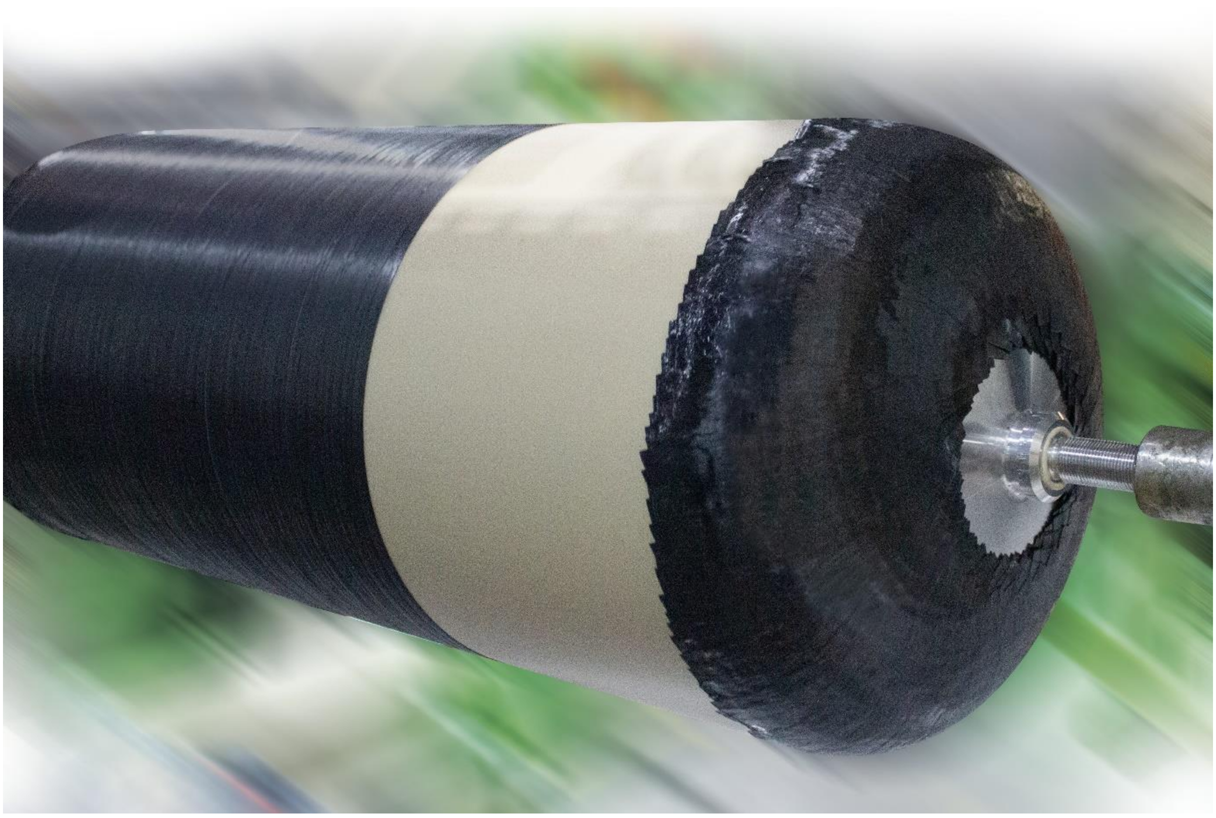

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Abstract

Cevotec, in collaboration with a tank manufacturer, winding equipment provider Roth Composite Machinery, and composite engineering service provider CIKONI, has undertaken a comprehensive project to explore and demonstrate the impact of dome reinforcements utilizing Fiber Patch Placement (FPP) technology for composite tanks. FPP allows for the direct placement of dome reinforcements onto the liner through an automated industrial process, significantly reducing overall carbon fiber consumption of the finished product This results in substantial weight and cost savings while maintaining the same mechanical properties.

The partnership aimed to optimize the composite design and the realization of a combined process of FPP technology with Filament Winding, leading to the successful creation of a full-scale demonstrator. The project focused on a 300 bar Type 4 pressure vessel as a challenging configuration due to its thinner composite overwrap. Despite these challenges, the third iteration achieved the required burst safety factor per BS EN 12245 with a 15% material saving.

The final iteration additionally demonstrated the potential for a 17% increase in storage efficiency within the same built space, compared to the reference vessel, indicating improved mass efficiency of the compressed H_2 in relation to the total storage system mass. In result, the material savings contribute to a significant reduction in the CO_2 footprint.

The collaborative effort showcases the practical application of FPP technology for pressure vessel optimization, offering economic and environmental benefits in composite tank manufacturing, making it a promising solution for the industry.

1. Introduction

Embracing sustainability, the EU Green Deal charts a course to curbing net greenhouse gas emissions by a remarkable 55 % before 2030 - measured against 1990 levels - and achieving full climate neutrality by 2050. The EU Hydrogen Strategy outlines a pivotal role for hydrogen in slashing CO_2 emissions, a driving force towards a greener future. Boosted by these developments, hydrogen-powered mobility is witnessing a remarkable surge, with projected compound annual growth rate for the hydrogen transportation market between 2022 and 2030 reaching an impressive 95 %[1]. Hydrogen's role is pivotal in sectors where pure electrification isn't feasible, particularly in heavy-duty and long-haul transportation.

Hydrogen can be stored through various methods, including compressed gas, liquid, and solid-state storage. For mobility applications, hydrogen is typically stored in composite tanks as compressed gas with up to 700 bars pressure. These Type 4 tanks leverage advanced composite materials to offer enhanced storage capabilities. Hydrogen tanks are made by winding impregnated fiber filaments (e.g. carbon or glass fiber) around a polymer liner providing a lightweight yet durable solution for containing high-pressure hydrogen.

Since the hydrogen market is witnessing dynamic growth, innovations in hydrogen storage continue to shape the industry, advancements in composite materials, variable tank sizes, pressure management, and safety considerations are collectively propelling the hydrogen revolution forward. The synergy between market developments and tank technologies underscores the critical importance of efficient and reliable hydrogen storage solutions in realizing a sustainable energy future.

For this reason, the three companies Roth Composites Machinery, CIKONI, Cevotec, in partnership with a renowned composite pressure vessel manufacturer, conducted a project to investigate the industry relevance of an innovative tank design with dome reinforcements:

1) Optimize tank laminate with numerical methods.
2) Apply local reinforcements in the dome sections of the liner.
3) Perform adjusted filament winding with less helical orientations.

In this design approach, a significant number of filament winding layers can be substituted by dome reinforcements, resulting in an overall reduction of needed composite material (for background reference, see Cevotec Whitepaper on "Improving storage efficiency of composite tanks"). This approach was first widely published by the US Department of Energy (DoE). The DoE concluded in year 2013 that local dome reinforcements can offer a solid opportunity to reduce the carbon fiber material usage by 15 %. *"The ABAQUS model considers the use of 'doilies' which are "strips" of carbon fiber composite placed strategically in the dome regions for local reinforcement. The purpose of the doilies is to reduce the stiffness discontinuity between the cylinder and dome sections, and the amount of helical winding needed to maintain the identical stress ratio as without the doilies. […] As a result, the stress distribution across the thickness of the composite is more uniform, and the total amount of carbon fiber composite needed is reduced"*[2].

The aim of the project is to confirm the published investigations and prove the manufacturability using automated technologies in an industrial setting. To this end, the conventional production

[1] JEC, JEC Observer; page 47, 2023
[2] S. McWorther et al., Department of Energy US, DOE Fuel Cell Technologies Office Record, 2013

method of filament winding is combined with Fiber Patch Placement (FPP) technology to enable an efficient and reproducible production process for this innovative tank design.

About Roth Composite Machinery:

Roth Composite Machinery specializes in designing and manufacturing specialized machinery for various industries, including Brushes & Brooms, Pleating & Coating, and Filament Winding & Prepreg. They are known for their high-performance mechanical engineering and offer customer-specific machine designs. In the world market leading business unit Filament Winding & Prepreg, they serve customers by suppling competitiveness increasing automation solutions by optimizing production processes with enhanced productivity, precision, and reliability. Their machines are used in the aerospace industry as well as by manufacturers of high-pressure tanks for compressed hydrogen and natural gas, supporting sustainable mobility concepts.

About CIKONI:

CIKONI is one of Germany's leading providers of engineering services related to composite materials. Having both internal product and process development capacities, CIKONI bridges the domains of structural performance and automation to develop new classes of composite materials products and manufacturing technologies. A dedicated work group for pressure vessels has been developing CNG and H_2 pressure vessels for years.

About Cevotec:

Cevotec empowers composite manufacturers to produce complex composites in high volume and high quality by lay-up automation based on Fiber Patch Placement technology. Their robotic-based production systems place carbon fibers, glass fibers, adhesive films and other technical fibers on complex 3D geometries – fully automated and quality-controlled. This enables their customers in aerospace and renewable energy to achieve the quality, cost and environmental targets of their composite production.

2. Motivation

Cevotec has developed an automated production technology for locally reinforcing the tank's dome areas to reduce the amount of carbon fiber needed for a composite tank. The general idea emerged after first investigations in 2013 & 2015 (funded by the US Department of Energy[2]), which concluded that local dome reinforcements of pressure vessels offer a solid opportunity to reduce carbon fiber material usage by up to 15 % while maintaining equivalent mechanical properties. Depending on the vessel characteristics (especially ratio between length and diameter L/D), this figure can even be surpassed. All these reductions translate into considerable weight and material cost savings as well as a reduction in composite laminate thickness. While this has some additional positive effects, e.g. reducing issues with fiber undulation and the risk of voids in the composite material, it can also be utilized to increase the storage volume in the same built space.

However, in 2015 it was decided that further research into this topic should be discontinued. At that time, no industrial process to economically produce those reinforcements was available.

Fiber Patch Placement (FPP) now is the first technology to lay-up dome reinforcements directly onto the liner in a fully automated, industrially relevant process which can be integrated with established wet or towpreg winding equipment.

By combining the unique capabilities of all four project partners to design, simulate, optimize, produce and test advanced composite tanks, this approach can be proven.

3. Material & process definition

3.1 General tank reference and materials

The investigations are based on an existing industrial Type 4 pressure vessel (PV), which was selected by the consortium's tank manufacturer. To create a relevant reference tank within the project, the filament winding laminate was numerically optimized by CIKONI and subsequently produced by the tank manufacturer (Demonstrator v00), resulting in characteristics displayed in **Fehler! Verweisquelle konnte nicht gefunden werden.**.

Table 1: General characteristics of the project's reference filament winding pressure vessel (v00)

Characteristic	Value
Outer diameter	316 mm
Length	894 mm
Total vessel weight	17.6 kg
Total vessel volume	46.5L
Ratio L/D	2.83
Nominal working pressure (NWP)	300 bar
Required burst safety factor (BS EN 12245)	3.00

This vessel represents a challenging set-up for the FPP reinforced vessels (v01-v03): Compared to 700-bar-class vessels, this class of vessels has a thinner composite overwrap with a lower number of layers to be replaced by dome reinforcements.

The materials used in the investigations are:

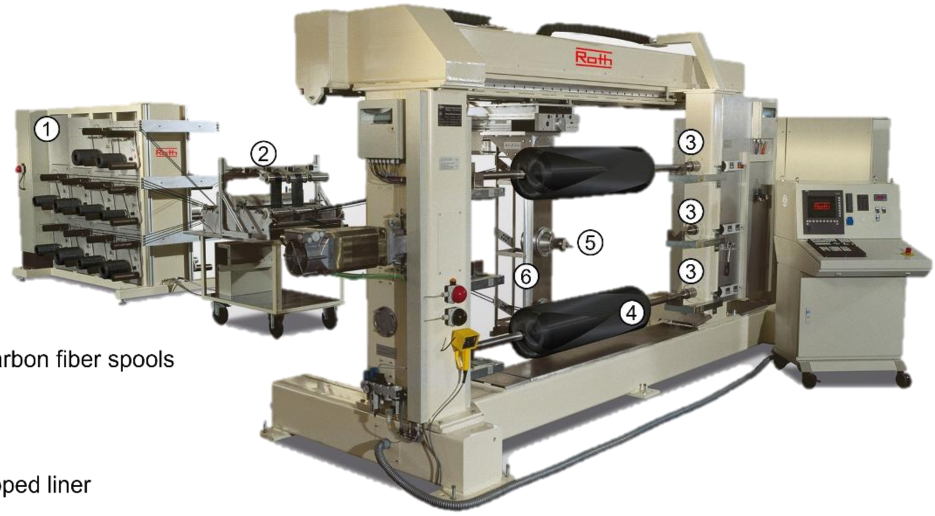
- Liner material: Thermoplastic liner, suitable for Type 4 pressure vessels
- Matrix material (winding & FPP): Industry grade epoxy-based resin for the winding and TCR resin system for FPP both with curing temperature up to 120°C
- Fiber material (winding & FPP): Toray T700

3.2 Automated manufacturing processes

3.2.1 Filament winding technology

Filament winding is the established state-of-the-art manufacturing technology for Type 4 composite pressure vessels. It involves winding of pre-impregnated tapes or continuous strands of reinforcement material ("rovings" or "tows") which have passed through a resin bath as they are being wound onto the rotating mandrel in a prescribed pattern. By varying the relative speeds of the winding axis and the translational carriage axis different winding angles are implemented for each layer of the laminate design. The resin matrix ensures that the composite material bonds sufficiently to give a durable structure after curing. **Fehler! Verweisquelle konnte nicht gefunden werden.** shows an exemplary PLC controlled winding machine with 3 spindles for simultaneous winding of 3 pressure vessels.

The common families of fiber orientation in pressure vessels are low angle helical (LAHL, sometimes designated “polar”), high angle helical (HAHL) and “hoop” patterns with typical angles of 8-15° (LAHL), 15-80° (HAHL) and 80-89° (HOOP) relative to the longitudinal axis of the tank.



1 | Unwinding unit with carbon fiber spools
2 | Impregnation unit
3 | Spindles
4 | Carbon fiber overwrapped liner
5 | Fiber delivery head
6 | Carriage for simultaneous movement of multiple delivery heads

Figure 1: Example of a 3-spindle Filament Winding machine for pressure vessel production
© Roth Composite Machinery

To raise productivity in the production of larger series the number of spindles can be increased. Furthermore, product change over processes (loading and unloading) can be automized by using (industrial) robot systems to reduce cycle time and gain productivity. In certain cases, the use of pre-impregnated fibers (towpreg fibers) offers increased speed potential and thus lower winding times.

3.2.2 Fiber Patch Placement

Fehler! Verweisquelle konnte nicht gefunden werden. shows the main process steps of the F PP technology. As a first step, either dry fiber tape with binder or prepreg tape is fed. An automated cutting unit discretizes the tape with an ultrasonic knife into patches of defined lengths. A first inspection camera checks the patch quality after cutting. If deviations or defects such as undulations or frayed edges occur, the patches are sorted out without interrupting the production process. Correct patches are further transported on a belt to the placement robot mounted with a gripper dedicated to the processed material. The gripper is made of flexible material and adapts to the surface of the tool during the lay-up. After the gripper has picked up the patch by vacuum suction, a second camera checks the position of the patch on the gripper. The system automatically corrects any misalignments to ensure an as-planned placement of the fiber reinforcement patch. Depending on the tape material, a heating unit integrated in the gripper (dry fiber) or external IR heating station (prepreg) adjusts the tackiness level of the patch for optimal lay-up results. The patch is placed directly on the tool mounted on a fixed or moveable holder. Optimized for pressure vessels, this toolholder is a rotational axis to receive the liner assembly for patching.

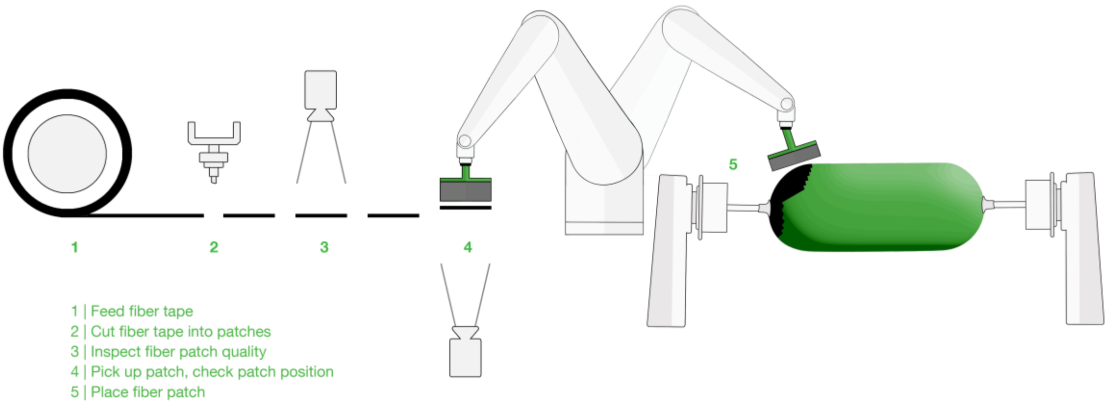


Figure 2: Principle of FPP process

The demonstrators in this project were manufactured on a SAMBA Pro manufacturing system available in Cevotec's FPP competence center. For future industrialization of the process, Cevotec is currently developing an FPP manufacturing system specifically tailored to PV reinforcement manufacturing.

The "Samba Pro PV" is a dedicated Fiber Patch Placement system for pressure vessel reinforcements. The system arrangement is fine-tuned to ensure fast cycle times on vessel liners while remaining flexible for various liners and vessel dimensions. It can be seamlessly integrated with existing production lines.

Samba Pro PV consists of 2 placement robots with 6 axes, and 2 automated feeding and cutting units with temperature-controlled material storage, in-process quality inspection of raw materials and an external IR-heating system to condition the patches directly prior to placement. The automated feeding and cutting units deliver quality-inspected fiber patches to the placement robots for pick-up and subsequent placement on the vessel liner. The placement unit, following a second on-gripper inspection to ensure precise positioning, fully automates the process of applying these patches to the vessel liner. A rotating axis, equipped with an adjustable length tool holder, facilitates the accommodation of pressure vessels of various sizes. The created patch reinforcements are compatible with both wet and towpreg winding laminates.

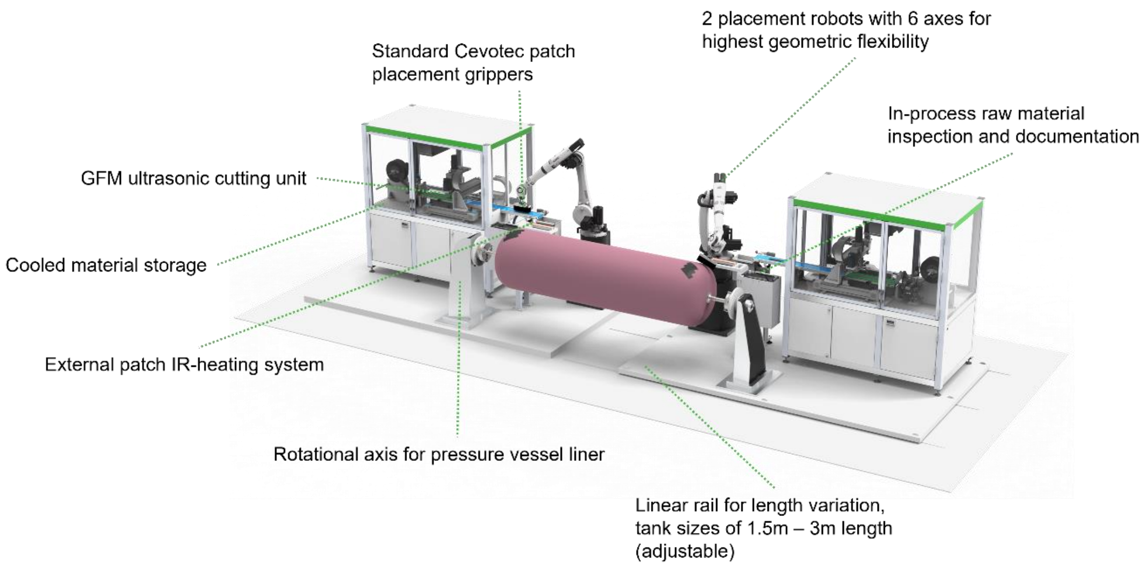


Figure 3: SAMBA Pro PV system for industrial dome reinforcement manufacturing (illustrative)

4. Development of optimized H_2 pressure vessel

4.1 Concept definition and design

4.1.1 Type 4 pressure vessel concept

The chosen pressure vessel (see section 3.1) comprises an internal thermoplastic liner for hydrogen containment and an outer composite shell for bearing loads and providing impact protection. Two aluminum bosses attached to the ends of the liner facilitate the connection of the hydrogen gas lines. The reference pressure vessel is an already industrialized design, where the main task was the optimal exploitation of the deployed composite's performance while using the manufacturing processes' full potential. Utilizing CIKONI's industry knowledge in the concept design regarding composite pressure vessels, typical design aspects and various standards were considered.

4.1.2 Local reinforcement of the dome section to reduce weight and cost

The filament winding process is by nature a continuous one and requires complete wrapping of each layer around the liner. However, the high number of helical layers limits the efficient use of the fiber materials. While these layers prevent dome region failure, their mechanical strength remains underutilized in the cylindrical section, resulting in unnecessary weight and costs. This presents an optimization opportunity to reduce the number of used helical layers while maintaining the mechanical performance.

By introducing Fiber Patch Placement (FPP) layers in the dome section, selected helical layers in the cylindrical region can be omitted. Thanks to the high flexibility of the FPP process, the vessel laminate can be designed according to the optimal stress state.

4.1.3 Engineering methodology for optimized pressure vessels

In the beginning, a robust design based on wet wound material properties was created, using CIKONI's internal software and methodologies. Fulfilling international pressure vessel standards, a safety factor for the burst pressure of 3,0 was selected for the optimization simulation. A non-geodesic filament winding path was selected. This helps with the holistic exploitation of the material properties. Following the creation of the reference design, the layers with potential to being eliminated or modified were selected and investigated in detail by domain specific Finite Element Analysis.

The developed stress state was systematically analyzed and the FPP patches of the dome reinforcement laminates were positioned onto the surface according to the increased loads resulting from the eliminated helical layers. Since the optimum FPP dome reinforcement layup interacts strongly with the overwound laminate, the pressure vessel had to be extensively optimized. Due to the complexity of the model, some assumptions on material properties and analysis regions had to be taken and calibrated in the consecutive experimental iterations (v01 and v02, see Table 2)

Table 2: Demonstrator iterations

Name	No. of FW plies	Composite mass (incl. FPP reinforcement
Reference v00	*undisclosed*	100 %
FPP v01	9	73 %
FPP v02	11	79 %
FPP v03	12	85 %

In the overall resulting design (v03), the thickness of the laminate on the cylindrical part could be reduced by 22% while achieving the same burst pressure prediction in the simulation. An overall mass reduction of 15% could be achieved.

4.2 Simulation & burst pressure prediction

The simulation of the complex and direction-dependent mechanical properties of the composite material poses a great challenge. The different failure behavior in fiber direction and transverse direction requires specific domain knowledge of both composite materials and pressure vessel characteristics. This complexity increases further by introducing to the design novel manufacturing technologies like FPP dome reinforcements.

The physical and mechanical properties of the wound laminate on a pressure vessel are influenced by geometry and process parameters, posing a significant challenge in describing these material characteristics within a thick-walled shell. Consequently, the structure exhibits non-linear behavior, revealing the limitations of static simulation techniques. This underscores the necessity of employing non-linear methods and specialized design software, where CIKONI's in-house methodologies and software proved exceptionally valuable. However, because of the specifics posed by the FPP dome reinforcement inclusion in the analysis, further methodology adaptations were required.

4.2.1 Utilized simulation methods

In order to predict the laminate properties, the Filament winding process was modelled using a process simulation tool. This enabled a realistic estimation of the resulting material properties.

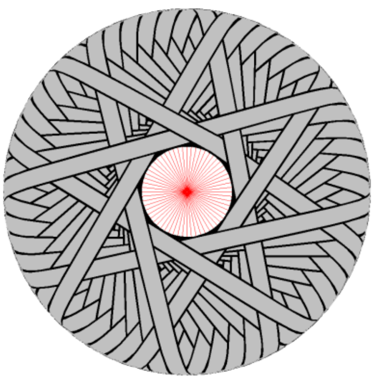


Figure 4: Process-simulated laminate model

Not only the complex structure of the wound laminate but also the prediction of the physical properties of the overlapping FPP patches is a demanding numerical challenge. Therefore, the process simulation was executed in two steps:

- Step 1: Simulation of the winding angle and thickness of the FPP dome reinforcements
- Step 2: Liner geometry optimization, followed by the execution of winding simulation

An optimization process was followed to reduce the weight and cost of the pressure vessel. First the optimum wound lay-up was found to be able to carry the loads in the cylindrical area by considering manufacturing constraints. Secondly the optimum dome reinforcement design was established based on the developed stresses caused by the complex laminate constellation in the dome region. In the third step, adjustments were made to the wound laminate to address the newly introduced out of plane stress state in the critical places of the wound laminate. Finally, a numerical investigation on the model's parameters was conducted.

To address complex stress and geometric alterations, two finite element (FE) methods were employed to model the intricate behavior of the pressure vessel efficiently. A shell model was introduced to optimize the laminate and minimize stress, providing a cost-effective approach to finding the best solution while saving on development expenses. Additionally, for more detailed analysis, a solid model was created, enabling a thorough examination of the complex layer overlapping.

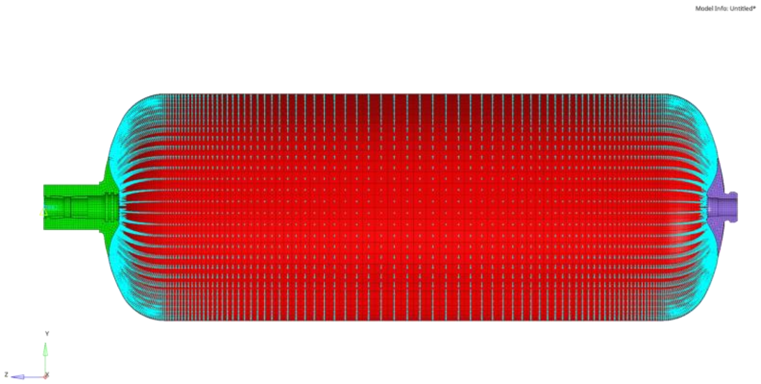


Figure 5: Numerical solid model of the chosen vessel

4.2.2 Results and discussion

By using the two-step optimization approach a high-fidelity simulation could be performed. Due to the high prediction quality of the simulation, the burst pressure of the wound vessel could be estimated accurately. The most critical part during the engineering phase was to model the cylindrical section to decrease the deviation of the fracture. The estimated burst pressure of the patched pressure vessel is above 900 bar.

Summarizing, to predict the complex laminate properties of the composite pressure vessel, a kinematic winding simulation was used. Both the fiber orientations and laminate thicknesses were realistically predicted. During the analysis of the stress state in the layers, it became apparent that the laminate constellation was critical in the dome region. To reduce the bending moments in the dome region an optimum sequence of low- and high angle helical layers were needed. By utilizing a modern simulation-driven design of the pressure vessel, an already industrialized pressure vessel could be further optimized while maintaining the load-carrying capacity.

5. Testing

5.1 Manufacturing and test set-up

The basic manufacturing and demonstrator stages are shown in Figure 6 to 9. The test followed the standard protocol for homologation, specifically conforming to the EN12245:2009+A1:2011 Standard. In this case, the hydraulic pressure burst test was executed, ensuring that the pressure increased in a controlled manner. The test took place under ambient conditions, with strict temperature maintenance, keeping the outer surface of the cylinder below 50°C. The rate of pressurization did not exceed 10 bar/s, and the test lasted for a minimum of 40 seconds. The maximum pressure recorded during the test was marked as the burst pressure, while close attention was paid to monitor the burst pressure, failure type, and the time-pressure curve.

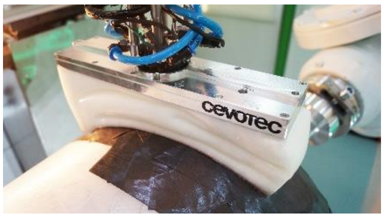


Figure 6: Placement of local dome reinforcement patches with FPP

Figure 7: Winding of dome reinforced Type 4 tank

Figure 8: Completely wound and cured vessel

Figure 9: Vessel after burst testing

It was essential that the minimum burst pressure exceeded two times the test pressure, equivalent to three times the working pressure, which was 900 bar (3 x 300 bar) Required Burst Pressure (RBP). The initiation of the burst was required to occur within the cylindrical part, and the liner could disintegrate into no more than three pieces.

The test took place within a closed chamber, commencing with the cylinder being filled to its maximum water capacity. Subsequently, a pump was employed to gradually pressurize the fluid at a controlled rate.

5.2 Experimental results

Three distinct iterations (including burst tests of demonstrator vessels) of the cylinder were carried out, with the partner companies dedicating time and effort to pinpoint areas for enhancement in their respective technology areas (simulation, design, manufacturing processes).

In Section 3, the vessel dimensions specified serve as our reference vessel, denoted as *v00*, which is succeeded by three iterations, *v01, v02, and v03*, each reinforced with FPP. *v00* acts as a reference vessel since it is entirely filament-wound and has undergone testing. In every iteration, three vessels are produced to ensure adherence to standards. Each vessel features a dome reinforcement using FPP followed by complete filament winding, and each has undergone a burst test in accordance with the test set-up outlined in Section 5.1.

Concerning *v00*, both *v01 and v02* delivered significant CFRP material savings of 27 % and 21 %, while reaching 79 % and 91 % of the required burst pressure, respectively. Although substantial weight savings were achieved, the first two iterations fell short of the RBP. In each iteration the laminate changes are incorporated according to the results from numerical analysis. In the third iteration (*v03*), with optimized simulation results from Cikoni and laminate modifications in FW and FPP, remarkable results were obtained. **This iteration *v03* yielded a 15 % CFRP material saving and a burst performance averaging 108 % RBP**. The results are charted in Figure 10.

Storage efficiency stands as a critical indicator for a pressure tank, indicating the mass of compressed H_2 in relation to the total storage system mass. Our solution reduces laminate thickness in the cylindrical section of the pressure vessel. This opens up the potential to increase the container volume of the liner in the same built space (i.e. outer diameter of the finished tank). In a combination of reduced weight and increased container volume, , the storage efficiency can reach 6.1 % for the regarded tank type, signifying a 17 % increase when compared to the 5.2 % storage efficiency of the reference vessel.

Table 3: Results overview

Name	**No. of FW plies**	**Composite mass (incl. FPP reinforcement)**	**Burst Performance (3*NWP[1])**	**Storage efficiency** mass H_2 / mass of (total vessel + H_2)
Reference v00	*undisclosed*	100 %	**100 %**	**5.2 %**
FPP v01	9	73 %	79 %	*Irrelevant*
FPP v02	11	79 %	91 %	*Irrelevant*
FPP v03	12	85 %	**108 %**	**6.1 %**

[1]NWP = 300bars

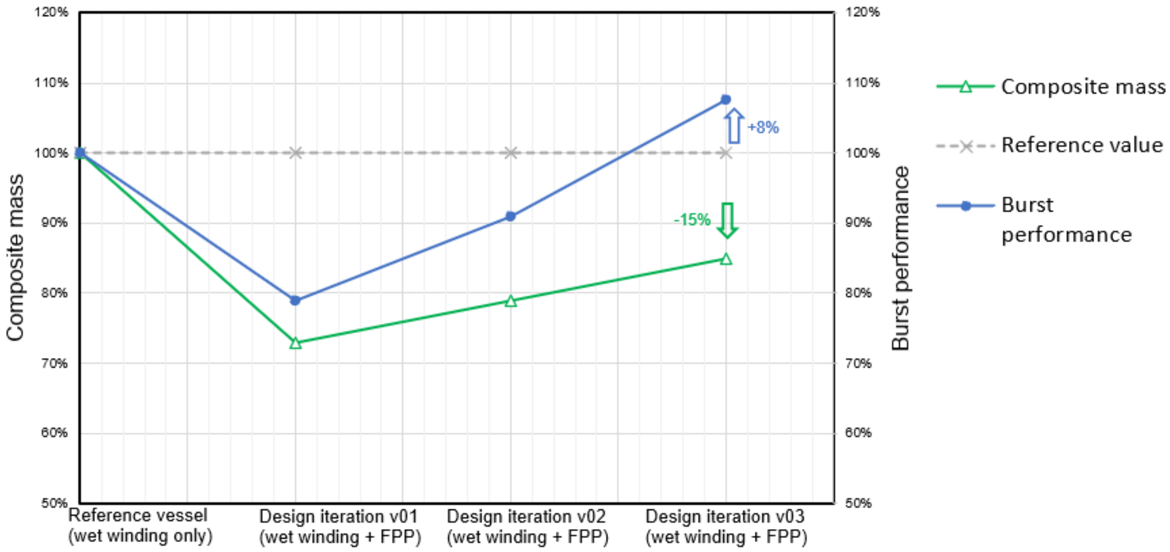


Figure 10: Composite mass reduction and burst pressure enhancement

5.3 Discussion and conclusion

This material saving benefit will translate to an even higher advantage for vessels with an increased L/D ratio. The longer the vessel, the greater the saving potential from eliminating high angle helical layers from the vessel. This effect, extrapolated based on actual project data, is illustrated in Table 4.

Table 4: Key pressure vessel characteristics

Characteristic	**Project value**	extrapolated **Example 1**	extrapolated **Example 2**
Length (mm)/ Diameter (mm)	894/316	1264/316	2528/ 316
Aspect ratio (L/D)	2.83	4.0	8.0
Weight savings for composite	15 %	16.7 %	18.8 %

The saving potential is unique to each composite vessel and increases also with operating pressure, as higher pressure typically requires a thicker laminate, which provides increased savings potential.

Furthermore, due to the material savings, the CO_2 footprint is reduced. Assuming a carbon fiber weight per vessel of 75kg (medium-sized vessel for commercial vehicles) and a yearly production of 10.000 tanks, the reinforcements enable material savings of 9 tons each year, just for one product line. The manufacturing of 1 kilogram of carbon fiber generates approximately 26 kilograms of CO_2 emissions, translating into a yearly saving of 234 tons of CO_2 for this exemplary tank product line.

Additionally, as the industry anticipates a shortage of carbon fibers given the exponentially increasing demand for H_2 tanks over the next 10-20 years, these potential savings from dome reinforcements significantly contribute to a more sustainable fiber consumption for composite tanks.

6. Conclusion

To create next-level pressure vessel products, new economical design approaches and laminate optimization are needed. While this can have benefit already for a pure winding laminate (see Chapter 4), a further step can be taken with introducing local reinforcements on domes.

While this concept is known since 2013[2] for its potential to decrease material need in pressure vessels by 15 % or more, it was lacking an industry-relevant production technology to integrate with the already established Filament Winding process. In the past years, Cevotec has advanced the development of FPP technology to provide an industrial automation solution for the lay-up of dome reinforcements.

To prove the fidelity of this approach, first a laminate optimization using detailed FE simulation was done. Here, the material utilization of the helical layers was analyzed while the optimum reinforcement angles of the patches could be determined. The subsequently derived reinforced second design contains less layers and maintains a more balanced stress state across the meridian. Next to the optimal patch angle, particular attention had to be devoted to the transition zone in the cylinder-dome-interface to comply with manufacturing restrictions.

Prototypes of this design were manufactured it a two-stage approach. First, a fully automated lay-up of the dome reinforcements on the pressure vessel liner assemblies was done, using a SAMBA Pro FPP production system. Second, the preformed liners were fed to an industrial Filament Winding machine to create the elaborated filament overwrap. These demonstrators were subsequently co-cured and subjected to burst pressure testing in several design iterations. With the final iteration, the required burst safety factor was successfully achieved.

With those activities all partners engaged in, the overall mass of the pressure vessel could be reduced by 15 % while maintaining the performance. This new technology approach can not only be applied to newly developed pressure vessel types, but can also be used to optimize legacy products, as was showcased in this project.

The proved material savings directly translate not only to reduced material cost and CO_2 footprint, but also offer the potential for enhanced storage performance in the same built space, providing the blueprint for next level pressure vessel products.

FPP technology & equipment	Winding equipment & integration	Laminate design & simulation
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