# PROCESS INNOVATION: H2 COMPOSITE TANK DOME REINFORCEMENTS WITH FIBER PATCH PLACEMENT

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## 1 INTRODUCTION

Composite Pressure Vessels (PV), which maintain pressures of up to 700 bars, are the key storage system for hydrogen-powered mobility. Current predictions of hydrogen-powered transportation over the next ten years forecasts exponential growth. The main cost driver for these hydrogen tanks is the carbon fiber material itself, representing over 50% of the total production cost. To increase the competitiveness of composite PVs, innovative technologies and processes are needed to improve the material utilization of the tanks.
In this paper and attached case study, composites manufacturing automation specialist Cevotec presents an industrial solution that reduces the amount of carbon fiber by 16 %, while increasing capacity and delivering a ROI of under one year.

## 2 PV REINFORCEMENT WITH FIBER PATCH PLACEMENT

### 2.1 Motivation for PV reinforcement

PVs are typically manufactured by winding filaments of impregnated fibers around a polymer liner with different principal fiber orientations as shown in Figure 1.

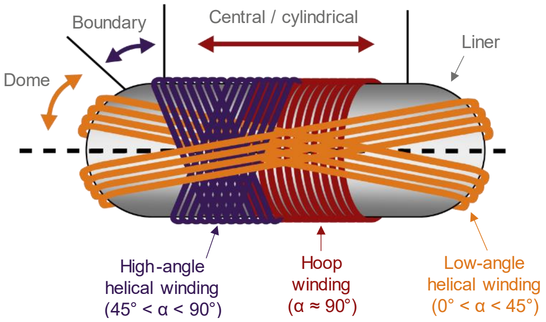


Figure 1. 3 types of principal fiber orientations in PVs

Focusing on the cylindrical part of a PV, the primary stresses are in the circumferential (hoop) and longitudinal (axial) directions. To counteract the hoop stresses, fiber material has to be placed in the circumferential direction (hoop layers, α ≈ 90°). The strength in the axial direction is ideally ensured by fibers placed in the axial direction (α ≈ 0°). However, standard filament winding (FW) technology does not have the capability to place fibers in a purely axial (0°) orientation, because the clamping device of the spindle is mounted at the center of the dome area. FW therefore places fiber material in a helical pattern, by winding it at different orientations relative to the axis of the PV. Here, Low-Angle Helical Layers (LAHL with α ≈ 10° - 30°) are used for the reinforcement in the axial direction.

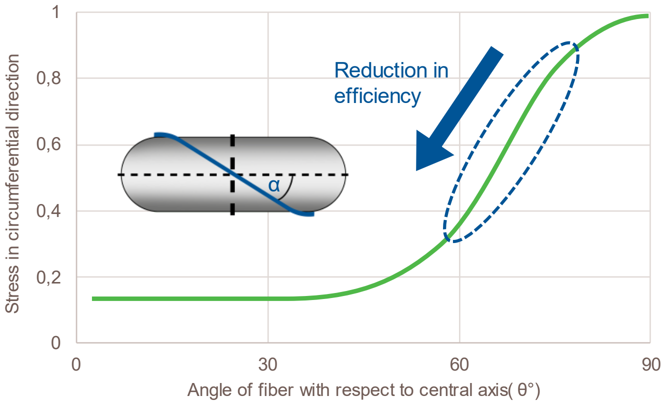


Figure 2. Portion of circumferential stress taken over by reinforcement in relation to fiber angle (to central axis)

Figure 2 illustrates that as the angular deviation between the fiber reinforcement and the principal stress direction increases, the strength of the composite laminate decreases significantly. In principle, the High-Angle Helical Layers (HAHL) deviate in the range of 20° to 75° from the primary stresses (hoop and axial). This means their performance ranges between 15% and 50% of the material's full potential. In simple words: The HAHLs on the cylinder are not utilized to their full potential. Nevertheless, the HAHL orientations are part of most laminate setups since they contribute significantly to the stress field at the cylinder to dome transition area (denominated as equator).

A solution to improve the HAHL fiber material contribution to the overall tank strength is to locally reinforce the dome areas, replacing the HAHL in the filament winding laminate. The reinforcements can counteract the stresses in the dome transition area while the cylindrical part will be covered only by the hoop windings and LAHL. This approach was originally suggested by the US Department of Energy in 2013 [1]. At that time, there was no industrial process available that was able to produce those reinforcements efficiently.

### *2.2 Automation technology for dome reinforcements*

Cevotec's Fiber Patch Placement (FPP) is the first technology to manufacture dome reinforcements directly onto the liner using a fully automated, industrial process. This can be combined with established filament or tow winding equipment.

The magnitude of potential benefits of dome reinforcements depends on the principal geometry of the vessel. Since the FPP dome reinforcements replace inefficient HAHL orientations from the cylindrical portion of the PV, the benefits from this solution increase as the aspect ratio of length/diameter increases, since inefficiently used material is removed from a larger cylindrical area. The engineering workflow to realize those reinforcements is presented in the next section.

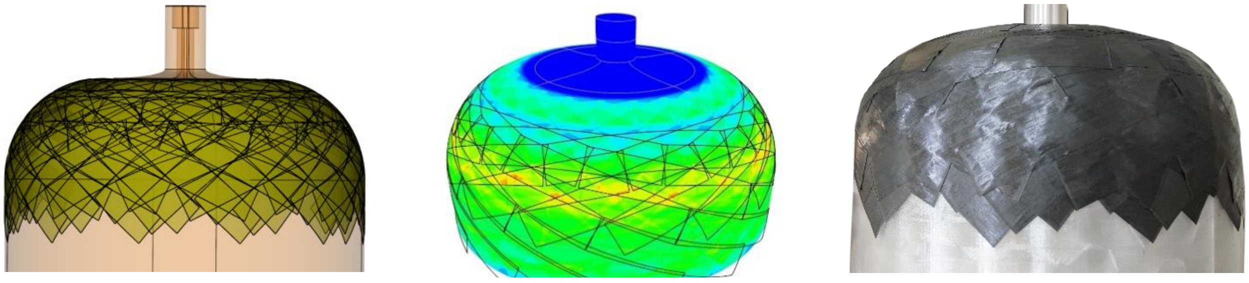


Figure 3. Dome reinforcement with Fiber Patch Placement

# 3 DEVELOPMENT PROCESS OVERVIEW

## 3.1 FPP laminate creation

After designing the PV in a standard CAD software, the geometry is imported into Cevotec's software *ARTIST STUDIO*, where the entire virtual design and production planning process takes place. The first step is the virtual laminate creation. Each of the HAHL to be replaced are defined using the CAD module *PATCH ARTIST*. The laminate is designed using the built-in curve creation algorithms. This results in a system of guide-curves being virtually placed on the PV CAD model. Patches are created on every curve with defined length and width. Transverse and longitudinal overlaps for the patches between layers are optimized to ensure structural strength. During the virtual laminate creation step, the thickness distribution can be monitored and calculated in real time, facilitating efficiency in laminate design iterations.

## 3.2 Offline robot programming

The next step in the virtual process development is to generate the offline robot program and perform a process simulation. The created FPP laminate is transferred from the *PATCH ARTIST* module to the CAM module *MOTION ARTIST*, which features the digital twin of the production system. The production system robot programming is fully automated and efficiently generated. The complete manufacturing process can then be simulated, including an automated collision check, with the goal to ensure safe operation of the FPP production system.

## 3.3 Manufacturing process

The final step is the actual manufacturing of the dome reinforcement using Cevotec's *SAMBA* FPP system. After the machine program is loaded onto the *SAMBA* system, material in tape form is fed and used by the *SAMBA* system to cut patches of the chosen geometry. Each patch is first checked by a vision system for geometrical accuracy and defects. Patches are then picked-up by Cevotec's form-adaptive gripper mounted at the placement robot. Each picked-up patch is again inspected to ensure correct positioning on the gripper. Potential deviations are corrected in-line during the final placement step when the patch is placed on the tool. A schematic of the process is shown in Figure 4. The patches can be placed directly on the vessel liner without additional post-processing steps. Afterwards, the tank is ready to be transferred to a FW station to apply the winding lay-up.

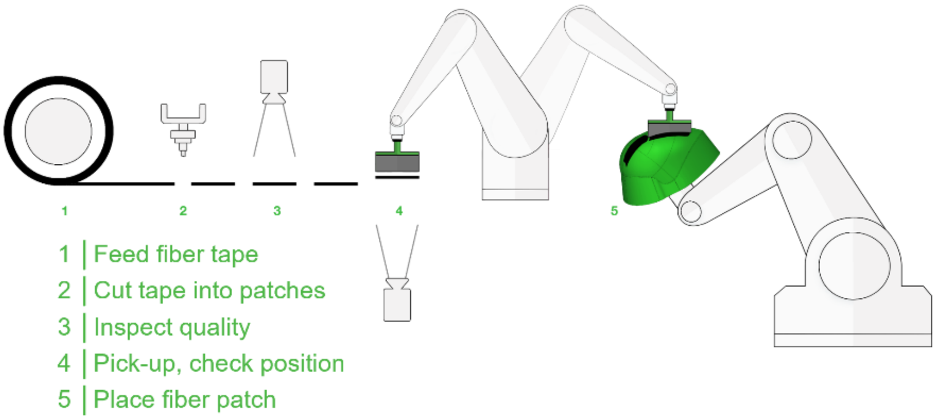
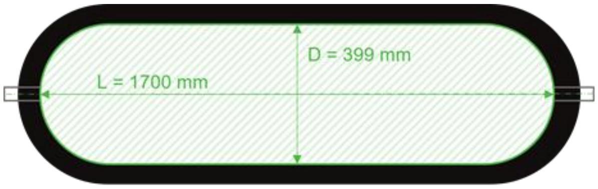


Figure 4. FPP process overview

# 4 CASE STUDY

## 4.1 PV geometry and laminate definition

The reference geometry of the PV demonstrator used for this case study is presented in Figure 5.



- Pole-to-pole length, L = 1700 mm
- Liner diameter, $D_{liner}$ = 399 mm
- Volume, V = 209.3 l
- Laminate thickness, $t_V$ = 33 mm
- Material:
    - Prepreg tape 290 gsm
    - Width: 38mm (1.5”)
    - Fiber volume content, $v_f$ = 65%
- Mass of carbon fiber composite, $m_{CF}$ = 75 kg

Figure 5. Reference geometry

The reference winding laminate considered in this case study featured 41 winding orientations with a distribution of 36 % hoop layers, 44 % LAHL and 20 % HAHL. This laminate was then adjusted by replacing the HAHL orientations with FPP dome reinforcements and reduced winding laminates. The result of implementing local dome reinforcements is a 16.3 % (-12.2 kg) reduction of the vessel’s composite weight. Additionally, the CFRP shell thickness on the cylinder section is reduced by 6.6mm. This leads to an increase on the inner diameter of 13.2 mm which will result in a +6.1 % (+12.6 litre) increase in volume and H2 capacity (assuming that the vessel size is restricted by outer dimensions).

## 4.2 Economic analysis

To perform an economic analysis of the dome reinforcement solution, the fiber lay-up of the reference vessel without reinforcements is compared to a dome-reinforced vessel with an adjusted winding laminate. In the following analysis, a dedicated unit-cost is used for this purpose, with the results being fed into an investment case. In the example of a prepreg filament wound only process, the fiber weight is 75 kg. With an assumed average winding speed of 1.6 m/s, the total lay-up time is 73.6 min. For an annual vessel production volume of 30 k units per year (based on 2-shift operation), the total cost of the laminate lay-up (before curing) is estimated at € 2,645, using a material cost of 35 €/kg.

For the FPP dome reinforcement vessel, the same material is assumed. It is cut into patches representing the 14 HAHL orientations in the dome areas, which were removed from the winding laminate. This saves up to 12 kg, or 16 % of the material. If the average patch cycle time is assumed at 4.5 seconds per patch, operating with a 2-robot-system, the overall process time will scale down to 57 min for both dome reinforcements, which is a reduction of 16 %. This translates into a capacity increase in the FW line of the same amount, as the FPP reinforcement process and FW process can run in parallel in a series production setting. Finally, the total cost (before curing) would decrease by 11 % to € 2,355.

The big saving potential of FPP leads to a high positive return on investment as well as a short payback period. The initial investment in year 0 amounts to approx. € 11.25 M including hardware and software. With 30 k units in production each year and a unit-cost difference of € 291 (net material cost + process time improvement), the cost savings amount to € 8.73 M p.a. In addition to these savings, manufacturers have a pricing advantage, as they can offer vessels with significantly better storage efficiency (less weight and increased volume for the same exterior space). With an assumed price / margin opportunity of € 175 per unit, the total benefits (material cost, process time, margin opportunity) amount to € 14 M p.a. This represents a very fast amortization period of just 10 months for the one-time investment.

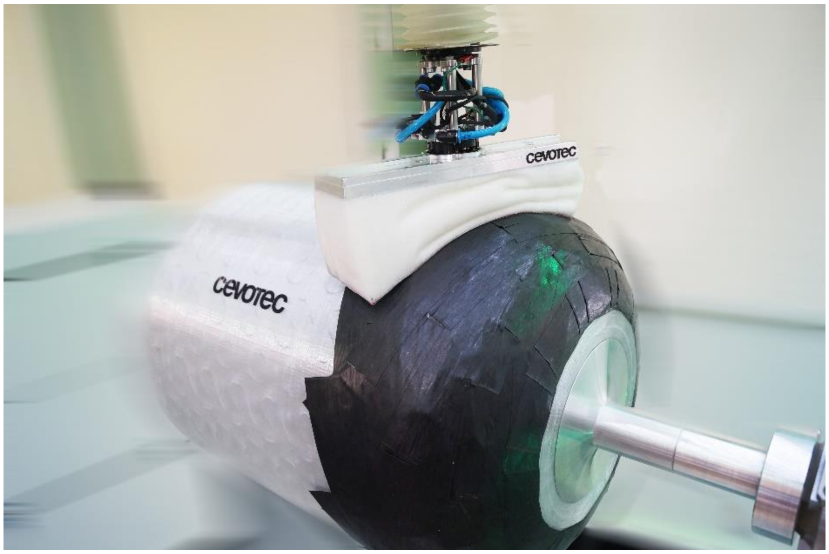


Figure 6. The form-adaptive gripper is placing the reinforcement patches directly on the liner

# 5 CONCLUSION

This paper describes and quantifies the expected benefits from using FPP dome reinforcements for composite pressure vessels. While the general benefits of this solution were established several years ago, the industrial equipment to implement it was not available until now. With FPP-based lay-up systems, dome reinforcements for composite tanks can be produced on an industrial scale, building on existing filament winding techniques. Most cylindrical PVs can be reinforced by using the FPP solution. The benefits increase with growing vessel aspect ratio.

The key benefits are an increase of storage efficiency – approx. 16 % less weight, 6 % volume increase – and an associated cost reduction of 11 %. It is noteworthy that implementing dome reinforcements also frees up almost 15 % capacity on existing winding equipment, as less material and cycle time are needed per vessel in the winding process. The resulting investment case is highly positive, with an amortization period of 10 months.

# 6 REFERENCES

[1] S. McWorther, G. Ordaz, Department of Energy USA. "*Onboard Type IV Compressed Hydrogen Storage Systems*". in DOE Fuel Cell Technologies Office Record, 2013.