DLR MODULAR FREE-SHAPEABLE CNG-TANK - A HYBRID, COMPOSITE-INTENSIVE DESIGN

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Abstract

In the automotive industry, natural gas is currently stored as Compressed Natural Gas (CNG) in cylindrical high-pressure tanks. In order to increase the range of vehicles, a more efficient use of the available design space is needed. For this purpose the Institute of Vehicle Concepts at the German Aerospace Center (DLR) is developing an innovative, lightweight, composite-intensive design for a high-pressure tank: "The DLR Modular-Free-Shapeable CNG Tank". The new manufacturing process, combined with the tank concept, leads to a volume gain of up to 38 % compared to conventional CNG storage systems, based on the available space in the vehicle. However, a new winding process has to be developed for this tank. This paper shows the results of the polar winding of non-rotationally-symmetrical vessels, complexity of the domes and the first tool for the 3D-Winding-System. The German Aerospace Center Institute of Vehicle Concepts is working on the first automated produced prototypes that can be scaled to an industrial level so that a low-cost, shape adaptable CNG tank is possible. With this storage system, CNG vehicles can gain a larger range, further the environment and society will gain an added value because of lower emissions than petrol and diesel, while by using synthetic methane it is possible to reach an emission free mobility.

1. Motivation for the use of a shape-adaptable gas tanks

Current fuels (petrol and diesel) are stored in the vehicle at atmospheric pressure. Because of that these tanks can be designed conform to the vehicle architecture. With the use of natural gas as CNG (200 bar operating pressure) the storage is done in cylindrical vessels. These vessels can be built in four types (type 1: "full metal tank"; type 2: "metal tank with hoop winding FRP"; type 3 "metallic liner with full polar winding FRP" and type 4: "plastic liner with full polar winding FRP") [1, 2, 3, 4]. Lacking shape-adaptability, the CNG storage systems result in a volume loss in relation to the available space. Often it is only possible to install a gas tank with a relevant volume by eliminating the spare wheel well [5, 6]. With the purpose to counteract this loss of customer benefit, while having a range in average vehicles of 400-500km [7], a freely-shapeable CNG-tank must be developed.

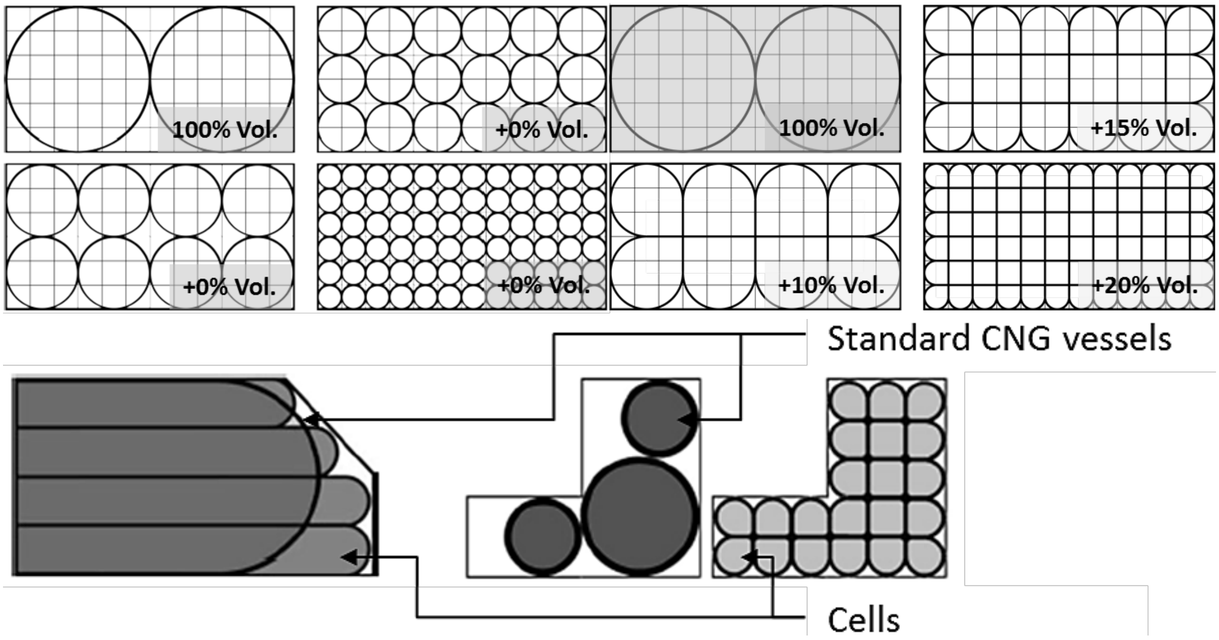


Figure 1. Space coverage by standard CNG tanks and cells of the modular free-shapeable DLR vessel [8]

As shown in Figure 1 (top row), a cell based CNG tank using non-rotationally symmetrical cells can gain volume up to 20% compared to standard cylindrical vessels in the described space by lowering the diameter. [9] has shown that, under the consideration of logical mathematical restrictions, only 78, 75% of the possible 100% volume can be used. Further by using non-rotationally symmetrical cells it is possible to mount a modular and shape adaptive tank shown in figure 1 on the pictures below. With this design solution it is possible to use 38% more volume in a vehicle shown in an internal DLR Study.

2. Production of an innovative and space-adaptive CNG high-pressure tank in fiber reinforced hybrid lightweight construction

The production approach of the shape-adaptable and modular CNG-tank pursues a customer oriented and automated path. It consists of four main production steps. First of all a gas-tight aluminum liner has to be built for every cell. Afterwards, because every cell has to bear the axial load, every cell has to be fully wound with Carbon Fiber Reinforced Plastic (CRFP). In [10] the axial load was taken by a fabric dome and a braided shaft. These preforms had to be stacked manually and had to be infiltrated with Vacuum Assisted Resin Infusion (VARI). This manufacturing process is complex and almost impossible to scale to series production. In the new production approach every CFRP process has to be automated and scalable to industrial range. Because of this the axial load has to be taken by polar winding. After every cell is wound, they have to be assembled. The DLR-modular free shapeable CNG-tank is assembled with a secure inner connector concept. Thanks to this, only one valve is necessary. The fourth and last production step is the process to bear the radial load. For this purpose a new tool has been designed, the 3D-winding tool.

In this paper both processes (polar winding to bear the axial load and 3D winding to bear the radial load) are presented and relevant results will be given.

3. Polar and full winding of non-rotation-symmetrical vessels

3.1. Properties of the dome

In order to achieve the goal of winding non-rotationally symmetrical vessels, the geometric shape of the caps (domes) has to approach to an isotensoid shape. Isotensoids are generally understood as structures with the same tension and deformation along the geometry [11]. While winding rotationally symmetrical pressure vessels the most common profiles for the dome are geodesic profiles [12, 13], there is still no method known for polar full winding of non-rotationally symmetrical vessel domes.
The adjusted domes used for the preform solution of [10] can’t be used for the winding process because of the change in the curvature continuity, shown in Figure 2.

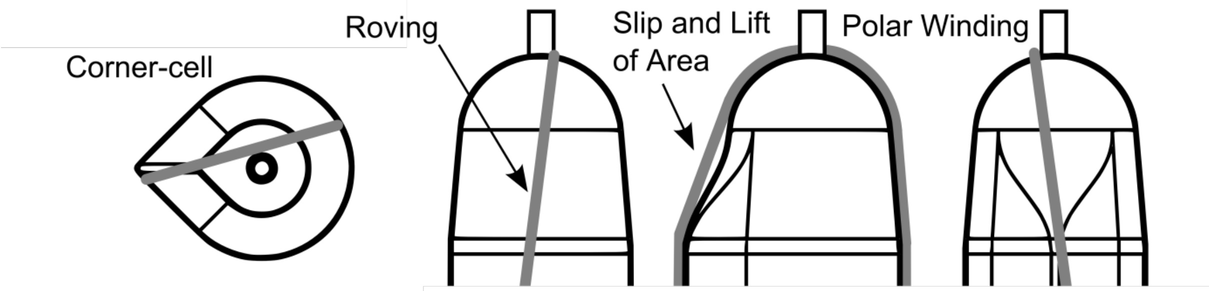


Figure 2. No windability because of the use of a dome that is defined by a change in the curvature continuity

The roving passes over a “Lift of Area” where there would be no contact between the aluminum liner and the CFRP. [14] defines the “contact” and “lift of safety” as prerequisite for windability. These prerequisites are not given in this dome geometry.
[15] describes the mathematical approach to design dome geometries for rotationally symmetrical vessels by using functions of dimensionless parameters. The designed domes have the properties of isotensoid domes and the meridian profile is determined by the integration of the following function (1).

$$Z'(Y) = \frac{Y(Y^2+rY_{eq}^2)}{\sqrt{\left(\frac{k+Y^2-1}{k+Y_{eq}^2-1}\right)^{k+1}(1+r)^{2}Y_{eq}^{6}-Y^2(Y^2+rY_{eq}^2)^2}} \tag{1}$$

The parameters are defined in Table 1.

Equation	Variables	Description
$Y = \frac{\rho}{c}$	• *ρ: Radius of the variable cap* • *c: Radius of the polar opening*	Ratio of the radius of the cap (variable) and the polar opening
$Y_{eq} = \frac{R}{c}$	• *R: Radius of the cap (max)*	Ratio of the radius of the cap (max) and the polar opening
$Z = \frac{z}{c}$	• *z: Height of the dome*	Ratio of the height of the dome and the radius of the polar opening
$r = \frac{F_a}{\pi P R^2}$	• *F_a: External, axial load* • *P: Pressure of the tank* • *R: Radius of the cap (max)*	

Table 1. Parameters that define the meridian profile of an isotensoid dome for rotation-symmetrical vessels

Considering this mathematical approach it is possible to design a new meridian profile for changing cap-radiuses *R*. By doing so it is possible to build the different type of domes for the different types of non-rotationally symmetrical cells, shown in figure 3. This approach has to be investigated by testing the automated winding process on a CNC-winding machine on different types of domes on models, showed in figure 4.

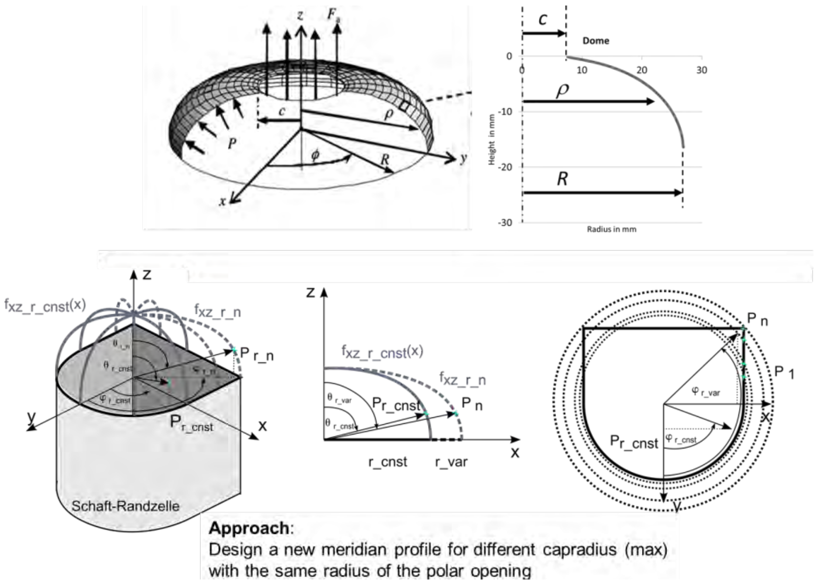


Figure 3. First approach to design isotensoid domes for non-rotationally symmetrical vessels with a figure from[Ko]

3.2. Experiment results and conclusion

As shown in figure 4 every test was done with a CNC-winding machine. The model was built up so that different types of domes could be validated. The first dome type (Nr.1) was designed as shown in figure 3. Table 2 shows the three tested dome types.

Figure 4. CNC-winding machine with a full wound non-rotationally symmetrical cell

The results in Table 2 show that it is not possible to close the corner elements of the No. 1 type dome. The 12k rovings splice and slip over the dome while winding. It has been shown that by designing the dome as shown in figure 3, the roving will get damaged at the corner area. In addition it has been observed that the roving lost its defined tray track in the corner area. A reliable winding procedure is not given. The dome geometry has to be reworked.
The main effort was to smooth the edges of the corner. For this purpose type 2 and type 3 were built up. Type 2 still has the same height than type 1 with the difference that the proceeding in the direction of the pole, the meridian of the corner, is continuously tangentially rounded till it reaches the pole. By designing the edge like this no more splicing rovings are seen. Nevertheless a slipping of the roving in the edge of the corner can be observed.

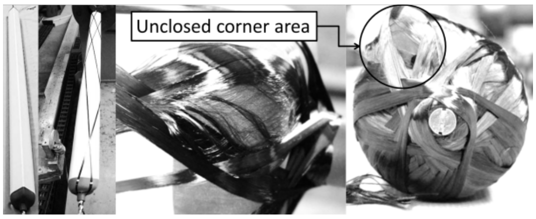
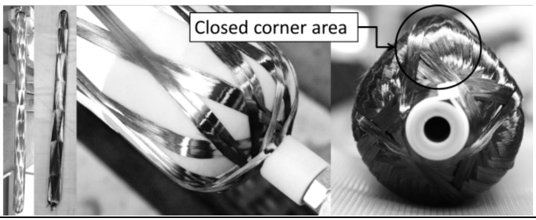
Dome type	**Geometrical properties**	**Result**
Nr. 1	• Dome geometry has been designed by the approach shown in fig. 3	
Nr. 2	• The meridian of the corner is rounded tangent continuous till it reaches the pole	
Nr. 3	• Rotation symmetric area is built mathematically by using (1) • Tangent continuous splines close the corner area	

Table 2. Experiment results of the full winding of non-rotation-symmetrical vessels with different dome geometries

Dome type 3 is the final design of the domes. The main design difference is that this dome's rotationally symmetric area is built after the formula (1) and the corner area is constructed by using two tangentially continuous splines that end in the isotensoid spline created by the formula (1). By using two tangentially continuous splines it is possible to design a continuous curvature corner area with no geometric leaps. By using this design method it is possible to fully polar wind a non-rotationally symmetric vessel. With the achieved winding angle of 7° the possibility of bearing the axial load has to be examined.

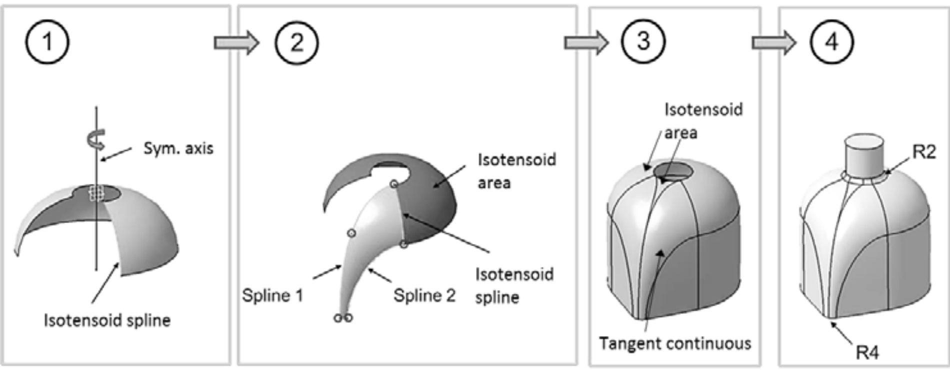


Figure 5. Construction of the full woundable dome for the non-rotationally symmetrical corner cell

4. 3D winding

4.1. Winding procedure

After it is shown that the axial load of every cell can be taken with polar winding of every cell, the radial load of the mounted cells of the shape adaptable tank has to be absorbed by a 3D winding layup, shown in figure 6.

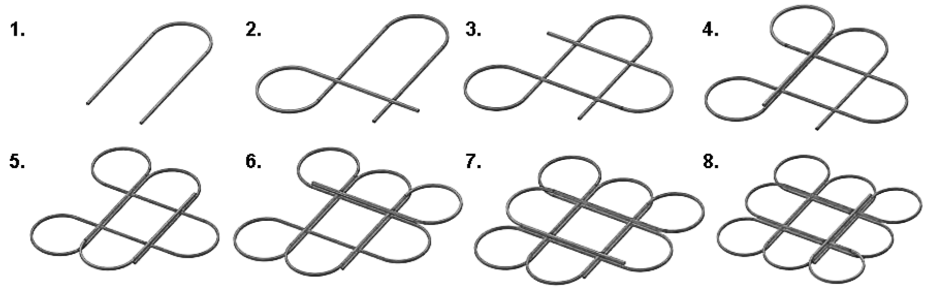


Figure 6. Example of the first lay of a 3D-winding layup for a 3x3 shape adaptable tank [strass]

Figure 6 shows the complexity of the 3D-winding layup. The roving has to pass by every cell. With this winding-layup it is possible to bear the radial load on the edges and corners of the composition (shown in the figure is a 3cell x 3cell layup).

4.2. 3D-Winding tool

One of the challenges in developing a tool that makes it possible to wind this complex layup is that the device has to have a maximal width of 2 mm and a length of 500 mm. By designing a tool with these properties it is possible to have a defined laying track. Further it is possible to work as a wet winding process while it is robot-controlled, so different construction principles (e.g. 3x3 cells, 3x6 cells, 5x12 cells) can be build up. Figure 7 shows the first machine to wind the 3D-winding layup, furthermore the 3x3 cell-mock-up is seen, and where the validation of the tool will be done.

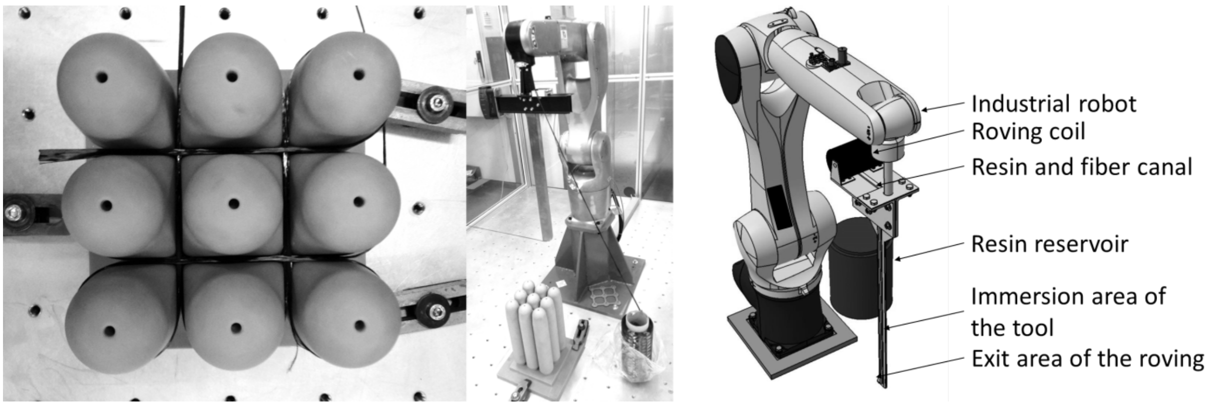


Figure 7. 3D-winding tool designed and first 3D-layup on the mock-up is shown

5. Summary

The new manufacturing process, combined with the tank concept, leads to a volume gain of up to 38 % compared to conventional CNG storage systems, based on the available space in the vehicle. For this a new winding process has been presented. This paper showed results of the polar winding of non-rotationally symmetrical vessels, the newly designed domes and the first tool for the 3D-Winding-System.

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