NOVEL STRUCTURE-INTEGRATED HYDROGEN STORAGE SYSTEMS FOR AEROSPACE AND AUTOMOTIVE APPLICATIONS

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Keywords: hydrogen, composite pressure vessel, composite design, manufacturing

ABSTRACT

This paper presents a novel pressure vessel design for gaseous hydrogen storage, addressing the need for efficient and reliable storage methods. The proposed design utilizes an innovative load introduction method to enable thinner configurations compared to state of the art pressure vessels and from this a better utilization of rectangular design spaces. The manufacturing process involves semi-automatic winding, with ongoing research focusing on full automation. Initial testing of a prototype showed promising results regarding leakage resistance, although improvements to the sealing concept are being developed. Burst pressure testing validated the load introduction concept, with no material failures or cracks observed. However, matrix cracks occurred above 40 MPa, highlighting the need for improved sealing of the load introduction. An enhanced sealing concept is being implemented, including an elastomeric sealing ring and a mechanical mechanism for pre-tensioning the load introduction. The novel pressure vessel design offers potential weight savings and efficient use of design spaces. Integration in applications like aircraft wings provides structural benefits. Future work involves manufacturing and testing new prototypes with the improved sealing concept. Overall, this work contributes to the development of efficient pressure vessels for hydrogen storage, supporting the transition to cleaner energy sources. The proposed design shows promise for addressing key challenges in hydrogen storage, promoting broader adoption of hydrogen as a sustainable energy solution.

1 INTRODUCTION

Over the last few decades, the concentration of CO_2 in the atmosphere has increased steadily due to the combustion of fossil fuels, measuring below 320 ppm in 1959 (Mauna Loa) and currently just under 400 ppm (Mauna Loa, 2010) [1]. To minimize further emissions of climate-active gases, researchers are exploring alternative energy sources, among which hydrogen (H_2) is a promising candidate. Hydrogen occurs naturally on earth only in chemically bound form and serves as a crucial feedstock for the chemical industry [1]. With its high gravimetric energy density of 33 kWh/kg, H_2 is suitable for various mobile applications [1]. Hydrogen can be stored in different forms, including pure H_2, chemically bound H_2, and surface adsorption [2]. Pure H_2 can be stored as a liquid, gas, cryo-compressed, or a mixture of solid and liquid (hydrogen slush) at the triple point, T=13.8K [3]. Chemically bound H_2 can be stored in metal hydrides, liquid organic hydrogen carriers, or in a chemical compound like ammonia NH_3 [2]. The different forms of storage have varying volumetric energy densities, with liquid, cryo-compressed, and hydrogen slush having the highest densities, albeit difficult to store due to their cryogenic temperatures. These storage forms are mainly used in the aerospace industry, while liquid and cryo-compressed systems can be employed in commercial vehicles [4, 5].

Pressurized storage in pressure cylinders is less complex and thus suitable for a wide range of applications. Common nominal pressures range from 20 MPa to 100 MPa, with 70 MPa considered optimal for storage as it offers the best trade-off between volumetric and gravimetric energy density [1, 2]. Previous pressure tanks can be categorized into four types. Type 1 consists of pure metal cylinders, the standard in mobile CNG applications (up to 30 MPa) [2]. Type 2 is similar to Type 1, but its metal shell is overwrapped with fiber-reinforced plastic in the cylindrical area. Type 3 has a complete FRP wrapping of the inner metallic tank, achieving weight reduction through a thinner metal shell. Type 4 is the current state-of-the-art, comprising a composite cylinder with a non-metallic liner and mostly metallic boss parts. Type 4 pressure tanks have a substantial weight advantage over the other types. Type 5 tanks are currently under research, where the composite material acts as a permeation barrier.
Pressure tanks are typically designed to have a spherical or cylindrical shape due to the favorable stress distribution they provide under high pressure loads. However, this design can lead to an incomplete use of the available rectangular design spaces, particularly for larger cylindrical pressure tanks. To address this issue, previous projects have investigated various designs and concepts, known as conformable tanks, that allow for better exploitation of the available design space. These flat tank designs must be able to withstand high pressure loads of up to 70 MPa and resist deformation, which requires vertical reinforcements to be applied when deviating from the cylindrical shape. Different design principles with various vertical reinforcements are used for such conformable tanks, including the use of fibers or rovings as tension rods [6–8] or the implementation of ribs [2, 9].

Another approach to better utilize the design space is to manufacture small, thin cylinders and reduce the gaps between them. By doing so, the shape of the cylinder suitable for high stresses can be retained while still exploiting the most of the design space [10, 11]. Several other concepts have also been described in previous works [7–9, 12–17], but many of these flat designs have faced issues such as leakage, challenging manufacturing processes, or poor weight efficiency. To address these issues, this work proposes a novel tank design with an innovative load introduction method.

2 NOVEL PRESSURE VESSEL DESIGN

In order to make the most efficient use of design space or to exploit small design spaces (e.g. wings), pressure vessels need to be manufactured in very thin configurations. However, the conventional wound pressure vessel design is very difficult to achieve this due to the need for a minimum radius to prevent fibers from slipping off the dome in the turning area and to ensure sufficient fiber tension during winding. As a result, most type 4 pressure tanks have a diameter larger than 220mm [2]. Thus, a new construction method is necessary to enable the manufacturing of slim tanks with diameters smaller than 200mm.

Pressure tanks are subjected to loads similar to tension/compression struts, where only axial and radial forces are present. Therefore, a patented form-fit load introduction, originally used for highly loaded tension/compression struts of the IVW, has been adapted for use as a tank boss part [18–21]. The load introduction is based on the splitting of the plies and the uniform distribution of forces into individual plies. The principle is shown in the figure below.

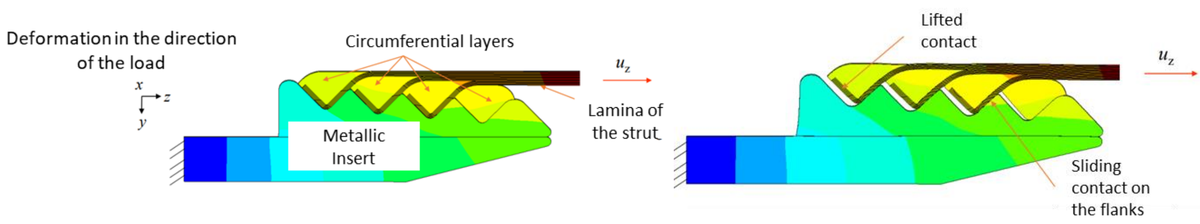

Figure 1: Principle of the IVW-load introduction [18–20]

The axial tube layers are placed in different grooves and are fixed with circumferential layers. Under load, the axial plies slide up the grooves-flanks and the tube expands. However, the circumferential layers that are subjected to tensile stress prevent this expansion and the resulting sliding along the contour. Similar approaches for form-fit load introduction can be found in [22–25].

One disadvantage of this variant is the relative displacement of the metallic insert and the FRP plies in relation to each other [26]. The extent to which this causes problems needs to be investigated, especially with cyclic loading, as it can lead to fatigue failure such as fretting [27].

This principle is now adapted for a cylindrical pressure tank. Struts need circumferential layers only in the load introduction. Only axial layers are otherwise present in the entire rod. In order to sustain the high pressure of 70 MPa, twice as many circumferential layers as axial layers must be provided according to the barlow's formula [28]. The circumferential layers are therefore no longer limited to the load introduction area, but extend over the entire length of the pressure vessel. Furthermore, axial compression forces are no longer to be expected. Accordingly, the grooves can be design differently. In addition to the laminate, a liner is integrated. For the first development, an aluminium liner is chosen. This can later also be replaced by another/lighter material (e.g. PE or PA). Tightness is ensured via the overlap area between the load introduction element and the liner. Due to the internal pressure, the end of the insert is pressed onto the liner and thus provides a self-reinforcing solution.

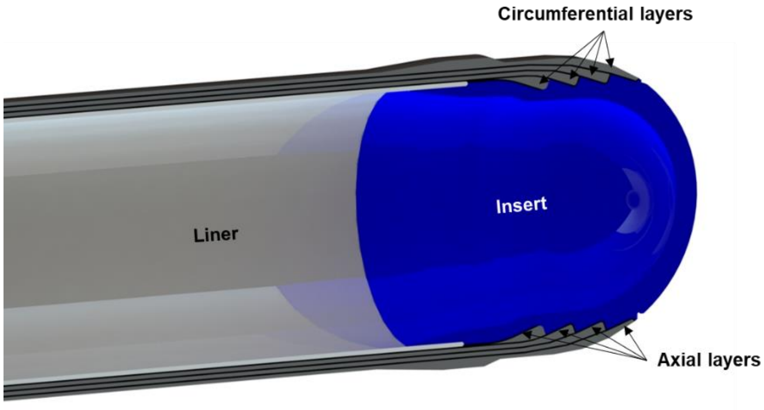

Figure 2: CAD-Model of the pressure vessel

The insert is also an aluminium part. Other materials (e.g. short-fiber reinforced plastics) are also feasible in further development stages. Since only the general concept is to be tested for the moment, the choice of a diameter is not crucial. The first prototype has a diameter of 70 mm. However, smaller or larger tanks are possible. The tank is designed for a burst pressure of 157.5 MPa. This corresponds to a nominal pressure of 70 MPa with the necessary safety factor of 2.25 [29].

By manufacturing very thin tanks, a high packing density can be achieved. In this way, optimal utilisation of the available (mostly rectangular) design space can be achieved. Here, a fictional design space of 1310 mm x 560 mm x 2200 mm is considered. In this design space, 27.5 kg of hydrogen can be stored in the tanks (70 MPa). The thin pressure vessels can also be integrated in design spaces where conventional tanks cannot be used due to their bigger diameter. An aircraft wing is a possible example. Thick winded tanks cannot be installed in the thin cross-section (here d=100 mm). The newly developed tank design, on the other hand, can substitute the normally necessary spars and stiffen the wing. This is possible because the laminate outside the load introduction has strength reserves. The load introduction is the limiting factor here, due to the complex three-dimensional stress interactions. Therefore, the usual laminate is slightly overdimensioned.

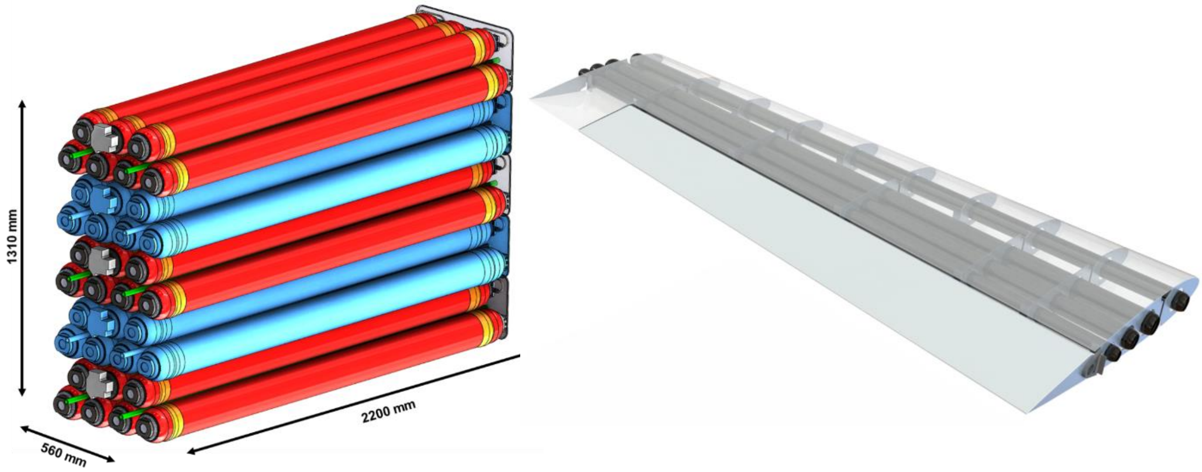

Figure 3: Examples for different applications of the pressure vessel; left: Stack of small cylinders in a Heavy-duty vehicle; right: pressure vessels integrated as load-bearing structures in a small aircraft wing

3 MANUFACTURING AND BURST PRESSURE TESTING

To validate the concept, a first prototype is produced using a semi-automatic winding process. To realize the axial layers, a winding star is needed, which is attached to both inserts, as shown in the lower left image 4. The inserts were anodized to prevent corrosion. Then, the metal parts are treated with a release agent to prevent adhesion of the metallic load introduction elements to the composite layers.

When winding the 0° layers, the carbon fiber roving is guided around the individual needles of the winding star. After the first layer is applied, the first circumferential layer is wound. The first grooves in the load introduction are completely filled with carbon fibers. Then, the axial layer is cut off at the end of the groove and the rovings are removed from the winding star. Then, the next 0° layer is applied. This process is repeated until all layers are applied to the container. The manufacturing process currently involves many manual steps and is therefore very time-consuming. A upfollowing research project focuses on the development of a full automated manufacturing process.

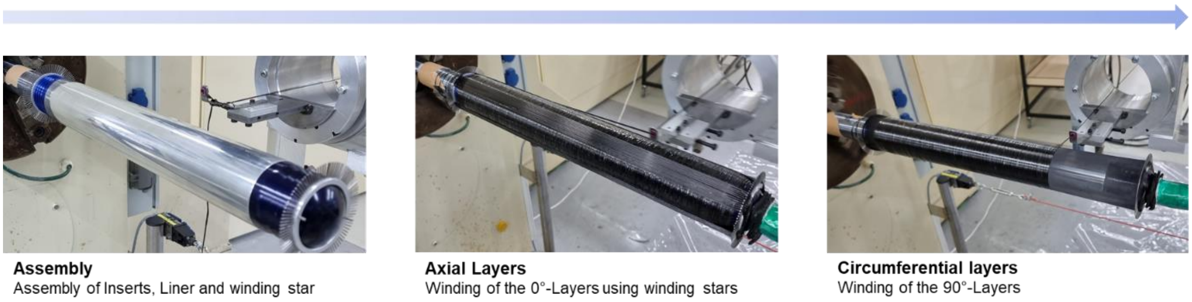

Figure 4: manufacturing process of the pressure vessel

The composite tank is then cured at room temperature, as increased temperature can lead to leaks due to different thermal expansion coefficients (aluminum - CFRP). After curing, the tank was post-cured at T = 50°C in the oven. The first prototype has dimensions of 70 mm x 500 mm. It weighs 1100 g and can store 45 g of hydrogen. However, this first prototype is oversized and a thicker liner as necessary was used.

Figure 5: First Demonstrator for burst pressure test

Therefore, there is a high potential for weight savings. The prototype was subjected to an initial leakage test in a protective chamber. This is carried out with water. A pressure level of 40 MPa was reached. At this pressure, the pressure could not be further increased, and water leaked through the shell. The diagram below shows the pressure-test.

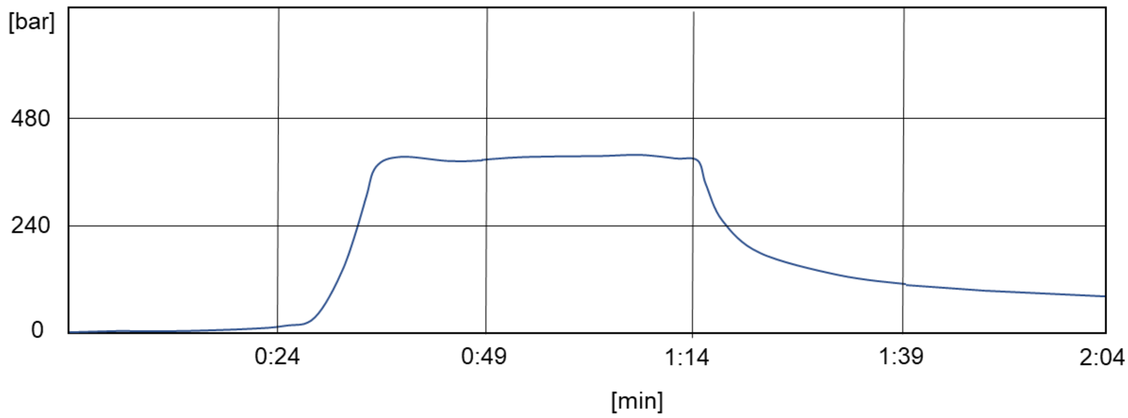

Figure 6: Pressure-time plot of the first burst pressure test.

In a subsequent leakage test up to 1 MPa, this container was again leak-proof. Therefore, it is suspected that the cracks have closed again. After the pressure test, the tank was cut and the load introduction was examined, as failure was suspected here. No cracks or material failures were visible. Therefore, it was concluded that the connection between the liner and insert was not leak proof. The water was pressed through between the liner and insert (see right picture in figure 7 and directly loaded the laminate. Above 40 MPa, matrix cracks occurred, and water leaked out of the shell at the different spots. This is shown in the left picture.

Figure 7: Burst pressure test of the pressure vessel

Nevertheless, the results confirm the basic concept of load introduction and thus of the H_2 pressure tank. In order to solve the leakage problems, an improved sealing concept is being developed. In order to ensure sufficient tightness already at the beginning of inflation, an elastomeric sealing ring is integrated into the insert. This sealing ring must be compressed. Therefore, a mechanical mechanism is designed which enables a pre-tensioning of the load introduction. This is implemented with a conical connection. The cone connection consists of two parts. An inner metallic cone and the outer metallic insert. By applying an axial tensile load, the inner cone slides along the tapered flank. This creates a radial force component which acts on the sealing ring and the load insert.

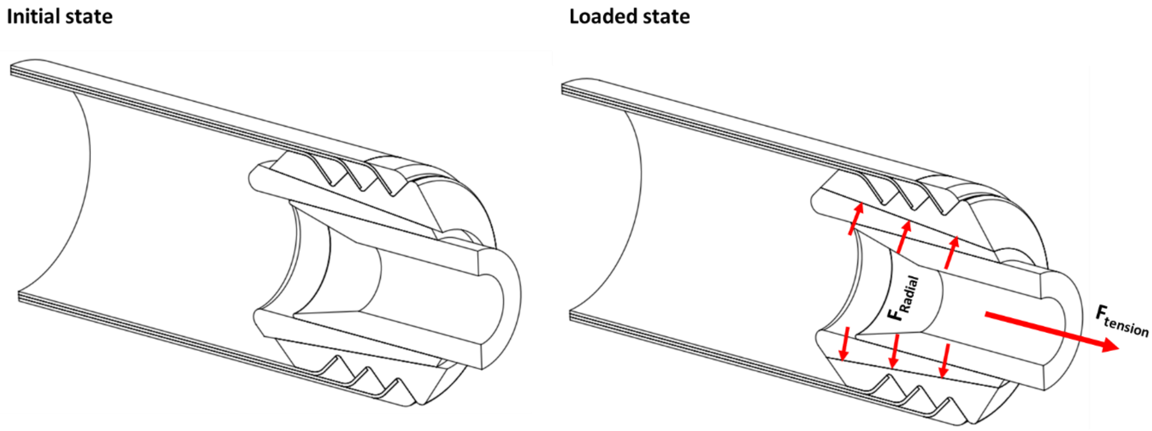

Figure 8: principle of the improved Load introduction (patented)

The pre-tensioning can be done with a tensile testing machine by means of adapters. The principle is shown in the figure 8. In addition to the sealing, the load introduction, or more precisely the circumferential layers, are also put under pretension. This reduces the relative displacement under internal pressure caused by the way the load introduction works. Also the stress peaks are reduced. As a result, a further improvement of the load introduction is achieved. When loaded by the subsequent internal pressure during operation, the cone is pushed even further outwards until it is eventually in the end position. To test the improved pressure tank design, new prototypes are now being manufactured and tested in burst pressure tests.

9 CONCLUSIONS

By using a load introduction for highly loaded tension rods, a new pressure tank design was implemented. This enables the production of very thin pressure tanks, which achieves an improvement in various application scenarios compared to previous conventionally wound pressure tanks. The new

design was successfully manufactured in an advanced winding process with the aid of winding stars. The new design was tested in an initial burst pressure test. Above 40 MPa, cracks appeared in the matrix and water leaked out. This suggested a leak in the load introduction. Therefore, the load introduction and the associated leakage concept were further developed. This further development achieved a significant improvement of the load introduction, a reduction of the stress peaks and the relative displacement in the load introduction. The simulation results are very promising.
The new design must now be tested in further bursting pressure tests.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the funding in scope of the project „WaVe - Development and prototype testing of hydrogen combustion engines as emission-minimizing drive systems for commercial vehicles in the medium-duty segment“ which is funded by the Federal Ministry of Economic Affairs and Energy on the basis of a decision by the German Bundestag (funding reference 19I21028K)

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