MODELLING OF COMPOSITE TANKS PRODUCED BY FILAMENT WINDING

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ABSTRACT

Gaseous storage of hydrogen in Type IV pressure vessels is an emerging technology, however there is still much to be explored around structure optimisation of these types of tanks in order to meet cost requirements. The filament winding process has become the industry leading technology for manufacturing this type of tank and provides a wide range of process factors to consider in order to create a reliable product. This work investigated the effect of stacking sequence of the hoop and helical layers that make up a Type IV hydrogen tank, to understand its role in stress distribution under pressure. ComposiCAD was used to establish the optimal helical winding angle required to provide full coverage of the tank, based on the tank geometry and size of boss. Netting theory was then used to calculate the thickness of hoop and helical layers required for the safety requirements for tank manufacture. The filament wound laminate was then studied with changing stacking sequences using the ANSYS APC module. The tank was simulated under a loading of 350 MPa. For the investigated sequences, the results show the considerable influence of stacking sequence on the laminate's ability to distribute the stresses at pressure. An alternating helical hoop wind was shown to the best performing stacking sequence.

1 INTRODUCTION

As a potential green energy carrier, the generation, delivery and end use of hydrogen continues to increase in popularity. As a result, there is an ever growing need for hydrogen pressure vessels. In all cases these vessels must adhere to strict safety regulations. With nominal working pressures typically between 350 Bar and 700 Bar [1], there is potential for serious injury if a tank were to fail. Various pressure vessel types have evolved in the last few decades, ranging from all metal (Type I) to fully fibre-reinforced (Type V) tanks where the primary aim is achieving weight savings while maximising pressure ratings. The filament winding process has become the industry leading technology for manufacturing Type IV hydrogen tanks, which is the focus of this work. There are many factors involved in the winding process and careful consideration is needed to create a reliable product [1]. In addition to the materials used to wind the tank, the winding angle is of upmost importance to the strength and ultimately the failure behaviour of tank [1], [2]. For example, during bursting it is important to ensure that the failure is concentrated in the mid-section of the tank, thereby ensuring that the metal boss components do not become projectiles if the tank were to burst [3]. The design, analysis and fabrication of wound pressure vessels is a complex task as they are:

- Multi-material structures with a great number of interfaces.
- They contain complex ply sequences.
- The dome shape depends on the variation of the thickness, angle of plies, and their stacking sequence in the cylindrical part.

In this work, various stacking schemes were analysed for a 350 Bar Type IV hydrogen storage tank. The tank design tools available within the filament winding software ComposiCAD were used to identify the appropriate helical winding angle for full coverage. Netting theory was used to calculate the laminate thickness to ensure the thickness was appropriately selected to withstand the nominal working pressure. A number of lay-up schemes were simulated to evaluate the effects of different stacking sequences on the strength of the tank. The ACP module within ANSYS was then used to define the composite material properties and model the selected winding angles.

2 METHOD

2.1 Identification of Helical Winding Angle

Determining the ideal helical winding angle for a filament wound pressure vessel requires careful analysis and consideration of various factors, including mechanical properties, structural integrity, and performance requirements of the tank. The appropriate angle for the tank must be identified to distribute the loads evenly throughout the pressure vessel, ensuring optimal utilisation of the material's strength. The helical winds in a pressure vessel provide torsional rigidity to the tank [1], so it is vital full coverage is achieved. The filament winding simulation software ComposiCAD was used to identify the optimum winding angle for an 800 mm x 300 mm diameter liner featuring a boss in either end.

The angle used is defined as the geodesic angle. At this angle, the angle of the fibre in the cylinder section results in a specific pole opening size, when following the geodesic path over the dome. This is the most stable path along the mandrel contour, where the least amount of friction is required to hold the fibre in place. The geodesic angle is defined as:

$$Geodesic\ angle = \ sin^{-1}\left(\frac{pole\ diameter}{cylinder\ diameter}\right) \tag{1}$$

Using Netting Theory, a wind angle of 54.7 degrees is required to ensure sufficient load carrying of the fibres for a pressure vessel wound utilising helical only wraps [4]. This, however, is too steep an angle to wind over the dome surface of the mandrel, causing excess slippage of the fibres. To mitigate the slippage effect, the dome regions fail to be completely covered as shown in Figure 1:

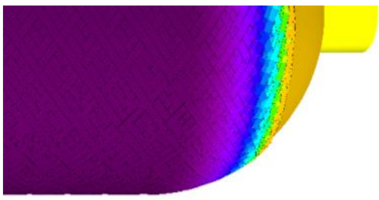

Figure 1. A section of the dome region of a mandrel wound at an angle of 54.7 degrees with the mustard coloured section showing the section of the mandrel that remains uncovered.

To ensure that there is complete fibre coverage of the mandrel, a number of circuits of the wind pattern is required. Too few circuits results in the tank having gapping between the fibres. Figure 2 shows a tank with a wind angle of 13.2 degrees, using 100 circuits, resulting in 69% coverage:

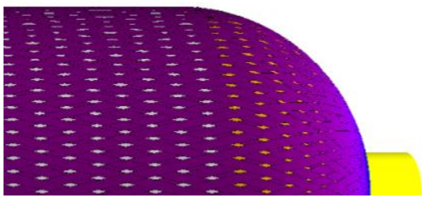

Figure 2. Tank wound at 13.2 degrees with 100 circuit repeats, yielding 69% fibre coverage.

Figure 3 shows a section of a tank wound at 13.2 degrees, using 145 circuits, resulting in the optimal 100% fibre coverage, while minimising overlapping tows and fibre slippage.

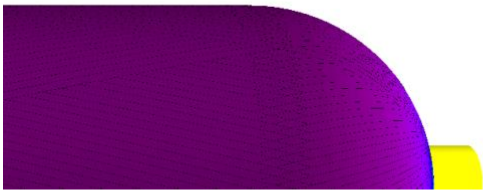

Figure 3. Tank wound at 13.2 degrees, using 145 circuit repeats, resulting in 100% fibre coverage.

2.2 Identification of Laminate Thickness using Netting Theory

Using netting analysis, the designer may compute a beginning thickness for hoop and helical layers. Netting analysis is a calculation of the composite layer thickness to which the tank has to be designed too to withstand pressurisation of the tank. Netting theory is used to compute the number of layers for hoop winding and helical winding as a simple and well-suited approach for the construction of filament-wound pressure vessels [5]. It is assumed that the fibres maintain the whole internal pressure and that the resin plays no role in bearing the load. Tew has stated that the fibre thicknesses of the hoop and helical layers of a wound shape can be calculated using Equations (2-5) [5].

$$N_\theta = PR, \tag{2}$$

$$N_\varphi = \frac{PR}{2}, \tag{3}$$

$$\tau_{hoop} = \frac{N_\theta \cos^2\alpha_2 - N_\varphi \sin^2\alpha_2}{\sigma_{\alpha 1}(\cos^2\alpha_2 \sin^2\alpha_1 - \sin^2\alpha_2 \cos^2\alpha_1)}, \tag{4}$$

$$\tau_{axial} = \frac{N_\theta \cos^2\alpha_1 - N_\varphi \sin^2\alpha_1}{\sigma_{\alpha 2}(\cos^2\alpha_1 \sin^2\alpha_2 - \sin^2\alpha_1 \cos^2\alpha_2)}. \tag{5}$$

Where,

τ_{hoop} = thickness of hoop layer
τ_{axial} = thickness of axial layer
N_θ = hoop load
N_φ = helical load
α_1 = helical winding angle
α_2 = hoop winding angle
$\sigma_{\alpha 1}$ = allowable fibre stress in helical direction
$\sigma_{\alpha 2}$ = allowable fibre stress in hoop direction
P = internal working pressure
R = inside radius

Teijin ITS50 material was selected as the material for both the hoop and helical layers. The method set out by Tew was used to find the allowable fibre stress, assuming a long term loading modifier (static fatigue) of 60%, a thermal degradation modifier of 80%, and a stress concentration factor modifier of 75% [5]. An allowable fibre stress of 1840 MPa was calculated. Using equations (2-5) method it was identified that the tank required 6.26 mm of hoop winding and 3.39 mm of helical winding to withstand the design pressure of 350 Bar, including a factor of safety of 2.25.

2.3 Simulation Setup

The design of composite layer was simulated using ANSYS ACP. Carbon fibre was used to investigate the effect of the helical and hoop stacking sequence on the stress distribution within the composite layer. The carbon fibre layers were applied at the hoop and helical winding angles selected previously, as illustrated in Figure 4. The number of plies needed to achieve the hoop and helical thicknesses, previously calculated using netting analysis, was obtained from the thickness of the tow of the Teijin ITS50 material. Table 1 sets out the properties for this material. With a tow thickness of 0.5

mm, 13 layers were needed for the hoop winding, and 7 layers for the helical. ANSYS Composite PrepPost (ACP), an integrated tool in the ANSYS workbench developed for composite laminate modelling, was used to apply these composite layers. The orientation of rosettes was set as cylindrical to match the circular winding pattern of the filament winding process.

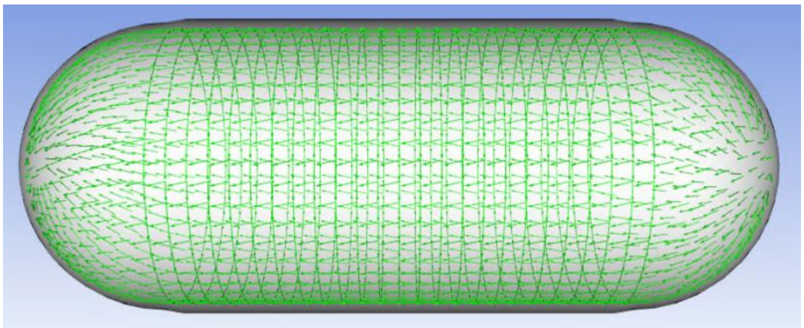

Figure 4: Illustration of the Applied Hoop & Helical Wind Fibre Directions.

Properties	**Teijin ITS50**
Bandwidth/ thickness (mm)	6.35 +/- 0.5 mm
Format	Pre-preg
Tex value or denier	>= 1600
Resin density	1.195 g/cm^3
Fibre density	1.80 g/cm^3
% Volume of fibre	65 +/- 2% fibre content
Ultimate fibre tensile stress	5100 MPa
Ultimate fibre tensile elongation	1.9 %
Modulus of elasticity for local axis 1, 2, 3	E1 168 GPa, E2 9 GPa, E3 9GPa
Poisson's ratio for local plane 12, 13, 23	V12 0.1, V13 0.1, V23 0.3
Shear modulus of elasticity for local axis 12, 13, 23	G12 5 GPa, G13 5 GPa, G23 3.7 GPa

Table 1: Material properties for Teijin ITS50.

ANSYS Static structural analysis was used to simulate the loading of the tank at its working pressure of 350 Bar. The composite ply structure was combined with the assembly of a Nylon 6 (PA6, Arkema Inc.) liner and 316 Stainless Steel metal bosses before conducting the static structural analysis. Fixed supports were added on both ends of metal bosses, allowing only sliding along the tank's length. All components were assumed to be 'bonded' to each other. Von–Mises maximum stress was obtained in all cases to analyse the effect of changing the stacking sequence on the performance of the tank.

2.4 Experimental Plan

Most studies in the past assume a helical-hoop alternating winding pattern [4]. This is referred to as Scenario 1 (S1) $[88/0/88]_7$. Six other scenarios of balanced stacking sequences, either hoop layer first or helical layer first, were analysed in the work to observe their effect on the burst performance of the tanks, as set out in Figure 5.

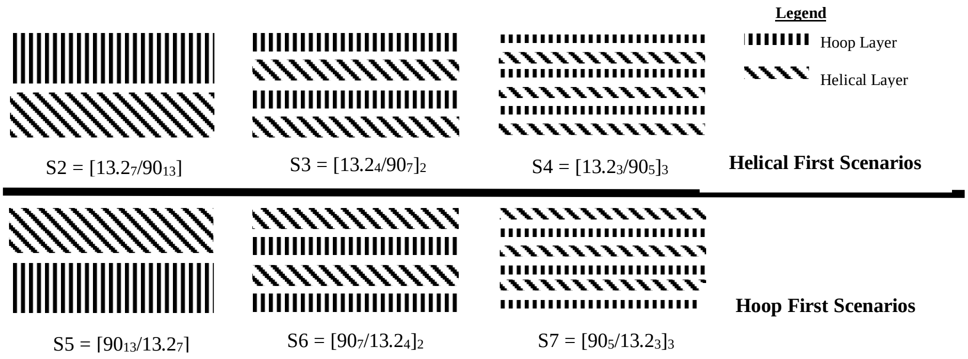

Figure 5: Schematic of the Analysed Stacking Sequences.

3 RESULTS & DISCUSSION

The following figures show how the stress distribution in the composite changes with varying stacking sequence. Figure 6 shows the stress distribution for an alternating helical – hoop winding pattern (S1). From the stress distribution it can be seen how the stress is mainly concentrated in the transition between dome and cylinder section of the laminate, with the stress being evenly distributed between both the internal and external laminate faces. The maximum stress predicted for this scenario was 1043 MPa.

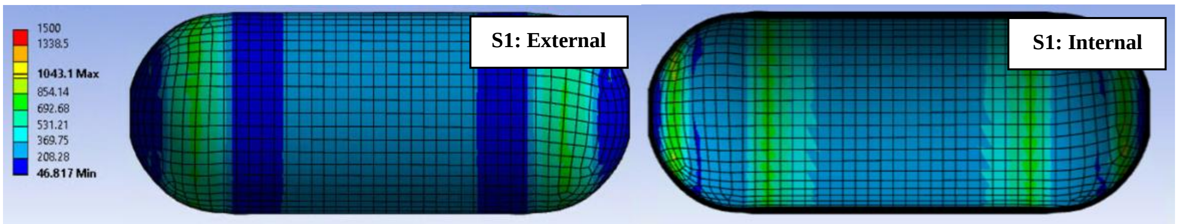

Figure 6: Stress Distribution for S1.

Figure 7 shows the stress distribution for S2 (helical layer first) & S5 (hoop layer first). In both scenarios all of the respective layers are stacked together. It can be seen that the maximum stress changes from the internal to the external laminate faces depending on whether the helical or hoop wind is first. The maximum stress (3057 MPa) was observed at the dome to cylinder transition area of the inner laminate face of S5.

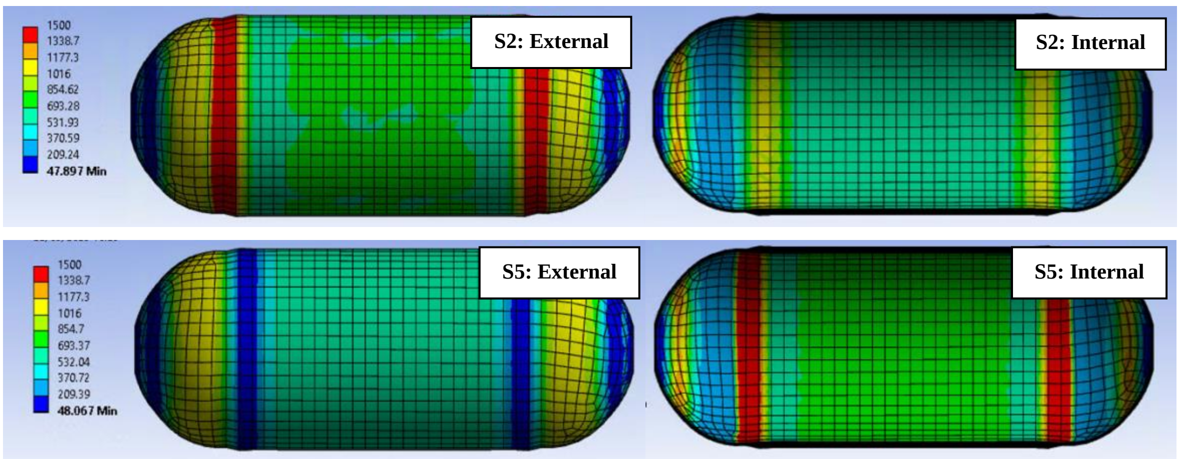

Figure 7: Stress Distribution for S2 & S5.

Figure 8 shows the stress distribution for S3 (helical layer first) & S6 (hoop layer first). As per Figure 7, the maximum stress changes from the internal to the external laminate surface depending on whether the helical or hoop wind was first. The maximum stress (2314 MPa) was again observed at the dome to cylinder transition area of the inner laminate face of S6.

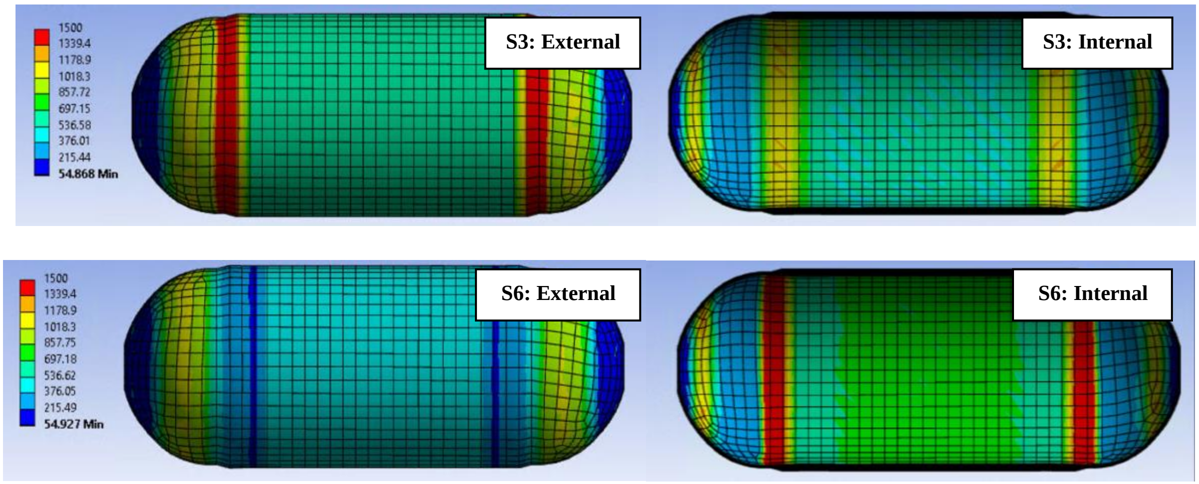

Figure 8: Stress Distribution for S3 & S6.

Figure 9 shows the stress distribution for S4 (helical layer first) & S7 (hoop layer first). As per Figure 7 and 8, the maximum stress again changes from the internal to the external laminate surfaces depending on whether the helical or the hoop wind is first. The maximum stress (1915 MPa) was similarly observed at the dome to cylinder transition area of the inner laminate face of S7.

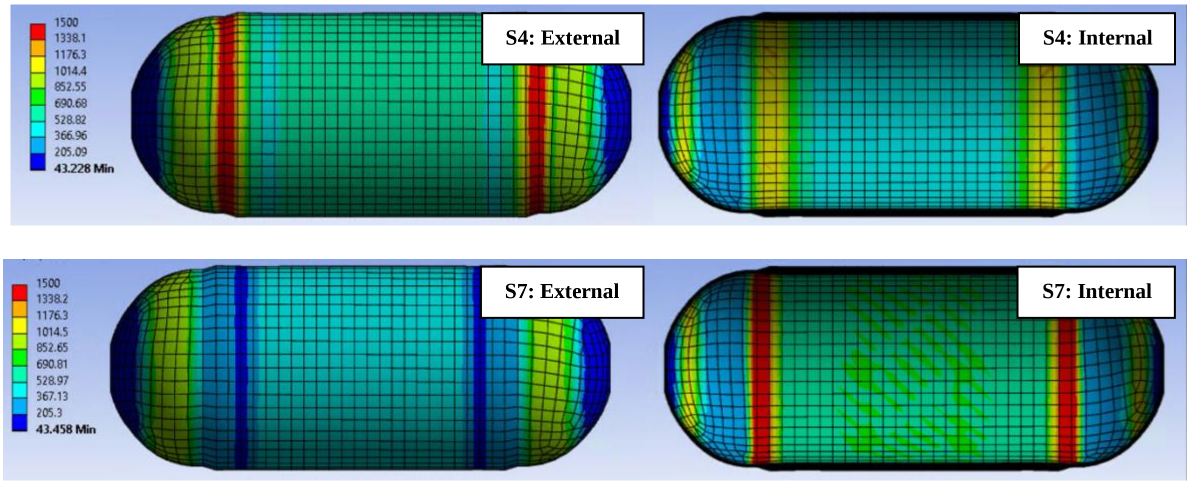

Figure 9: Stress Distribution for S4 & S7.

S1 with an alternating helical hoop wind was shown to the best performing stacking sequence. This is why this stacking sequence is commonly practiced within industry [6]. All of the results agree with previous findings which have shown that the stacking sequence has a considerable influence on the laminate quality.

4 CONCLUSIONS

This work investigated the effect of stacking sequence of the hoop and helical layers that make up the composite outer layer of a Type IV hydrogen tank to understand its role in stress distribution under pressure. ComposiCAD was used to establish an optimal helical winding angle required to provide full coverage of the tank, based on the tank geometry and size of boss. Netting theory was then used to calculate the thickness of hoop and helical layers required for the safety requirements associated with tank manufacture. The filament wound laminate was then studied with changing stacking sequences using the ANSYS APC module. The tank was simulated under a loading of 350 MPa. For the investigated sequences, the results show the considerable influence of stacking sequence on the laminate's ability to distribute the stresses at pressure. An alternating helical hoop wind was shown to the best performing stacking sequence.

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