GENERAL SYMPOSIA | MODELING AND SIMULATION

Design Optimization of Rotationally Molded Hydrogen Pressure Vessels

Alex Pritchard, Peter Martin, Mark McCourt and Mark Kearns

DOI: https://doi.org/10.51573/Andes.PPS39.GS.MS.3

December 2024

View Online
Export Citation

Design Optimization of Rotationally Molded Hydrogen Pressure Vessels

Alex Pritchard, Peter Martin, Mark McCourt and Mark Kearns[1]

Abstract: Type IV hydrogen pressure vessels are made up of three components: a metallic boss, a polymer liner, and a composite overwrapping layer for reinforcement. Leakproof design of bosses is critical for safety, ensuring a gas-tight seal to prevent explosions due to leaks. Yet, their design has been largely overlooked. Using rotational molding it is possible to fully encapsulate bosses within liners during molding, but numerous challenges must be overcome relating to boss design for effective molding. FEA software was applied to virtually prototype boss designs and optimize their mechanical performance under pressure. CAD and FEA software were integrated in this work, enabling basic geometry constraints to be input in CAD, which were then fine-tuned in FEA in response to stress distribution results. This allowed the FEA model to optimize boss designs autonomously. To ensure moldability, initial boss designs were generated using existing rotational molding experience regarding the encapsulation of small inserts during molding. The autonomous optimization technique was then applied to minimize the boss weight by controlling the size of design features, while ensuring mechanical performance constraints were met.

Keywords: Rotational, Molding, Hydrogen, Boss, Simulation

1 The authors Alex Pritchard (a.pritchard@qub.ac.uk), Peter Martin, Mark McCourt and Mark Kearns are affiliated with the School of Mechanical and Aerospace Engineering at Queen's University Belfast in Northern Ireland.

DOI: https://doi.org/10.51573/Andes.PPS39.GS.MS.3

Introduction

Hydrogen is set to be an important energy vector as the world experiences more global warming and energy security challenges. With advances in technology and wider interest in storage vessels, the polymer industry could diversify their product offerings into new markets. Type IV hydrogen tanks are expected to become more important for storage in dynamic applications (such as cars, buses, trains, etc.). The tanks are made up of three major components, a polymer liner, a composite reinforcement, and metal bosses to allow gas management systems to be attached to the tank (see Figure 1).

Bosses facilitate the loading and unloading of gases from the tanks, and often serve as a mounting point to secure the tank within a larger assembly, such as a vehicle chassis, for example. Boss designs vary based on the process used to produce the tank liner. In blow molded tank liners, the bosses are added in a secondary welding process, however issues with hydrogen leakage have been acknowledged with liners made in this way [1]. Another technique used to produce the liners is rotational molding. This is a process used to produce hollow plastic components such as outdoor furniture and can feature small threaded inserts for assembly [2]. Rotationally molded tank liners can have the boss to fully encapsulated within the liner, providing a stronger connection to withstand leakage [3]. Figure 2 shows an example of a boss for a rotationally molded tank liner, illustrating the size and complexity of the dome that is embedded within the polymer liner.

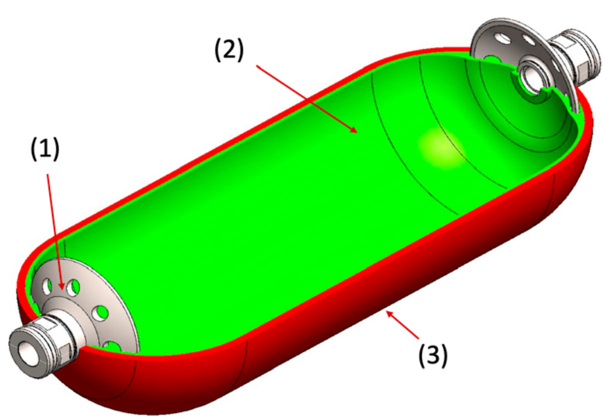

Figure 1. Schematic detailing the (1) bosses, (2) polymer liner, and (3) composite overwrapping of a Type IV hydrogen storage vessel.

Figure 2. Example of a 316 stainless steel tank boss.

Hydrogen storage vessels usually have a nominal working pressure between 350 bar and 700 bar. The filament winding process has become the industry's leading technology for manufacturing Type IV hydrogen tanks. In general, there are two types of winding patterns, known as hoop and helical windings, as shown in Figure 3. High angle hoop windings are used to provide circumferential strength to the tank, while lower angle helical windings provide greater longitudinal/axial strength. As illustrated by the example of a wound tank in Figure 4, the process involves winding fibers (usually glass or carbon) under tension around a rotating mandrel, which is the tank liner and bosses itself for Type IV hydrogen tanks. While the liner rotates around a spindle, a delivery head moves back and forth horizontally in line with the rotating axis, laying down the fibers onto the rotating liner in the desired angle to the rotational axis. There are many factors involved in the winding process and careful consideration is needed to create a reliable product [4]. The major cost in hydrogen tank manufacturing is the carbon fiber layer, and hence there is research that has focused on understanding optimization and minimization [3-6].

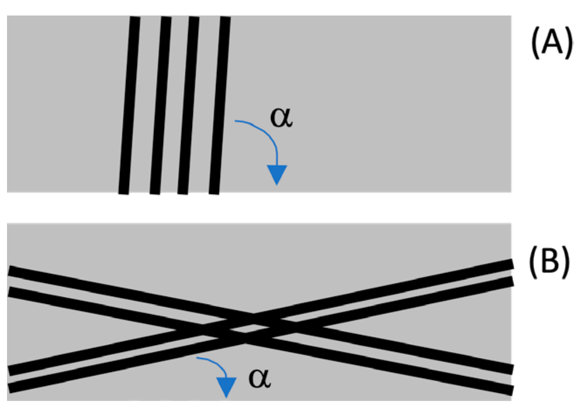

Figure 3. Schematic illustrating the difference between a (a) hoop and a (b) helical winding angle.

Figure 4. Example of a filament wound Type IV hydrogen tank.

For rotational molders, the most challenging aspect of molding tank liners is the encapsulation of the metallic bosses within the polymer liner. Adequate encapsulation is vitally important as this junction poses a potential hydrogen leak path if the liner material were to separate from the metallic boss. To date there is very little research published regarding the optimization of boss designs for the rotational molding process. It is necessary to understand how design elements contribute to the performance of a boss both during molding and throughout its life in the tank. This work explores the of modeling and simulation to virtually prototype boss designs.

Method

Boss Design Simulation & Optimisation

Figure 5 summarizes the design methodology used in the work. The process began by establishing the design constraints of the tank, including the tank diameter, length, nominal working pressure, on-tank-valve thread size, and design safety factor. Following this, the boss diameter was found using the on-tank-valve thread size and nominal working pressure. Non-conformable tanks typically have a boss at one or both ends, forming a hole in the composite layer known as the polar opening (pole diameter). For optimal winding, the geodesic angle must be found using equation 1. At this angle, the angle of the fiber across the cylinder section results in the required polar opening size, when following the geodesic path over the dome. The geodesic angle is also the most stable path along the mandrel contour, where the least amount of friction is required to hold the fiber in place.

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

Figure 5. Type IV hydrogen pressure vessel design methodology followed in the work.

Netting theory, a tool commonly used to estimate the composite thickness needed to withstand the maximum design pressure of composite pressure vessels, was applied [7]. A geodesic winding angle of 13.4 degrees was obtained based on a polar opening size of 70 mm, and total laminate thickness of 14.8 mm were required. The simulation tools available in ANSYS were used to optimize the constituent components of the tank, refining the initial estimations. The models were simulated as axisymmetric models to reduce computation time, studying ¼ of the total tank. Certain dimensions, such as the diameter of the boss (the part embedded within the liner), were set as global parameters, allowing the simulation to drive their values. For improved accuracy, the laminate was modeled using the ANSYS Composite PrepPost (ACP) module, allowing fiber direction, fiber and resin properties, and stacking sequence to be taken into consideration. The materials properties are set out in Table 1 [8]. Standard materials of Nylon 6 (PA 6) for the liner and 316 Stainless Steel for the bosses were used, along with the default mesh settings. Surfaces where the boss to liner, and boss to laminate, were in contact were assumed to be bonded together. A pressure of 35 MPa was applied uniformly to the inner surfaces, representative of the working pressure of commericially available tanks used in heavy goods vehicles.

Prototype Boss Encapsulation Study

A final design was selected to be trialed using state-of-the-art robotically controlled electronically heated rotational molding equipment (courtesy of AMS, Belgium). The boss was 3D printed in stainless steel using a MetalX 3D printer and molded into a liner using settings typical of a PA6 moulding in the industry to access its encapsulation performance. An articulating borescope (Extech, HDV540) was used to inspect the encapsulation after demolding.

Table 1. Material properties for Teijin ITS50 [8].

Properties	
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

DOI: https://doi.org/10.51573/Andes.PPS39.GS.MS.3

Properties	
% 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	E_1 168 GPa, E_2 9 GPa, E_3 9GPa
Poisson's ratio for local plane 12, 13, 23	ν_{12} 0.1, ν_{13} 0.1, ν_{23} 0.3
Shear modulus of elasticity for local axis 12, 13, 23	G_{12} 5 GPa, G_{13} 5 GPa, G_{23} 3.7 GPa

Results and Discussion

Design Optimization

A range of boss designs were generated, making use of existing knowledge of sintering and densification during the molding process, and other boss features not typically considered due to machining constraints. Example designs are shown in Figure 6.

The direct optimization tool within ANSYS was used to identify the effect of the three common boss design features (holes, ribs, and castellations) by controlling their respective sizing within preset limits. The objective given to the tool was to minimize stress in the boss component while also minimizing weight. Figure 7 shows the optimal designs for each of the three scenarios. It was identified that the use of ribs resulted in the highest strength to weight part (σmax 340 MPa, weight 2.1 kg). Although holes are typically found on used rotationally molded metal inserts to encourage polymer bridging through the boss, to date no research has been conducted on the optimization of such features. In this study, it was found that stress concentrated at the edges of the holes (Figure 7[c]), which resulted in the optimization tool trying to make the holes as small as possible. To work effectively during molding though, the holes would need to be large enough to encourage polymer powder to pass freely through them during molding. It is acknowledged that for Type IV pressure vessels 'the dominating failure mode is directly related to the liner,' and that 'defects in the area of the connection between a boss and the liner material' are found during hydraulic testing of poorly constructed liners [9]. Although encouraging polymer bridging through holes in the boss could help to strengthen the connection between the boss and liner.

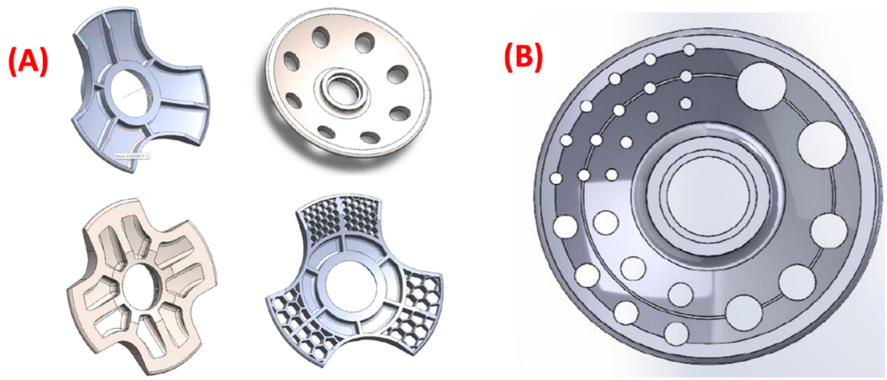

Figure 6. (a) Example boss designs based on parameters optimized for rotational molding, (b) Example of a boss design for identifying the optimum hole size for molding.

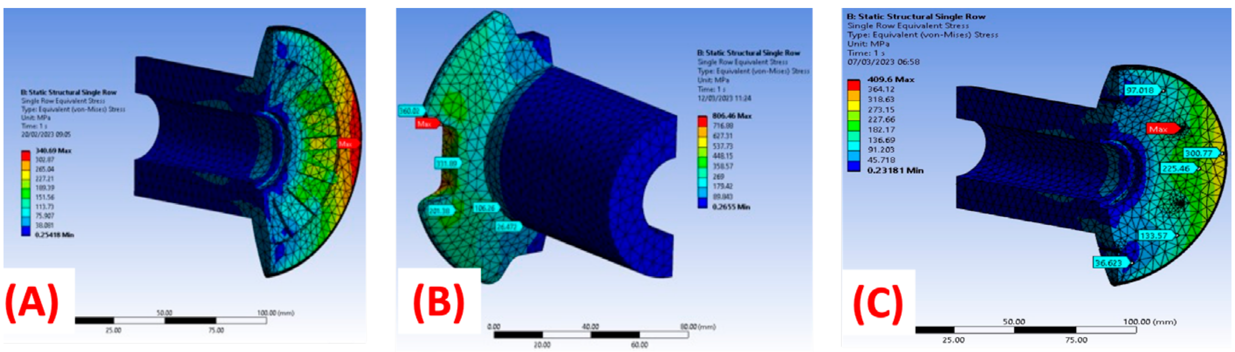

Figure 7. (a) Stress distribution on metal boss using ribs, (b) castellations, and (c) holes.

Industrial Encapsualtion Study

Molding trials were conducted using an electronically heated rotational molding tool, as shown in Figure 8(a). Tanks with 3D printed bosses encapsulated within them were produced, as shown in Figure 8(b). As previously indicated, bosses act as a heat sink and although additional metal may increase the part strength in a simulation, it may not perform well during molding. This effect is illustrated in Figure 8(c) and (d). Boss designs featuring thinner sections were found to be more encapsulated within the polymer during molding, due to their ability to absorb heat energy from the polymer being reduced. Designs featuring holes were found also to increase encapsulation of the polymer, bridging through the boss and acting to lock the boss in place, as illustrated in Figure 8(e).

DOI: https://doi.org/10.51573/Andes.PPS39.GS.MS.3

Figure 8. (a) Liner molded using electronically heated rotational molding tool, (b) Example of a single ended tank liner with a boss, (c) Boss acting as a heat sink resulting in poor encapsulation, (d) Onset of encapsulation on the inside face of a boss, (e) Part of a Metal Printed Boss Prior to Molding.

Conclusion

This work investigated the design of Type IV hydrogen tanks through virtual prototyping tools. ANSYS ACP was used, allowing the model to account for composite properties such as fiber direction and fiber and resin properties. Dimensions such as the diameter of the boss (the part embedded within the liner) were set as global parameters. The direct optimization tool was applied to study the effect of three common boss design features (holes, ribs, and castellations) by controlling their respective sizing within preset limits. The use of ribs resulted in the highest strength part with the lowest mass (σmax 340 MPa, weight 2.1 kg). Designs with holes showed high stresses around the hole, resulting in the optimization tool minimizing hole diameter. These designs which would not mold effectively as polymer powder would not pass through the holes. However, the polymer bridging caused larger holes during molding could be beneficial to strengthening the bond between the polymer and boss to prevent hydrogen leakage. Further work is ongoing to explore boss designs for polymer bridging while minimising stress.

DOI: https://doi.org/10.51573/Andes.PPS39.GS.MS.3

Acknowledgments

This work is supported by the Center for Advanced Sustainable Energy (CASE). CASE is funded through Invest NI's Competence Centre Programme. The author also thanks the Engineering and Physical Sciences Research Council (EPSRC) for supporting his participation in this conference.

References

1. Motaharinejad V, Delnaud L, Fouque M, Lucas A, Shirinbayan M, Fitoussi J, et al., “Enhancement of adhesion between the polymeric liner and the metallic connector of high-pressure hydrogen storage tank”, *International Journal of Material Forming*, vol. 14, pp. 249-260, 2020.
2. Wallin, Steelcore Plastics, Johnson, Durus Industries, Inc. (Presentation), “Where Metal Meets Plastic”, *19th Annual Fall Meeting, Association of Rotational Molders*, 1994.
3. Munzke D, Duffner E, Eisermann R, Schukar M, Schoppa A, Szczepaniak M, et al., “Monitoring of type IV com-posite pressure vessels with multilayer fully integrated optical fiber based distributed strain sensing”, *Materials Today: Proceedings*, vol. 34, pp. 217-223, 2021.
4. Azeem M, Ya HH, Alam MA, Kumar M, Stabla P, Smolnicki M, et al., “Application of Filament Winding Technology” in Composite Pressure Vessels and Challenges: A Review. *Journal of Energy Storage*, vol. 49, 103468, 2022.
5. Alam S, Yandek GR, Lee RC, Mabry JM., “Design and development of a filament wound composite over-wrapped pressure vessel” *Composites Part C: Open Access*, vol. 2, 100045, 2020.
6. Nebe M., Asijee T.J., Braun C., van Campen J.M.J.F., Walther F., “Experimental and Analytical Analysis on the Stacking Sequence of Composite Pressure Vessels”. *Composite Structures*, vol. 247, 112429, 2020.
7. Tew B.W., “Preliminary Design of Tubular Composite Structures using Netting Theory and Composite Degradation Factors”, *Journal of Pressure Vessel Technology*, vol. 117, pp. 390-394, 1995.
8. Teijin Limited (Personal Communication, 2022). ITS50 24k/ Epikote 05940 (Epikure 05900 towpreg).
9. Gąsior P, Wachtarczyk K, Błachut A, Kaleta J, Yadav N, Ozga M, et al., “Validation of Selected Optical Methods for Assessing Polyethylene (PE) Liners Used in High Pressure Vessels for Hydrogen Storage”, *Applied Sciences*, vol. 11, 5667, 2021.