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Effective Structural Design Procedure for Composite Hydrogen Tanks

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1 Introduction

On-board storage of hydrogen is a major challenge in the development of future fuel cell based automotive propulsion systems [5]. One standard is the pressurized storage at 700 bar in composite tanks [13]. Several systems including metal or plastic liners are currently under development or in small scale production. However, the conventional technology is unlikely to fulfill the increasing demand for an affordable product in mass production [4]. The expanding market will offer novel opportunities for existing and new suppliers, but any competitive solution will require an optimization of the tanks with respect to both structural efficiency and manufacturing aspects like productivity and reliability.

The key driver for the efficient design of composite pressure tank systems is the understanding of the structural behavior of the complete vessel during the product's life time - including manufacturing. An effective development process will apply adequate modeling and analysis techniques early and integrative to reduce time and cost. The modeling should include the simulation of the manufacturing process to capture decisive factors for product performance and reliability. Evaluation of the structural performance will generate feedback for manufacturing parameters during the optimization loop. Manufacturing and testing of prototypes will generate further feedback necessary for accurate modeling. An effective structural design procedure can only be conceived as integral part of the development process and not as an afterthought to cope with upcoming problems.

The simulation-based design procedure was applied in the H_2 700 NRW project and contributed to the optimization of the developed 700 bar hybrid composite hydrogen tank for automotive applications [7]. Procedural details from this project will be presented together with experiences from similar development projects for composite pressure vessels.

2 Composite Pressure Vessels

The typical composite pressure vessel comprises four main components as shown in Figure 1: Composite hoop windings, composite helical windings, the liner and fittings [6]. The fittings are necessary to connect valves or pipes. The liner is responsible for the gas tightness and may be made of metal or plastic material. From a conceptual point of view the metal liner can be considered to be load carrying or non-load carrying (thin metal liner), the plastic liner is practically never load carrying. In the case of a metal liner the fittings may be an integral part. If they are not, special attention must be paid with respect to the proper connection between fitting and liner.

The composite helical windings cover the entire or most of the surface area of the pressure vessel and have very specific properties due to the nature of the filament winding process [11]. Finally, the hoop windings are only present in the cylindrical part of the pressure vessel and form a purely circumferential reinforcement. The composite hoop and helical windings together have to take all or a substantial part of the pressure load. A successful design will consider all parts of the pressure vessel – individually and with respect to their interaction. In the following we will focus on the structural design of the composite winding and the metal liner.

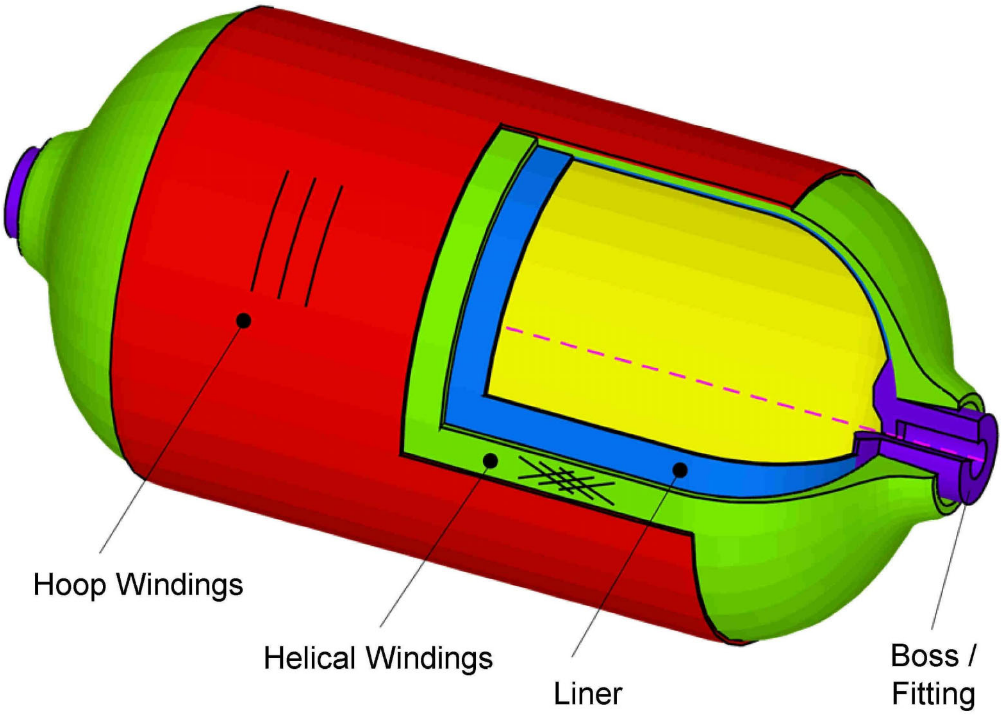

Figure 1: Composite pressure vessel.

3 Structural Behavior

The two overriding concerns with respect to the safety and economy of high pressure vessels are the burst pressure and the number of cycles to fatigue failure. Furthermore, the nature of the respective failure mode is of importance. Typically, both minimum burst pressure and the minimum fatigue life – as well as the circumstances of the related failures – are prescribed in the applicable regulatory codes for pressure vessels (e.g. EIHP [1]). Eventually, conformance of these properties has to be demonstrated by testing to fulfill the safety requirements. From an economic point of view it is necessary not to exceed the safety requirements in any substantial way. Otherwise the resulting product will not be competitive. It is impossible to strike the balance between safety and economy by trial and error alone. The key driver for success is understanding of the structural behavior of the pressure vessel.

4 Modeling Approach

Due to the complicated multilayered, anisotropic composite overwrap and the nonlinear elastic-plastic behavior of the metal liner only detailed modeling and numerical analysis can lead to the required understanding [3,8]. The finite element method is the established and generally accepted method of analysis for demanding engineering systems. It is therefore obvious to use finite element methods for the analysis of composite and hybrid pressure vessels. However, it is less obvious how these models can and should be constructed, given the complexity of the filament wound composite structure. To achieve accurate results it is important to take the details of the manufacturing process into account. This can be achieved by filament winding simulation as shown in Figure 2 [9].

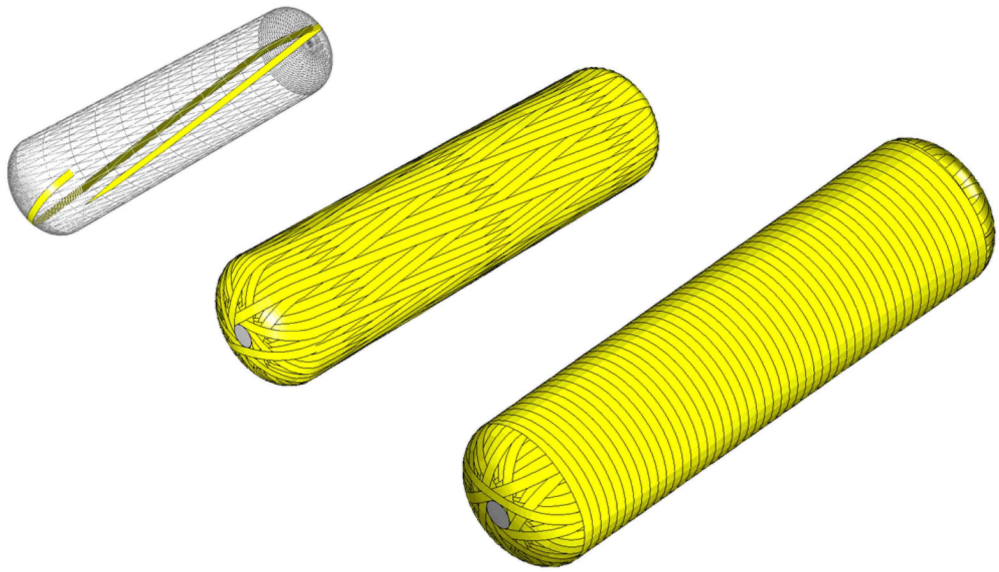

Figure 2: Filament Winding Simulation.

5 Filament Winding Simulation

The exact placement of the filament band on the winding surface is simulated for each wound layer. The final result is a detailed description of the entire composite laminate. A decisive requirement for an economic modeling of the composite structure is, that the detailed description of the laminate is transferred automatically into the finite element model. This can only be achieved by specialized software.

It is noteworthy that the helical layers show a complicated behavior in the end caps of the vessel. The winding angle changes continuously from the cylindrical part to the polar opening (Figure 3). Furthermore, the layer thickness increases due to the progressive overlap of the filament bands on the end caps. Thus, each helical layer is a complex entity in itself. The combination of multiple layers is even more intricate and no longer accessible to simple reasoning. This is reflected in the mechanical properties of the filament wound structure and is manifested in the deformation behavior of the pressure vessel and the stress distribution in the individual layers under internal pressure. The situation is made even more difficult by the dependence of the result on the shape of the dome contour.

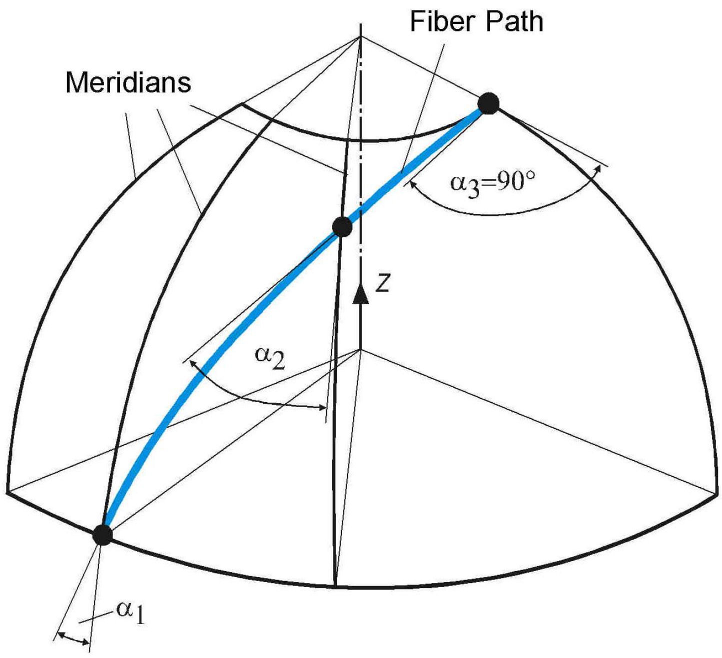

Figure 3: Filament winding path.

6 Iterative Analysis and Design

Under these circumstances neither optimal dome contour nor optimal winding angle combinations are obvious. The best strategy is to simulate the behavior of a given design, evaluate the result and feed back the understanding gained into the design of an improved pressure vessel. This process has to continue until an acceptable result is found. More ambitious optimization procedures (e.g. based on design of experiments) also require the generation and evaluation of large numbers of simulation models [12]. Again, this can only be achieved in an economic way by the support of specialized software. For instance, the evaluation of the stress or strain distribution in each individual layer of the composite laminate must be automatic and should be presented in an understandable way.

An effective way to do this is the creation of path evaluation diagrams of any quantity of interest along a meridian path of the structure (Figure 4).

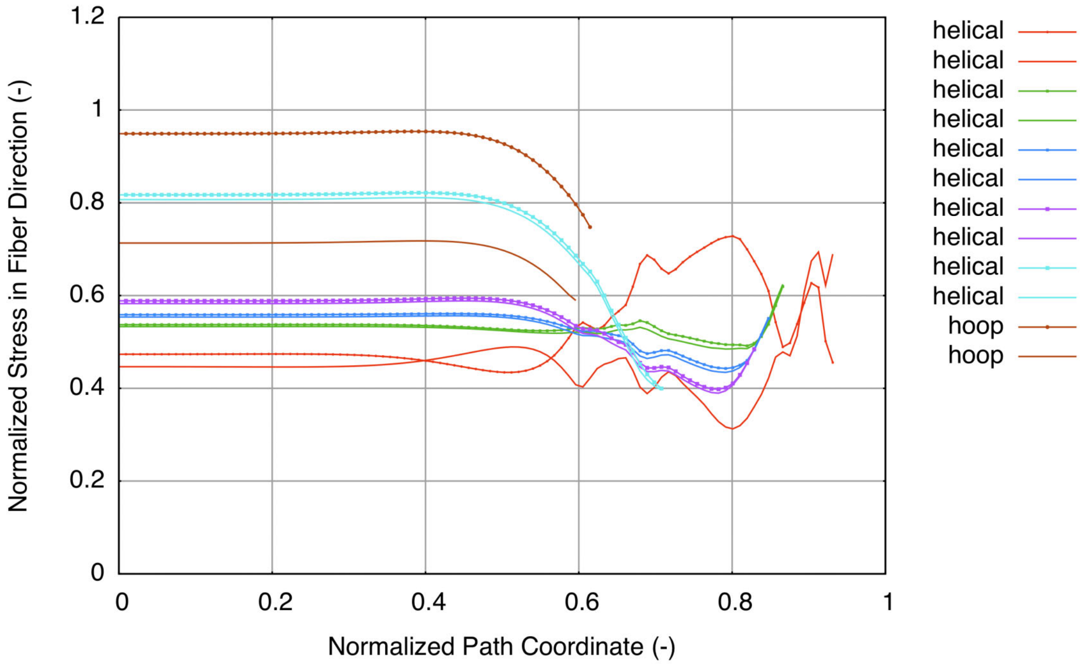

Figure 4: Sample path evaluation.

7 Analysis of Hybrid Vessels

The analysis of hybrid pressure vessels consisting of a composite overwrap on a load-carrying metal liner is more complicated due to the load sharing between the two structural components [2,10]. Fatigue of the metal liner is frequently the primary design issue. Therefore, analysis of the liner is as important as the analysis of the composite laminate. The behavior of the liner will depend strongly on the manufacturing process, namely any forming operation of the liner prior to filament winding as well as the so called autofrettage step. During autofrettage the over-wrapped liner will be pressurized beyond the yield point. This will result in compressive eigenstresses in the liner after pressure relief due to the plastic deformation of the liner. The net effects are a greater elastic stress range and a reduced maximum stress during operational load cycles as well as a negative mean stress – all beneficial factors with respect to fatigue.

Understanding and proper design of this process involves the simulation of multiple load steps as show in Figure 5. This simulation process is best set-up and evaluated automatically since multiple design iterations for liner and composite overwrap are inevitable.

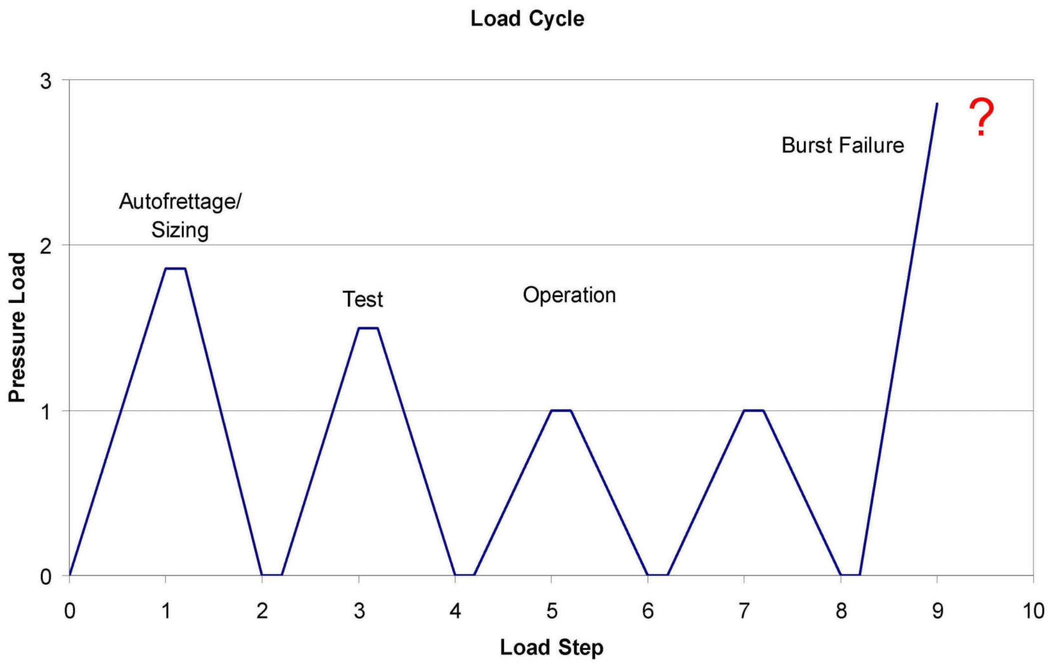

Figure 5: Simulated load steps.

8 Conclusions

As has been shown, analysis and design of composite pressure vessels is complicated and often time-consuming and expensive. On the other hand, the potential of detailed finite element analysis for the optimization of pressure vessels for the storage of hydrogen is undeniable. Therefore a great demand exists to make accurate modeling more timely and economic. ISATEC meats this demand by the development of the ISAWIND® software and process for rapid modeling and analysis of composite pressure vessels including hybrid vessels with metal liners. This process combines filament winding simulation and finite element analysis to an automatic end-to-end procedure for structural analysis from specification to result presentation. With ISAWIND® pressure vessel studies are conducted in a very efficient way. Vessels with different length and different diameters are easily compared concerning their gravimetric storage density, material and production effort. Alternatively a specific configuration is analyzed in detail and optimized by means of ISAWIND® in order to reach the best solution for the given specification in a very short time.

References

[1] European Integrated Hydrogen Project (EIHP): GRPE Informal Group: Hydrogen/Fuel Cell Vehicles, Draft ECE Compressed Gaseous Hydrogen Regulation, Revision 12b, www.eihp.org, 2003

[2] Anders, S.: Sensitivitätsanalyse des Eigenspannungszustandes eines Composite - Hybridhochdruckbehälters, BAM - Dissertationsreihe, Band 37, Berlin, 2008

[3] Betten, J., Multhoff, J.: Untersuchung des Versagensverhaltens von Höchstdruckbehältern aus Faserverbundwerkstoff, Abschlussbericht, DFG-Vorhaben

Be766/40-1 und Be 766/40-2, Lehr- und Forschungsgebiet Mathematische Modelle in der Werkstoffkunde, RWTH Aachen, 2003

[4] Herres, W.-U.: The Hydrogen Fuel Cell Vehicle – A Future Application For Composites, Proceedings of Filament Winding Congress, Brussels, 2005

[5] Krainz, G., Bartlok, G., Meinert, M., Novak, P.: Anwendungsorientierte Entwicklung von Wasserstoff-Speichersystemen für den automotiven Einsatz, Der 4. Deutsche Wasserstoff Congress 2008 – Tagungsband, Schriften des Forschungszentrums Jülich, Band 12, 2008

[6] Krieger, J.: Auslegung und Berechnung von Hochdruckbehältern aus Faserverbundwerkstoff, Dissertation, Lehr- und Forschungsgebiet Mathematische Modelle in der Werkstoffkunde, RWTH Aachen, 2003

[7] Krieger, J., Multhoff, J.B.: Auslegung von Composite-Hochdruckbehältern für H2-Speicherung bei 700 bar (im H2 700 NRW Projekt), Der 4. Deutsche Wasserstoff Congress 2008 – Tagungsband, Schriften des Forschungszentrums Jülich, Band 12, 2008

[8] Multhoff, J.B., Loures da Costa, L.E.V., Krieger, J., Betten, J.: Numerical Simulation of Damage and Failure of Composite Pressure Vessels, COBEM 2003, 17th International Congress of Mechanical Engineering, São Paulo, 2003

[9] Multhoff, J.B., Krieger, J.: Design of Composite Pressure Vessels Using Finite Element Analysis, Proceedings of Filament Winding Congress, Brussels, 2005

[10] Novak, P.: Ein Beitrag zur Strukturoptimierung dickwandiger Hybrid-Hochdruckspeicher, Fortschritt-Berichte, VDI Reihe 18, Nr. 306, VDI-Verlag, Düsseldorf, 2006

[11] Peters, S.T., Humphrey, W.D., Foral, R.F.: Filament Winding – Composite Structural Fabrication, SAMPE Publications, Covina, 1991

[12] Ribeiro, R.O., Loures da Costa, L.E.V., Multhoff J., Milioni, A.Z.:
Composite Pressure Vessel Quality Evaluation using Design of Experiments and Simulation, ENEGEP 2002, XXII International Conference On Industrial Engineering and Operations Management, Curitiba, 2002

[13] Züttel, A.: Hydrogen storage methods, Review, Naturwissenschaften 91, Springer-Verlag, Heidelberg, pp. 157-172, 2004