Kurzfassung

Die effektive Nutzung der attraktiven Materialeigenschaften von Verbundwerkstoffen, insbesondere die der langfaserverstärkten Polymere in Großserienbauteilen, macht nicht nur die Entwicklung entsprechender Fertigungsverfahren sondern einhergehend prognosefähige Berechnungsmethoden für Werkstoff und Bauweise notwendig. Praxistaugliche Berechnungsmodelle beschränken sich in der Regel auf bewusst einfach gehaltene analytische Modelle zur Grobdimensionierung oder auf Finite-Elemente-Analysen. Letztere erlauben, lokale Konstruktionsaspekte darzustellen und detaillierte Einsicht in das Strukturverhalten zu nehmen.

Am Beispiel von mit der Wickeltechnik hergestellter zylindrischer Vollkunststoff-Druckbehälter wurden Auslegungsmethoden für unidirektional verstärkte FKV-Strukturen erörtert, experimentell validiert und zusammen mit analytisch formulierten Randbedingungen bzw. Modellen zu Geometrie, Werkstoff und Fertigung in ein vollparamtrisches, dreidimensionales FE-Auslegungsmodul implementiert. Durch die Auflösung der tragenden Tankstruktur in die einzelnen Wickellagen und der parametrischen Variation von Lagenaufbau und Domgeometrie gestattet dieses eine effektive Bauweisenoptimierung hinsichtlich Gewicht und Werkstoffausnutzung. Insbesondere die neuartige, experimentell verifizierte Beschreibung der einzelnen Wickellagendicken im Behälterdom erlaubt eine der Fertigung entsprechende, im jeweiligen Wicklungslagenende wulstfreie Behältermodellgenerierung.

Gewebeverstärkte thermoplastische Halbzeuge können oberhalb ihrer Verformungstemperatur wiederholt mittels Stempelumformprozess in aufeinander abgestimmten Werkzeughälften umgeformt werden. Für eine effektivere Auslegung solcher Bauweisen durch Verbesserung der Werkstoffmodellierung wird erstmalig die Prozesssimulation mit der Strukturanalyse gekoppelt. Die hierfür entwickelte Schnittstelle vollzieht neben der Datenübersetzung die automatisierte Aufbereitung des Simulationsschalennetzes zum voluminösen Strukturmodell nebst Modellbeschneidung und beinhaltet erste Ansätze zur Abschätzung der Werkstoffkennwerte des infolge der Drapierung nicht mehr orthogonal gewebeverstärkten FKV. Die Berücksichtigung von Fadenorientierung, Dickenverteilung und auftretenden Falten durch Übertragung des Simulationsnetzes erlaubt eine im Vergleich zum Stand der Technik realitätsnähere, durch Bauteilprüfungen validierte Abbildung des mechanischen Strukturverhaltens.

Abstract

The effective use of the attractive material properties of fiber reinforced plastics (FRP), especially of long fiber reinforced polymers in mass production, requires an advanced development of suitable manufacturing processes and prognostic design and analysis methods for the material and structural behavior. This paper resulted out of two research projects, accompanied by industrial, close to series development tasks. The objective was to increase the efficiency of the material, structure and manufacturing aspects of the prototype development through improved modeling methods in analysis and simulation in close relationship with the design, material development and testing facilities.

Mass production capability of thermoforming processing in combination with weight saving potentials on the one hand and thermal and electrical insulation advantages of thermoplastics in comparison to steel on the other hand was the motivation for the development of a safety toe cap for safety shoes made of canvas reinforced thermoplastics. An innovative analysis method for structures made of canvas reinforced plastics which was initiated by this development program focus on a realistic reproduction of the non-orthogonal fiber reinforcement of the woven fabric after the thermoforming process. Canvas reinforced thermoplastics can be simplified as an alignment of small unidirectional fiber reinforced sections in weft and warp direction. The underlying design theories for unidirectional FRP were rehashed and advanced in the framework of a full plastic high pressure vessel development program. To improve the effectiveness of the pressure vessel design work, the mentioned design theories and further specific manufacturing models were implemented in an innovative, full-parametric design module validated by burst pressure vessel tests.

Of importance for the dimensioning and wide application of FRP-structures is the ability to forecast the material behavior, particularly with regard to the frequent lack of measured material properties in practical design work. The conceptual formulation was augmented for the quality assessment of the accomplished design work with a systematic evaluation of the most well known estimations in regards to stiffness and strength properties of unidirectional and canvas reinforced plastics. For non-orthogonal canvas reinforced FRP, as in case of thermoformed components, no appropriate material model is available. A relative easy handling material model for orthogonal canvas reinforced FRP known in literature was augmented to non-orthogonal.

This paper is not dealing with lightweight construction methods but in fact with the objective to improve the praxis relevant design methods of unidirectional and bidirectional fiber reinforced plastics; i.e. including estimations for material properties and manufacturing influences.

The fundamentals of the presented analyses are the consideration of fiber orientation and ply thickness close to reality by analytical models implemented in the FEA like the description of the fiber deposition in a filament winding process.

A significant improvement of the design and analyses methods for unidirectional FRP exemplarity in the case of high pressure vessels made of full plastic has been done by the comprehension of relevant manufacturing parameters, especially through the improved description of the ply thickness in the vessel domes. This was achieved by combining two models, each separately known in literature, to level the bulges at the end of each ply due to increasing fiber coverage and their mathematical description. This leveling meets the practical corrections that also have to be done in a filament winding program in the manufacturing process. Validating measurements on pressure vessel prototypes were performed and showed excellent accordance.

Beyond it, the developed parametric FE analysis tool for cylindrical pressure vessels produced with the filament winding technique enables a time efficient design optimization and analysis because of it's automated model generation. The analysis or evaluation of variants of the load bearing FRP lay-up, the influence of different valve geometry and dome contours necessitates now solely the modification of the input parameters.

For a specific forecast of the achievable burst pressure of a pressure vessel design additional work has to be done. A degradation model has to be implemented in the analysis tool to evaluate the increasing local ply failures until the vessel burst. The main objective for the unidirectional FRP essay of the paper was to improve the model generation and to increase the time effectiveness of the design analysis, which has been achieved. The originally planed implementation of a strength evaluation of pressure vessels in the analysis tool were set back to future work due to the unsufficient amount of vessel tests and for the benefit of a challenging design analysis concept for canvas reinforced FRP.

For thermoformed canvas reinforced FRP the fiber orientation and play thickness can be determined by process simulation. Interfaces to the structural analysis that particularly include the theoretical estimation of material properties and the material modeling are not available in the commercial market. Hence, even the structural analysis of such constructions can not be assumed to be state of the art. Previous analyses of thermoformed constructions depend on material isotropy or neglect the canvas shearing during draping; i.e. the thermoformed woven fabric material is modeled with orthogonal fiber orientation and constant ply thickness. The objective of this paper is to combine forming simulation and structural analysis in a way, that beside the pure data translation, the interface performs an automated transformation of the shell based process simulation FE net to a volumetric structure model including the model trimming and the estimation of the non-orthogonal material properties. The consideration of fiber orientation, thickness distribution and eventually occurring crinkles transferred with the FE net of the process simulation into the structural analysis allows a much more reliable reproduction of the mechanical structure behavior as in comparison to the traditional state of the art analysis which has been validated by extensive prototype tests.

The static, non-linear analysis of the toe cap made of canvas reinforced thermoplastic is accompanied by very successful prototype tests, which in turn pushed this toe cap design ahead. This series are closely linked to material development, as well as new manufacturing technology.