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Evaluation of modeling techniques for a type III hydrogen pressure vessel (70 MPa) made of an aluminum liner and a thick carbon/epoxy composite for fuel cell vehicles

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ABSTRACT

Stress distributions in the composite layers of a Type III hydrogen pressure vessel composed of a thin aluminum liner (5 mm) and a thick composite laminate (45 mm) were calculated by using three different modeling techniques. The results were analyzed and compared with the plausible stress distribution calculated by a full ply-based modeling technique. A laminate-based modeling technique underestimated the generated stresses especially at the border between the cylinder and dome parts. A hybrid modeling technique combining a laminate-based modeling for the dome part with a ply-based modeling for the cylinder part was also tried, but it overestimated the generated stresses at the border. In order for the ply-based modeling technique to carry out precise analysis, a fiber trajectory function for the dome part was derived and the composite thickness variation was also considered.

1. Introduction

Recently, hydrogen energy has become a strong candidate as the next generation pollution–free clean fuel to replace conventional fossil fuels, which emit noxious gases including CO_2 gas [1,2]. The fuel cell is one of the promising energy conversion devices that aims to generate electric energy by burning hydrogen with only water (H_2O) being the only by-product. To use hydrogen practically and extensively in many application fields such as a fuel cell vehicle, we must find a way to store hydrogen gas safely. Many hydrogen storage techniques have been developed: liquefaction, hydrogen gas storage in a tank under high pressure, and hydrogen gas impregnation into metals etc [3]. Among these storage techniques, the hydrogen gas storage method has been commercialized, but the low energy density of hydrogen gas requires a special pressure vessel that can resist the extremely high pressure needed for application of hydrogen energy to vehicles [4]. For the design of high capacity pressure vessels (Type II and Type III) to contain compressed natural gas (CNG) and hydrogen gas etc., pressure vessel structures made of fibrous composites have been studied by finite element analysis and parametric study [5–9]. Of main concern in the finite element analysis was the technique to model the shape of the vessel structure fabricated by the filament winding process and the application of anisotropic material properties to the finite element model. In those previous works, relatively thin composite structures with simple winding patterns were analyzed without consideration of the exact dome geometry. Meanwhile, the autofrettage process, which generates compressive residual stress in a metal liner, was simulated to find ways to enhance the static and fatigue

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Nomenclature

α	Angle between the meridian and a fiber direction at a dome (°)
Ψ	Winding angle in a cylinder part (°)
Φ	Angular position at a dome (°)
E	Young's modulus, GPa
G	Shear modulus, GPa
ν_{12}	Major Poisson's ratio
ν_{21}	Minor Poisson's ratio
X_t	Tensile strength in fiber direction, MPa
Y_t	Tensile strength in transverse direction, MPa
S	In-plane shear strength, MPa
$[Q_{ij}]$	In-plane stiffness matrix in the orthotropic direction, GPa
$[\overline{Q}_{\alpha\beta}]$	Rotated stiffness matrix, GPa
$(FI)_i$	Failure index (i = 1, 2, 6)
$[T_1]$	Stress transformation matrix
$[T_2]$	Strain transformation matrix
z/L	Normalized position in a cylinder
Φ/ξ	Normalized position in a dome
σ_{yield}	Yield stress of aluminum, MPa
$\sigma_{ultimate}$	Ultimate stress of aluminum, MPa
$\varepsilon_{ultimate}$	Strain at the ultimate stress of aluminum
A	Angle to define the meridian line (°)
$A_{\alpha\beta}$	In-plane stiffness, MN/m
D	Arbitrary position on a dome surface
n	Total number of ply
h	Laminate thickness, mm
R	Cylinder radius , mm
r_0	Shortest length from the central axis of a dome to a fiber when α is 90°, mm
r_i	Shortest length from the central axis of a dome to a fiber, mm
$f(r_i)$	Function of a dome shape
$\vec{F}$	Position vector of the fiber
$\vec{V}$	Position vector of the meridian
$\vec{F}'$	Slope vector of the fiber
$\vec{V}'$	Slope vector of the meridian
σ_1, σ_2, τ_6	In-plane ply stresses in ply axis
σ_θ, σ_Z, $\tau_{\theta Z}$	In-plane ply stresses in laminate axis
ε_θ, ε_Z, $\gamma_{\theta Z}$	In-plane ply strains in laminate axis
$\vec{e}_x$, $\vec{e}_y$, $\vec{e}_z$	Unit vectors

strengths of a structure [10–12]. But these efforts (the finite element analysis and numerical simulations) were unable to find the optimal winding pattern and the corresponding appropriate autofrettage pressure of Type II or Type III pressure vessels. Because the autofrettage process involves the non-linear plastic deformation of a liner and anisotropic composite behavior, a more accurate modeling technique was required. The major two modeling techniques of composite laminates of pressure vessels are the laminate-based modeling and the ply-based modeling [13,14]. The former one deals with the average anisotropic properties; therefore, it is a relatively simple way to model pressure vessels but without much accuracy. On the other hand, the latter technique applies the orthotropic ply property to finite shell elements, considering each fiber direction in every single composite layer to predict accurate stress distribution, but it has high modeling complexity. When the composite laminates are relatively thin, both modeling techniques produce almost the same results [14] but as the composite laminates get thicker, both techniques produce results that show large differences. Among the many types of pressure vessels, the Type III pressure vessel, composed of a metal liner and a composite laminate (carbon/epoxy composites), is regarded as a strong candidate for hydrogen gas storage tanks from the perspective of allowable pressure levels (classes of 35 MPa and 70 MPa) [4]. Even though Type III pressure vessels containing high-pressure gases may explode, they are structurally stable because a gas leakage decreases the internal gas pressure, mitigating a catastrophic explosion.

In order to estimate the reliability of hydrogen pressure vessels made of carbon/epoxy composites more advanced design methods have been studied. Liu et al. [15–18] and Zheng et al. [19] investigated reliability of composite pressure vessels using effective parametric studies. In their studies, burst pressure of composite vessels was predicted according to the design parameters related to the composite structures. Camara et al. [20] tried to determine the range of lifetimes for a certain class of hydrogen pressure vessels using statistical study and they evaluated failure probabilities of the pressure vessels as a function of internal pressures. For more precise prediction of the composite failure various finite element modeling techniques were introduced and damage evaluation of the pressure vessels was also taken into account. Bie et al. [21] estimated the fatigue lifetime of composite pressure vessels by a theoretical model using the combination of micromechanics and continuum damage mechanics and the analyzed results were compared with the experimental results. Design methods of composite pressure vessels have been evolved from a simple finite element analysis to advanced optimal design schemes. Park et al. [22] calculated winding patterns of a filament wound composite structure for arbitrary surfaces and then those winding patterns were used in finite element analyses for evaluating structural performance. They verified their finite element analysis results by using experimental data. Various optimal design algorithms were also introduced for the design of composite pressure vessels to find the optimal winding angle, composite thickness and so on [23–26]. Optimal shape design of other types of hydrogen pressure vessels was also carried out by controlling fiber trajectories on vessel surfaces [27–29].

This paper aims to provide the most appropriate practical modeling technique for a Type III hydrogen pressure vessel composed of a metal liner and a thick composite layer. Three different modeling techniques are introduced to model the Type III hydrogen pressure vessel, and stress distributions are calculated and compared with each other to check the accuracy of the results according to the modeling technique. To determine the variable fiber angle in the dome part, a simple formula is derived according to the angular position of the dome structure. The winding pattern used in this paper is not