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Analysis of multi-layered thick-walled filament-wound hydrogen storage vessels

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ABSTRACT

In this paper a three-dimensional elasticity analysis on multi-layered thick-walled filament-wound hydrogen storage vessels is outlined. An exact solution to stresses of the metal liner and each anisotropic layer is presented, based on Lekhnitskii's theory and the generalized plane strain assumption. The governing equation for determining the radial displacement of the hydrogen vessel is derived and the stresses in the cylindrical coordinates are then obtained. The matrix equation that determines the integration coefficients of the governing equation is formulated by considering the boundary and interface conditions. The normal and in-plane shear stresses and the twisting rate of the vessel are calculated for various thicknesses of the aluminum liner; the results are then compared to those presented by Xia et al. It is shown that the addition of the liner significantly reduces the stress magnitude of the hydrogen vessel; this stress magnitude decreases as the liner thickness increases. The results also revealed that the twisting effect is reduced by increasing the liner thickness. The ratio of hoop-to-axial stress is no longer a constant through the vessel wall and varies within the wall thickness. In addition, various combinations of anisotropic composites and isotropic liner materials are here examined to pinpoint preferable material combinations that lead to a lower equivalent stress level of the liner and higher strength reserve of the composite laminate.

Introduction

Filament wound composite pressure vessels have been employed since decades as a lightweight solution to containing gas or fluid under pressure. The filament-wound hydrogen storage vessel is about 70% lighter than steel and about 30%–50% lighter than aluminum lined tanks. In order to achieve a bigger driving range for hydrogen-powered fuel cell vehicles while staying within the volume envelope, weight and cost budget (to be competitive with conventional gasoline vehicles), hydrogen storage vessels are generally expected to operate at pressures higher than 70 MPa; this leads to the need for thick-walled designs. Therefore, thick composite hydrogen storage vessels are important structural elements for on-board hydrogen storage system, which cannot be analyzed by traditional membrane approaches due to through-thickness effects.

The cylinder is one of the most common-used shapes for hydrogen storage vessels; hence the attention is here focused

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on the cylindrical section of a multi-layered thick-walled filament-wound hydrogen storage vessel involving an isotropic metal liner that is fully overwrapped with resin impregnated fibers. The analysis of cylindrical hydrogen storage vessels by elasticity solutions can be divided into "thin wall" and "thick wall". The division point is often chosen as a radius-to-thickness ratio of 10. Thick shells have several distinctly different features from thin shells. One of these features is that in thick shells the through-thickness stress and strain gradients are no longer considered negligible. For thick-walled analysis the radial stress distribution through the wall of the vessel is very important and must be incorporated in the shell analysis. Traditionally, simplified composite analysis techniques rely on the assumption of plane stress, and therefore they are only applicable to thin laminates.

The general theory of anisotropic cylinders has been published by Lekhnitskii [1]. He investigated the plane stresses in a cylindrical shell subjected to internal and external pressures, which is cylindrically orthotropic. By layering a number of such shells and by matching the radial stresses and deformations of adjacent shells at their interfaces, he developed relations describing the stresses and strains in a multi-layer cylindrical shell [2]. Tsai [3] has extended Lekhnitskii's work to the case of generalized plane strain, in which the axial strain of the cylinder is a non-zero constant ($\varepsilon_z = \varepsilon_0$), and applied it to a filament-wound cylinder where each layer of Lekhnitskii's model corresponds to a 'winding layer' of the cylindrical pressure vessel. The assumption based on the generalized plane strain can introduce small errors because the restraint condition itself superposes its own stresses due to internal Poisson's action [4]. Roy et al. [5,6] proposed a simple and efficient design method for thick multilayered composite cylindrical and spherical vessels; the stress analysis is based on the state of generalized plane strain for both open-ended (pipes) and closed-ended (pressure vessel) cylinders. Xia et al. [7] conducted an investigation into multilayered thick-walled filament-wound pipes under internal pressure and developed an exact elasticity solution for stresses and deformations of the pipes based on 3D anisotropic elasticity. It is worth mentioning that this work can be regarded as a theoretical foundation of the simplified elastic solution for thick-walled filament-wound pressure vessels. In addition, Xia et al. [8] outlined an elastic analysis on the stresses and strains in a filament-wound sandwich pipe under combined internal pressure and thermal loading, and under pure bending [9]. Noor and Burton [10] have systematically evaluated the effects of variation in the lamination and geometric parameters of multilayered composite cylinders on the accuracy of the static and vibrational responses predicted by eight modeling approaches. Kitao and Akiyama [11] analyzed and evaluated the progress of failure in thick-walled FW pipes with different winding-angles under internal pressure. Tabakovin [12] presented an exact analytical solution for closed-ended laminated cylinders limited to five layers. Wild and Vickers [13] developed an analytical procedure to assess the stresses and deformations of filament-wound structures under combined centrifugal loading, internal pressure and axial loading. Hyer [14] discussed the results of a layer-by-layer analysis of a thick-walled cross-ply graphite-epoxy cylinder subjected to external hydrostatic pressure. Sayman [15] investigated multilayered closed composite cylinders under hygrothermal loading by using analytical and finite element methods. Ruddock and Spencer [16] proposed a new numerical method for the determination of stress and deformation in laminated and inhomogeneous, anisotropic, elastic and thermo-elastic plates and shells, without recourse to any thin plate or shell approximations. Kokan and Gramoll [17] described techniques for calculating the elastic stresses and strains that would be encountered as a result of manufacture and utilization. Ren [18] presented a 3D elasticity solution for an anisotropic laminated circular cylindrical shell, simply supported under axisymmetric loads and used the power series method for analysis of anisotropic laminated circular cylindrical shells under axisymmetric loading. He also obtained exact solutions for cross-ply laminated cylindrical shells [19]. Chandrashekhara and Gopalakrishnan [20] presented an elasticity solution for a long transversely isotropic multilayered circular shell. An approximate 3-D elasticity solution has been presented for an infinite, thick, orthotropic laminated cylindrical shell of revolution subjected to a distributed pinch load [21]. A three-dimensional analysis of cylindrical shells can be also found in works of Noor and Rarig [22], Grigorenko et al. [23], Noor and Peters [24], and others.

The in-plane twisting phenomenon, caused by the lack of exact symmetry in ply stacking, can be calculated on an individual lamina basis using the methods presented by Sherrer [25]. It has theoretically been shown [26,27] that filament-wound cylinders under internal pressure exhibit twisting even though the lay-up is that of a symmetric angle-ply, i.e., $[\pm\alpha]_n$. This is because the off-axis laminate causes a non-zero resultant in the coupling terms of the transformed reduced stiffness matrix. This twisting gives in-plane shear strains of the cylindrical shell. Hoa and Mannarino [27] investigated twisting in filament-wound cylinders under internal pressure and used two approaches to give a rigorous proof for the existence thereof. The twisting effect has also been taken into account in references [4,5,7,14].

In this paper, a three-dimensional (3D) stress analysis is conducted on multi-layered thick-walled filament-wound hydrogen storage vessels. The hydrogen storage vessel consists of an inner liner for preventing gas diffusion and an outer multi-layered composite overwrap for reinforcing the structure. Several hypotheses are proposed for the formulation of stresses and strains. The equilibrium equations of a representative element in the cylindrical coordinate system are derived and simplified according to the above-named hypotheses. The governing equations for the radial displacements of the liner and each composite layer are determined by substituting the related stress–strain and strain–displacement relations into the equilibrium equations, and by taking the in-plane twisting effect into account. A matrix-formulated system of equations for obtaining the integration constants of the governing equation is given by the traction and interface conditions. The effects of the liner and its thickness on the stress distribution of the composite overwrap layers are evaluated using various liner thicknesses. The Von Mises equivalent stress of the metal liner and the Tsai-Wu strength ratio of the composite overwrap are also calculated for various liner/fiber/resin material combinations to find the best material combination.