Lightweight multilayer composite structure for hydrogen storage tank

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Abstract

Composite pressure vessel has been applied by NASA for the first time. Safe low-cost efficient composite hydrogen-storing device is a key technique affecting the generalization and application of hydrogen energy. By combining the shear theory and based on the highly heave-stable shear behavior shell structure lightweight design, this paper describes researches on the lightweight design of pressure vessel lining and, on the basis of completing the numerical analysis of hydrogen storage tank, extracts its stress isogram, achieving the conformity or tangency of fiber weaving type with stress load isoline and accomplishing lightweight design of the tank and reduced production cost. The method herein can be further generalized to the storage of hydrogen energy and pipe component design.

Introduction

A composite pressure vessel normally consists of composite reinforcing layer, lining layer and protective layer. Over the latest years after application of composite pressure vessel by NASA for the first time, its application fields have been constantly developed and extended [1–3].

Because of the constant differentiation of technologies, the role played by lightweight design and lightweight material is becoming more and more important in fields like aeronautics/astronautics, automobile manufacturing and construction. The benefit is obvious: lightweight can save material on the one hand and save energy in the power system of kinetic structures on the other hand. For large-scale utilization of hydrogen energy, people must address themselves to such key techniques as the making, storage and transport of hydrogen and hydrogen energy conversion. Transport of hydrogen represents a very large part of the entire hydrogen energy supply chain in respect of economy, energy consumption and emission performance. For the generalization of hydrogen energy, therefore, there is an urge to study the lightweight design of hydrogen storage devices and meet requirements on their economy and safety [4–6].

By combining the shear theory, this paper describes researches on the lightweight design of pressure vessel lining and, on the basis of completing the numerical analysis of hydrogen storage tank, extracts its stress isogram, achieving the conformity or tangency of fiber weaving type with stress load isoline, attaining a digitalized 3D auto fiber placement technique, and accomplishing the lightweight design of the hydrogen storage tank and reduced production cost.

Multilayer structure and carbon fiber cross-ply lamination based hydrogen storage tank lightweight design

70Mpa high-pressure gas tanks are used on Toyota Mirai for hydrogen storage. Toyota Mirai carries two hydrogen tanks

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with internal volume of 122.4 L (front 60 L and rear 62.4 L) and total storing capacity of 5 kg. So the weight of fuel is actually not heavy and, on the contrary, the tanks are remarkably cumbersome. With the help of carbon fiber reinforced plastics (CFRP), Toyota Mirai vehicular hydrogen storage tanks attain shell lightweight. At the same time, the physical properties of various fibers can be brought into effective play through combined application of multiple fibers and different fiber weaving types to accommodate forces on different tank areas; hence 40% reduction of fibers used, as shown in Fig. 1.

To ensure driving safety on the premise of withstanding 700 atm, the hydrogen tanks have been designed to have a four-layer structure. The aluminum-alloy tank is lined internally with plastic lining and wrapped externally in a protective layer of carbon fiber reinforced plastics, with one more shock-absorbing protective layer of fiber glass material added outside that protective layer. Fiber grain on each of the layers has been additionally optimized, depending on different positions where it is on the tank, so that the fibers run along the direction of pressure distribution to enhance the effect of the protective layers.

This paper will analyze round-section hydrogen storage tanks with finite element software ANSYS. Since the tanks have a symmetrical structure, we just need a 1/4 model to save our calculation cost, with a tangible unit used as lining and shell unit as wound composite, as shown in Fig. 2. Data in Ref. [7] are used as tank parameters:

1. Wound carbon fiber resin system: its tensile modulus is 135 GPa, compressive modulus is 108 GPa, tensile modulus in the vertical fiber direction is 8 GPa, shear modulus is 5 GPa, Poisson’s ratio is 0.3, tensile strength is 2,400 MPa, compressive strength is 1,000 MPa, shear strength is 76 MPa, and density is 1,800 kg/m³;
2. Metal lining material: $E = 210$ GPa, Poisson’s ratio is 0.3, density is 7,800 kg/m³, yield strength is 800 MPa, and tensile strength is 1,100 MPa.
3. Condition under pressure: the pressure vessels remain under internal pressure of 35 MPa.

Achieving metal lining reinforcement with shear field theory

Mechanical properties of hydrogen storage tanks fiber composite have something to do with stress load direction and fiber orientation

Conventional containers are liable to heave for their shell structure style. To increase heave load and heave safety remarkably, braces or ribs can be used to diminish the main heave field. For the nodal line on the heave outline, these braces or ribs have sufficient stiffness. For shear load (as caused by the bending and twisting of lateral force), however, the stiffness and strength of rib lattice structure are often not great enough. To fill the gap, a layer of thin shell can be introduced to sustain the main shear stress load.

When the heave safety of the thin shell is increased, note that, although the heave field can be kept at a very small value by mounting braces, their bending stiffness and torsion stiffness may be just great enough to induce the nodal line on the heave outline. On the other hand, the lattice shape of rod structure is fairly sensitive to shear stress load and therefore addition of a layer of shell over the structure is of great benefit as it can sustain shear force (as caused by lateral force or torsion). Fig. 3 shows the effect of these two kinds of reinforcement; d) into which a) shell and the brace lattice comprised of b) longitudinal beams and c) ribs are combined has a highly heave-stable shear behavior shell structure [8].

Cylinder heave-proofing stability calculation and analysis

Cylinder stress can be solved by the section method, but not all the problems can. Helical seal head is an example, where the radius of curvature differs from point to point and stress inside the wall varies. Such problems can be solved only by
taking a representative elemental volume from the shell and analyzing its deformation under pressure.

For the heave of a homogeneous linear-elastic thin-wall load-bearing cylindrical shell axially under pressure, its theoretical classical heave stress can be solved through a differential equation derived from the Donnel Equation [9].

Thus in this paper, a shell structure and a highly heave-stable shear behavior shell structure with equal mass and a volume of 60 L are devised and given numerical simulation analysis. It can be known from the result of finite element analysis that the stress values of the two have a same order of magnitude, but the latter is less deformed and, under the action of externally applied concentrated lateral load, has increased flexural stiffness and can bear a greater heave-proofing load.

Stress load size and direction based multilayer fiber path placement

Numerical analysis based round-section hydrogen storage tank stress load size and direction calculations

Based on the mode of construction of fiber composite and a lot of material parameters, relevant direction and position design is carried out according to the state of stress load for the material performance of a composite structure. The anisotropy of the material characteristic values of composite single-layer and laminated plates is of decisive significance in this case. The variation curves shown in Fig. 4 is a comparison between the mechanical characteristic values of carbon fiber epoxy resin composites; they can explain the effect of applied load direction and fiber distribution direction on tensile strength and elastic modulus on the laminated surface. Here, the composites have a same number of layers while the laminated constructions are unidirectional, orthogonal and multidirectional respectively [8]. The laminated single layer shown in Fig. 4 indicates the fiber direction of relevant variation curve instead of the mode of laminated construction. The tensile strength and elastic modulus of cross composite become largest when stress load direction conforms to fiber direction (0° and 90°).

This paper takes a lining externally wrapped with a layer of carbon fiber composite. Numerical analysis is intended to obtain a load pressure distribution isogram for tank body position so that fibers run along the direction of pressure distribution and form cross composition to enhance the effect of the protective layers.

Hydrogen storage tanks are up against more complex circumstances, such as high temperature and high pressure. This implies new requirements on pressure vessel design. Conventional round pressure vessels can meet requirements no longer and researches on non-round ones have started off widely.

The experimental stress method, analytical method and numerical method are main methods currently for stress analysis. The numerical analysis method has been widely applied to engineering. Han Min [10] used ANSYS finite

![Fig. 3 – Highly heave-stable shear behavior shell structure lightweight design.](image)

**Fig. 3** – Highly heave-stable shear behavior shell structure lightweight design.

![Fig. 4 – Comparison between laminated mechanical behavior values of carbon fiber epoxy resin composites.](image)

**Fig. 4** – Comparison between laminated mechanical behavior values of carbon fiber epoxy resin composites.
element software to carry out stress analysis of pressure vessel and got an analysis result that is basically consistent with the true situation. Ma Ya-juan [11] used the finite element method to carry out stress analysis of pressure vessel seal head and the error between her numerical analysis and test is 10% or so.

A stress cloud chart for linings outermost layer is then extracted by ANSYS in accordance with the numerical analysis method stated in Refs. [10,11]. See Fig. 5.

**Fiber path placement with consideration given to hydrogen storage tank stress load and direction**

The helical winding angle on the cylindrical section as taken in Ref. [12] is determined by Equation (1):

\[ \alpha = \arcsin \frac{d_0}{D_0} \]  (1)

where \( d_0 \) is the diameter of the polar axis of the interlining and \( D_0 \) is that of the cylinder.

Helical winding is a geodesic path. Winding angle \( \alpha \) decreases continuously from 90° at the polar axis to \( \alpha_0 \) on the cylindrical section and is determined by Equation (2):

\[ \alpha = \arcsin \frac{d_0}{D} \]  (2)

where \( D \) is the swing diameter.

In ANSYS, Utility Menu > PlotCtrls > Device Options is shown in the mode isoline. In the popped-up dialog box, the check box behind Vector mode (wireframe) is chosen and made on. By clicking on OK, an isogram is generated, as shown in Fig. 6.

Stresses on the cylinder mainly include axial tensile stress \( \sigma_m \) generated by the internal pressure that acts on the end cap, which is known as radial stress or axial stress, and a tensile force known as belt stress or circumferential stress expressed as \( \sigma_q \), which is generated in the tangential direction on the circumference as a result of uniform outward swell of the cylinder under the action of the internal pressure. Since a cylinder is usually a thin-wall container, \( \sigma_m \) and \( \sigma_q \) can be viewed as uniformly distributed and radial stress \( \sigma_r \) is negligible. Therefore orthogonal composition formed through hoop winding and radial winding is a guarantee of conformity of fiber winding direction with load direction. The isogram can reflect areas with same stress rather than the relation between stress variation and the curvature of the camber where the point is located. The method proposed in this paper corresponds to the high-angle helical winding for fringe strengthening and low-angle helical winding for bottom strengthening as used for hydrogen storage tanks on Toyota Mirai.

It can be known from the stress isogram that low-angle helical winding is used at the bottom of the body due to concentration of stresses. Hoop fiber placement at the opening of some model of hydrogen storage tank is optimized. As shown in Fig. 7, the paths of the full lines are the fringe paths of tows while those of the dash lines are tracks taken by the placing robot in the case of full-fiber placement. Using the hoop placement algorithm, tows meet the stress isoline run requirement except for those placed along the hoop in the opening area which, however, play a certain role in remitting stress concentration in that area.

Reinforcement is a must for an opening set up over a composite structure. The opening will cause some fibers in the composite placement layer to be cut off and a hole-side high-
stress area will come into being at the same time; moreover, the anisotropy of composite plate results in a peel-off stress arising in the hole-side area at the time of load bearing due to the fringe effect. All of these will impair the static strength and fatigue strength of the structure. The opening also results in a new boundary occurring to the composite structure so that the composite members have more possibilities of delamination damage and their safety is thereby reduced. Therefore an effective reinforcement measure must be taken for the opening on the composite structure. See Fig. 8.

Conclusion

This paper innovatively proposes a shear field theory based metal lining design for hydrogen storage tank, making it a highly heavy-stable shear behavior shell structure. Based on the technique of numerical analysis of finite element, it replots a stress isogram from post-treatment results, and has them as guide line on the composite placement layer, thereby meeting the cross lamination requirement for laminated material placement layer. This paper directs the lightweight optimization design largely at round-section hydrogen storage tank, which can be further generalized to hydrogen storage device and hydrogen-powered pipe design.

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