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Numerical Simulation of All-Composite Compressed Natural Gas (CNG) Cylinders for Vehicle

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Abstract

Failures of all-composite CNG cylinders for vehicle in service were mainly caused by defects such as crazes, and cracks, etc. in cylinder liners. Authors adopted ANSYS software to conduct numerical simulation of all-composite CNG cylinders, and used a top-down modeling approach to model cylinders, obtaining the cloud diagrams of stress and strain under operating pressure, test pressure and bursting pressure. The main causes of defects were insufficient strength of liner material and unreasonable structure of cylinder. Therefore, designer should select the liner material reasonably and improve the structural design of the transition area from the cylinder body to valve.

Keywords: gas cylinder; all-composite; finite element analysis; simulation; compressed natural gas

1. Introduction

All-composite gas cylinders belong to a novel type of compressed natural gas (CNG) cylinder, which has the advantages of light weight, corrosion resistance, fatigue resistance, and simple production processes, etc. In respect of safety, all-composite gas cylinders will not generate fragments even if bursting due to external force or high-speed impact[1]. A high-pressure gas cylinder for vehicle is one of the key parts of compressed natural gas vehicle, and its safety and reliability will directly influence the operation safety of the vehicle. Four burst accidents of all-composite CNG cylinder for vehicle occurred successively in Henan Province and Sichuan Province in 2004 and 2005 [4] and there are a series of issues exposed in use and regular inspection of all-composite CNG cylinders, so people have queried the

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safety of all-composite gas cylinders now and the development and application of all-composite gas cylinders are encountering bottlenecks[2]. Therefore, it is urgent to study the safety of all-composite CNG cylinders for vehicle.

2. Regular inspection results of all-composite gas cylinders

There were 11,843 pieces of 90-L all-composite gas cylinders for vehicle in Beijing, among which only 3,574 pieces, accounting for 31.2%, passed the inspection. The gas cylinders with the defect of liner bulging and crazing account for 84.85% of total gas cylinders, and the defect is the primary failure [6]. Thus, to improve the safety performance of all-composite CNG cylinders so as to promote the development of all-composite CNG cylinders in China, it is very important to study the causes of liner bulging and crazing.

3. Numerical simulation of all-composite gas cylinder

3.1. Structure and parameters of all-composite gas cylinder

For the structure and geometric dimensions of the all-composite gas cylinder, we referenced the design data of all-composite gas cylinder provided by Xi'an Tianjie Aerospace Technology Co., Ltd. The geometric dimensions of the liner of the 90-L all-composite gas cylinder for vehicle were as follows: overall length 1,400 mm; cylinder body section length 1,145 mm; outside diameter of liner 314 mm; cylinder nozzle length 51 mm; inside diameter of cylinder nozzle 56 mm; outside diameter of cylinder nozzle 80 mm; wall thickness of cylinder body 7.5 mm; and wall thickness at end plate, increasing gradually from 7.5 mm to 29 mm. The dimensions of the gas cylinder with outer reinforcement layer wound: overall length 1,500 mm; outside diameter of cylinder body section 350 mm.

The operating conditions of the all-composite gas cylinder are shown in Table 1.

Table 1. The operating conditions of all-composite gas cylinder [2]

Operating temperature	Operating pressure	Filled medium	Water test pressure	Design bursting pressure	Air tightness test pressure	Service life	Fatigue cycle
-40℃–60℃	20 MPa	Natural gas	30 MPa	73 MPa	20 MPa	10 years	≥ 7500 times

The liner used high density polyethylene (HDPE) material, of which the properties and application-level technical indexes are shown in Table 2 [7].

Table 2. The properties and application-level technical indexes of high density polyethylene (HDPE)

Density (g/cm^2)	Tensile strength (MPa)	Elastic modulus (GPa)	Poisson's ratio	Elongation at break (%)	Linear expansion coefficient (10^{-5})	Heat resistance (continuous) (℃)	24h water absorption (%)
0.92–0.95	10–16	69.2	0.499	≥550	16–18	80–100	<0.003

The thickness of FRP layer of the 90-L gas cylinder was about 18 mm. The composite material should meet the property requirement that the inter-layer shear strength is not less than 30 MPa; the mechanical properties of EP/GF composite laminated board are shown in the following Table 3.

Table 3. The mechanical properties of EP/GF composite laminated board

Transversal stretching				Longitudinal stretching				Radial stretching			
Strength (MPa)	Elastic modulus (GPa)	Poisson ratio	Max strain (%)	Strength (MPa)	Elastic modulus (GPa)	Poisson ratio	Max strain (%)	Shear strength (MPa)	Shear modulus (GPa)	Poisson ratio	Max tensile strain (%)
380	20.6	0.117	2.41	334	17.2	0.112	2.47	324	17.3	0.114	11.2

3.2. Establishment of finite element model for all-composite gas cylinder

3.2.1. Selection of element type and setup of relevant attributes

We used the ANSYS11.0 software to solve for the Von-Mises stress cloud diagrams of all-composite gas cylinders under various operating conditions with constraints and loads applied onto the all-composite gas cylinders according to the actual situations, and verified the safety and reliability of this type of gas cylinder according to the strength of the all-composite gas cylinders and the max deformation[5].

On the ANSYS software platform, we established a model for all-composite gas cylinders by adopting the section commands for SHELL181 and directly defining such attributes of composite layer as number of sub-layers, thickness of sub-layer element, material selection, and winding angle, etc[6]. The cylinder body section of a gas cylinder contains 23 sub-layers, among which the first one is a plastic sub-layer made of material 1 and defined as the liner with a thickness of 7.5 mm and the other 22 ones are outer glass fiber winding sub-layers made of material 2, which include 10 helically wound sub-layers with thickness of 0.9 mm each and 12 hoop wound sub-layers with thickness of 0.75 mm each.

3.2.2. Material defining

The properties of plastic liner material are shown in Table 2. The properties of unidirectional plate of the outer reinforcement layer are shown in Table 3.

3.2.3. Modeling of geometric entity

A top-down modeling approach was used to model an all-composite CNG cylinder; owing to the symmetry of the gas cylinder, its 1/2 was employed for modeling analysis.

3.2.4 Finite element gridding

Mapping approach was used for gridding the geometric model. The joint places between cylinder body and end plate are stress concentration areas, where grid refinement was conducted and of which the gridding adopted equal-thickness elements in modeling. The gridded finite element model of 1/2 of an all-composite gas cylinder is shown in Fig 1.

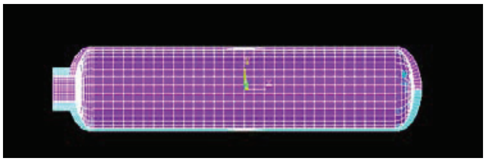

Fig. 1. All-composite gas cylinder gridding

3.2.5. Boundary condition defining

The boundary conditions for an all-composite gas cylinder were determined by the constraint and load conditions on the gas cylinder during actual use [3]. All gas cylinders for vehicle on the buses in Beijing City were mounted on the roofs, and each of them was applied with hoop constraints for fixation on two boundaries of the cylindrical section and its inner wall surface was applied with pressure according to the actual situations

3.3. ANSYS-based numerical simulation analysis

3.3.1. Mises stress analysis under different pressures

When the all-composite gas cylinder was applied with operating pressure 20 MPa, water test pressure 30 MPa and bursting pressure 73 MPa, we calculated the equal-proportion Mises stress cloud diagrams, as shown in Figs 2 and 3.

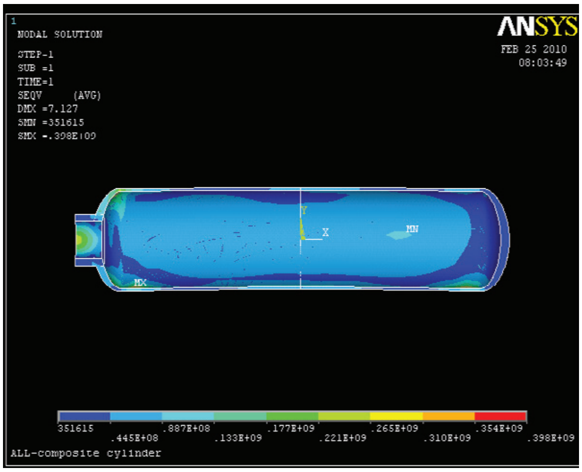

Fig. 2. Mises stress cloud diagram of all-composite gas cylinder under 20 MPa

The stress of the gas cylinder under operating pressure 20 MPa is relatively concentrated in the transition area from the cylinder body section to the cylinder nozzle, which is consistent with the failed part of gas cylinder found during actual gas cylinder inspection; the max stress is 398 MPa and the stress in the cylinder body section is about 44.5 MPa, see Fig 2.

The allowable stress of the composite unidirectional plate is shown in Table 3, σ_1 = 380 MPa, σ_2 = 334 MPa, σ_3 = 0 MPa; according to the fourth strength theory (refer with: eq.1),

$$\sigma = \sqrt{\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_3 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2]} = 619\text{MPa} \tag{1}$$

The max stress of the gas cylinder is 398 MPa, far less than 619 MPa, so the stress in the winding layer of the all-composite gas cylinder under the operating pressure is within the required strength range of material and the safety performance requirement for the all-composite gas cylinder can be ensured.

In addition, it can be seen from Fig 2 that the stress in the cylinder nozzle part is relatively concentrated, so there are often such phenomena as gas leaking, cylinder nozzle valve loosening at the cylinder nozzle of the all-composite gas cylinder during actual use, which require further improvement in the structural design of the cylinder nozzle part.

The stress in the cylinder body section of the gas cylinder under normal operating pressure 20 MPa is about 44.5 MPa, and it can be found that the HDPE tensile strength of the plastic liner of the all-composite gas cylinder is 10–16 MPa, far less than 44.5 MPa, the stress in the cylinder body section of the gas cylinder under operating pressure 20 MPa, so it was thought during the design and manufacturing of the all-composite gas cylinder that the outer winding layer of the all-composite gas cylinder mainly has the pressure bearing function and the liner only has air tightness function. In fact, in the body of the gas cylinder, the stress reduces from the inner wall surface to the outer wall surface and the stress in the liner of the gas cylinder should be the max stress value in the cylinder body section, more than 44.5 MPa. Insufficient strength of the liner is the main cause of such defects of gas cylinder as craze, and crack, etc.; therefore, the strength of the liner material must be increased so as to better ensure the safety and reliability of the all-composite gas cylinder.

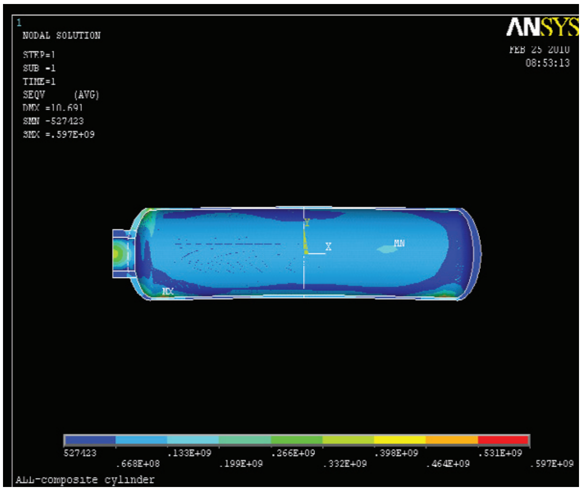

Fig. 3. Mises stress cloud diagram of all-composite gas cylinder under 30 MPa

Under water test pressure 30 MPa, the stress distribution cloud diagram of the all-composite gas cylinder is shown in Fig 3. The max stress in the gas cylinder is 597 MPa, and the stress in the cylinder body section is basically about 66.8 MPa; they are less than the allowable stress of the winding layer material σ = 619 MPa when similarly verified according to the fourth strength theory. Under the test pressure, the strength of the winding layer material can ensure the safety performance requirement for the gas cylinder.

The Mises stress cloud diagram of the all-composite gas cylinder under the bursting pressure 73 MPa is shown that similarly, when verified according to the fourth strength theory, the max stress of the gas cylinder is about 969 MPa and even up to 1.45 GPa, the stress in the cylinder body section is approximate 163 MPa, and the stress in the location with the most concentrated stress, i.e., the transition area from the cylinder body to the cylinder nozzle, exceeds the allowable strength of the material.

3.3.2. Deformation and displacement analysis under different pressures

Under operating pressure 20 MPa, water test pressure 30 MPa and bursting pressure 73 MPa, we used

Ansys for simulation to obtain the deformation and displacement cloud diagrams.

Under 20 MPa, the max hoop displacement occurred in the cylinder body section of the gas cylinder. Since the ends of the cylinder body section were applied with hoop constraints when the gas cylinder was applied with constraints, the displacement in the middle part of the cylinder body section was relatively large. The max hoop displacement was 5.134 mm and the min hoop displacement was 0.386328 mm, and they are within the elasticity range of the material. The max axial displacement of the gas cylinder occurred in the cylinder body, and it was 0.81644 mm, and the axial displacement of the cylinder body section within the elasticity of material was relatively small; in the cylinder body section, the compression and deformation in the innermost sub-layer were the largest in the glass fiber winding layer.

The distribution of axial displacement and hoop displacement of the gas cylinder under 30 MPa was basically the same as that under 20 MPa, and only the strain was increased under 30 MPa, compared with that under 20 MPa, but it was within the elasticity range of material.

Under 73 MPa, the all-composite gas cylinder had large axial deformation, its max axial displacement was 2.98 mm and its elongation reached 1.12%; its hoop displacement was also large with max value up to 18.738 mm and min value of 0.828546 mm. The hoop displacement at most places of the gas cylinder was within 5–7 mm, which is within the allowable range of material, and local displacement was too large with elongation up to 6.38%, which exceeds the max elongation of material, 5%.

4. Conclusions

(1) The places of any all-composite gas cylinder, where failure is easy to occur, are consistent with those where failure actually occur, which proves the reasonableness of the modeling approach.

(2) Under operating pressure and test pressure, the strength of the winding layer of any all-composite gas cylinder meets the pressure bearing requirement for gas cylinders and the displacement is within the allowable normal range of the material, and that under bursting pressure 73 MPa, the gas cylinder reaches its burst limit. The strength of the liner material HDPE of the gas cylinders is obviously insufficient and is far from meeting the strength requirement for gas cylinders under operating pressure 20 MPa

(3) The material selection for the liner of all-composite gas cylinders for vehicle requires further study with the liner strength fully considered. The structural design of gas cylinders has some defects and the stress in the transition area from the cylinder body section to the cylinder nozzle is evidently concentrated, so the structural design of the transition area is to be further improved.

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