Auto-frettage Process Analysis of Composite Pressure Vessels

Guiming Zhang, Jihui Wang, Lei Zu

School of Materials Science and Engineering, Wuhan University of Technology, Wuhan 430070, China

zhangguiming20@whut.edu.cn

abstract

Compressed natural gas (CNG) as an alternative automobile energy has been widely used. The CNG cylinder is one of the most key storage apparatuses of CNG-powered automotives. The manufacturing process of CNG cylinders inevitably undergoes winding, cure, and auto-frettage process according to the relevant standards.

According to the American standard (DOT-CFFC) dedicated to CNG composite cylinders, the stress distributions of the metal liner and the composite overwrap under two loading processes were obtained, which are (1) the working pressure → hydrostatic test pressure → minimum burst pressure; (2) the auto-frettage pressure → zero pressure → working pressure →hydrostatic test pressure → minimum burst pressure. The results showed that the equivalent stress level of the metal liner was significantly reduced by applying auto-frettage pressure to the cylinder prior to zero pressure.

In the paper, the winding parameters and the composite layup were determined based on the winding principle and FEM analysis. The influence of the application of the auto-frettage pressure on the stress level of the metal liner was evaluated. The results are able to offer a theoretical basis for design and production of composite CNG cylinders. The best auto-frettage pressure is 34 Mpa.

Keywords: Auto-frettage; CNG; Pressure vessel; FEM

Introduction

Carbon fiber reinforced polymer composites have been increasingly employed in various industrial fields including aircrafts, fuel cell vehicles, electricity generation, and communication power systems due to their high strength/stiffness-to-weight ratio, excellent resistance to fatigue and electrochemical corrosion as well as satisfactory durability. Since the stiffness and strength of an individual layer are much higher in the fiber direction than those in the transverse direction, the properly designed composite layers sufficiently bring the better mechanical performance in the principal directions of composite structures in order to suit the anticipated load-bearing distributions[1-2].

Applications include breathing device, such as self-contained breathing apparatuses used by fire-fighters and other emergency personnel, scuba tanks for divers, oxygen cylinders for medical and aviation cylinders for emergency slide inflation, opening doors or lowering of landing gear, mountaineering expedition equipment, paintball gas cylinders, etc[3]. Compressed natural gas (CNG) as an alternative automobile energy has been widely used. The CNG cylinder is one of the most key storage apparatuses of CNG-powered automotives. The manufacturing process of CNG cylinders inevitably undergoes winding, cure, and auto-frettage process according to the relevant standards.

Considering the volume of the cylinder, the use of space, the production process and other constraints, we determine the mandrel geometry, the winding parameters, the layer angle & thickness based on the netting theory and windability. The symmetrically helical patterns are used to produce the cylindrical and dome sections. An aluminum alloy lined composite CNG cylinder (80L) is taken as the design example. The results provide an important theoretical basis for design and production of on-board composite CNG pressure vessels.

Modeling of the CNG pressure vessel

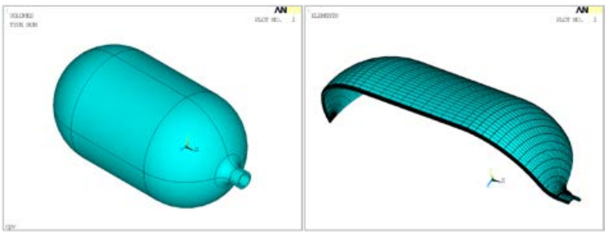

Fig.1 The model of the pressure vessel

Finally, finite element analysis with ANSYS on of a CNG pressure vessel was carried out based on the APDL language, which is applied to the whole modeling, meshing, imposing constraints and boundary conditions and solving process. The maximum stress, Hoff-man, Tsai–Hill and Tsai–Wu failure criteria are employed respectively to determine the failure loads of the composite pressure vessel. According to the American standard (DOT-CFFC) dedicated to CNG composite cylinders, the stress distributions of the metal liner and the composite overwrap under two loading processes were obtained, which are (1) the working pressure → hydrostatic test pressure → minimum burst pressure; (2) the auto-frettage pressure → zero pressure → working pressure →hydrostatic test pressure → minimum burst pressure. The results showed that the equivalent stress level of the metal liner was significantly reduced by applying auto-frettage pressure to the cylinder prior to zero pressure.

Results and discussion

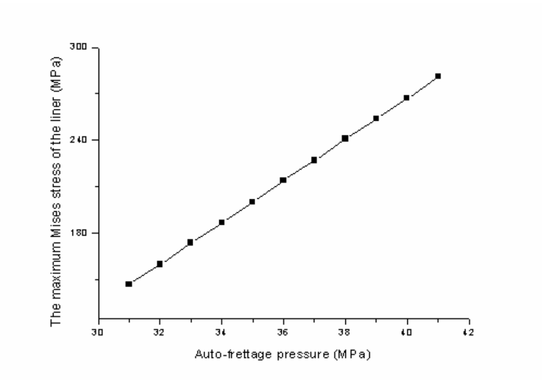

Fig.2 The curve of maximum Mises stress of the liner at zero pressure

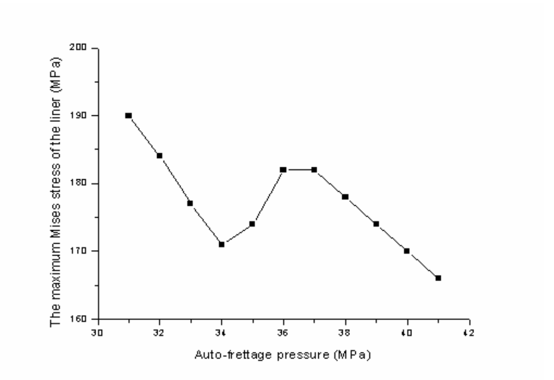

Fig.3 The curve of maximum Mises stress of the liner at working pressure

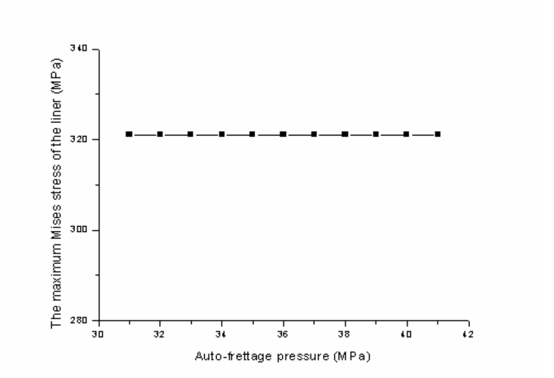

Fig.4 The curve of maximum Mises stress of the liner at minimum burst pressure

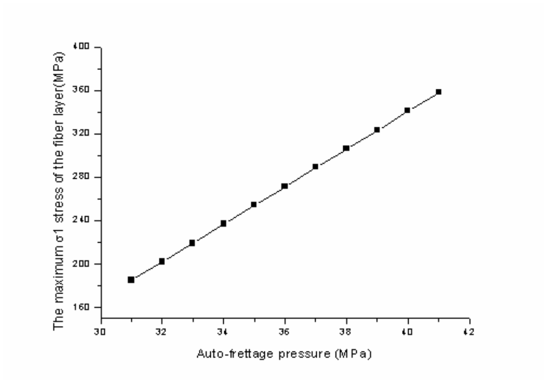

Fig.5 The curve of maximum σ1 stress of the fiber layer at zero pressure

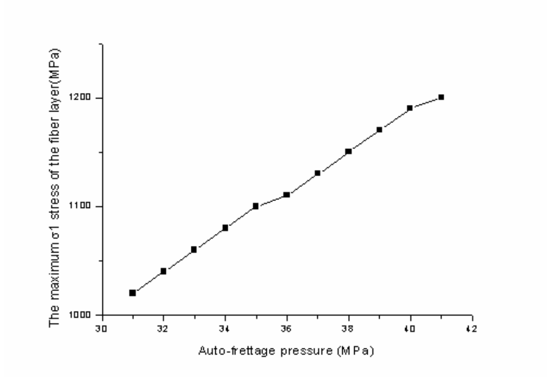

Fig.6 The curve of maximum σ1 stress of the fiber layer at working pressure

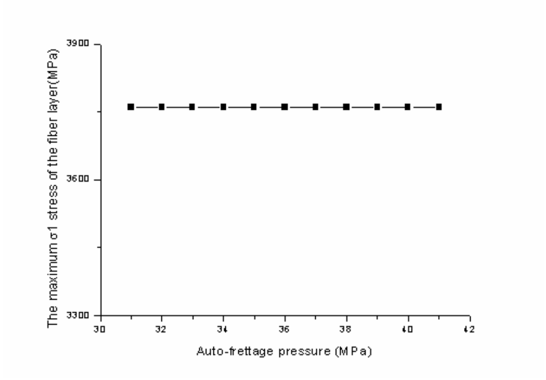

Fig.7 The curve of maximum σ1 stress of the fiber layer at minimum burst pressure

Under the zero pressure, the stress of the liner and the fiber layer increase linearly with the auto-frettage pressure increasing. Under the working pressure, the maximum Mises stress of the liner decreases to 171 Mpa, then increase to 182 Mpa. when the auto-frettage pressure is more than 37 Mpa, the maximum Mises stress of the liner decreases. The maximum σ1 stress of the fiber layer almost increases linearly with the auto-frettage pressure increasing. It was revealed that the stress of the composite overwrap under working pressure was greatly increased after auto-frettage process. It was also concluded that the minimum burst pressure was not affected by whether or not applying the autofrettage process to the cylinder as shown in Figs. 4

and 7.

Conclusions

In the paper, the winding parameters and the composite layup were determined based on the winding principle and FEM analysis. The influence of the application of the auto-frettage pressure on the stress level of the metal liner was evaluated. The results are able to offer a theoretical basis for design and production of composite CNG cylinders. The best auto-frettage pressure is 34 Mpa.

References

[1] Cox BN, Yang QD. In quest of virtual tests for structural composites. Science,2006;314:1102-7.

[2] Chapelle DD, Perreux D. Optimal design of a Type 3 hydrogen vessel: part I-analytic modelling of the cylindrical section. Int J Hydrogen Energy,2006;31(5):627–38.

[3] Onder A, Sayman O, Dogan T, et al. Burst failure load of composite pressure vessels[J]. Composite Structures, 2009, 89(1):159-166.