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Optimal Shape Design of ANG Fuel Vessel Applied to Composite Carbon Fiber

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탄소섬유 복합재료를 적용한 ANG 연료용기의 최적 형상설계

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ABSTRACT

The development of adsorbed natural gas (ANG) has emerged as one of potential solutions. It is desirable to reduce the weight of vessel by applying light-weighed a composite carbon fiber in order to response to a egulation of CO_2 emission. Through understanding of a composite carbon fiber, and material characteristic of a composite carbon fiber is required in order for better application of a reduction of weight and an analysis of material characteristic.

Herein, this study suggest the composite carbon fiber vessel applied to the characteristic of carbon fiber, and it decides the preliminary shape based on the test of material characteristic for ANG vessel applied to a composite carbon fiber, and its basic shape calculate through on the netting theory. Moreover, the detail shape design is analyzed by a finite element analysis, and in the stage of detail sahp design and analysis of stress was performed on the typical shape using a finite element analysis, and the result of preliminary design was verified.

Key Words: Fuel Vessel(연료용기), Composite Carbon Fiber Material(탄소섬유 복합재료), Fuel Vessel Design (연료용기 설계), Material Characteristic Testing(재료 특성실험), FEM Stress Analysis(FEM 응력해석)

1. Introduction

The global natural gas vehicle market is growing rapidly as countries with natural gas resources are promoting natural gas vehicles supply policy. According to the NGV Global Knowledge-base[1-2], the number of natural gas vehicles worldwide has sharply increased. The natural gas vehicle market of South Korea is showing a trend similar to that of the global market, and the introduction of compressed natural gas (CNG) buses is increasing continuously due to the air pollution reduction policy[3-5]. LNG fuel tanks are efficient because of the high energy density achieved, but require expensive investments and technologies to maintain cryogenic temperature. CNG

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fuel tanks cost less, but are not economical due to low energy density and have a safety issue due to high pressure. To solve this problem, absorbed natural gas (ANG) fuel tanks that can efficiently store natural gases using an absorbent that allows the storage of natural gases at a relatively low pressure are being developed.

This study determined through a material property experiment the basic shape of an ANG fuel tank using a composite carbon fiber material[6-7], conducted preliminary design by applying a net theory to the composite material fuel tank, and determined the initial thickness of the composite carbon fiber material. Furthermore, in the detailed shape design stage, the results of the preliminary design were verified by analyzing the stress of the basic shape through finite element analysis(FEM).

2. Shape Design and Analysis of ANG Fuel Tank Using Carbon Fiber Composite Material

2.1 Basic shape of ANG fuel tank

The ANG fuel tank produced in this study is a 9.2 ℓ pressure vessel made of Torayca® T700S carbon fiber impregnated with epoxy resin wound in the spiral and circumferential directions around the inner aluminum liner.

Fig. 1 shows a model of an ANG fuel tank with a seamless liner made of heat-treated Al6061-T6, produced by deep drawing of an aluminum pipe to prevent cracks.

The total length of the carbon fiber composite ANG fuel tank is 533 mm including the boss, and the outer diameter is 169.1 mm after autofrettage at the maximum. The inner diameter of the liner is 160.9 mm at the maximum, and the thickness is 2.1 mm. Table 1 shows the design specifications of the fuel tank.

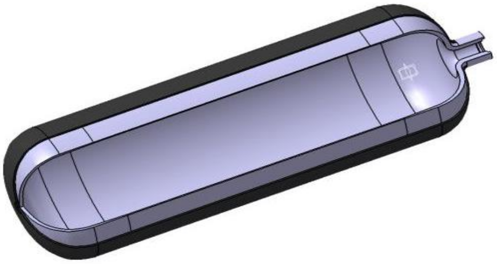

Fig. 1 Model of 9.2 ℓ, 60bar pressure vessel

Table 1 Design specification of pressure vessel

Item		Design value	Remark
Operating pressure	bar	60	at 20℃
Safety factor		3.0	-
Internal volume	ℓ	9.2	±3.0%
Max. diameter	mm	169.1	after autofrettage
Max. length	mm	533	-
Max. weight	kg	3.0	-

As shown in Table 1, autofrettage is a process that increases resistance to stress corrosion cracking of the liner and improves fatigue performance by applying a constant autofrettage pressure to the composite pressure vessel and generating plastic deformation to the aluminum liner after completing filament winding and hardening, causing a compressive residual stress on the liner after removing the pressure. In this study, the autofrettage pressure was set at 125 bar.

2.2 Material property test of ANG fuel tank

T6 heat treatment was performed for the liner made of Al6061, and a tensile test was conducted in accordance with KS B0802. Two specimens were manufactured for the tensile test. Table 2 shows the average values of the test results. To measure the inter-laminar shear strength, the composite carbon fiber was impregnated in the epoxy resin, and

Table 2 Tensile test results of Al6061-T6 liner

Item		Results	Min. requirement
Tensile strength	MPa	306.55	260
Tensile modulus	MPa	338.13	300
Elongation	%	12.89	10

bending test was performed with a ring specimen according to ASTM D 2344. Before the bending test, the specimen was exposed to 100℃ water for 24 h in accordance with KGS AC412 or to 100℃ water for 4 h in accordance with KS F2246. The strength standard differs by water exposure time. The inter-laminar shear strength must be at least 13.8 MPa when exposed for 24 h, and 35 MPa if exposed for 4 h. KS F2246 was applied to the inter-laminar shear test of the epoxy resin used in the carbon fiber composite vessel. Test results showed inter-laminar shear strength of 44.58 MPa, which satisfied the standard.

2.3 **Basic shape design of ANG fuel tank**

The initial design of the composite carbon fiber material fuel tank is performed and the initial thickness of the composite carbon fiber material is determined by applying the net theory. In the detail design stage, the result of initial design is verified through finite element analysis and the vulnerable parts are reinforced. The net theory is applied to the initial design of a filament-wound pressure vessel using composite material. It is assumed that the wall of the pressure vessel shows membrane behavior and does not receive out-of-plane bending or shear load perpendicular to the surface of the pressure vessel wall. In Fig. 2, the stacking angle can be expressed using the cross-sectional area A and Ax as follows:

$$\cos\alpha = \frac{A}{A_x} \tag{1}$$

When the stress, σ_f on the spiral fiber is divided into the axial stress, σ_x and the vertical stress, σ_y the axial load is as follows:

$$\sigma_x A_x = \sigma_f A \cos\alpha \tag{2}$$

Therefore, the axial stress can be determined from Eq. (1) and (2) as follows:

$$\sigma_x = \sigma_f \frac{A}{A_x} \cos\alpha = \sigma_f \cos^2\alpha \tag{3}$$

In the same way, the vertical stress is as follows:

$$\sigma_y = \sigma_f \sin^2\alpha \tag{4}$$

Therefore, from Eq. (3) and (4), the stacking angle, α, is as follows:

$$\tan^2\alpha = \frac{\sigma_y}{\sigma_x} \tag{5}$$

If a thin cylinder with an inner diameter of d and a thickness of t receives the internal pressure, p, with one side blocked, the axial stress, σ_x, and circumferential stress, σ_h are as follows:

$$\sigma_x = \frac{p\,d}{4\,t} \tag{6}$$

$$\sigma_h = \frac{p\,d}{2\,t} \tag{7}$$

Therefore, the thickness, t_f, of the axial, that is,

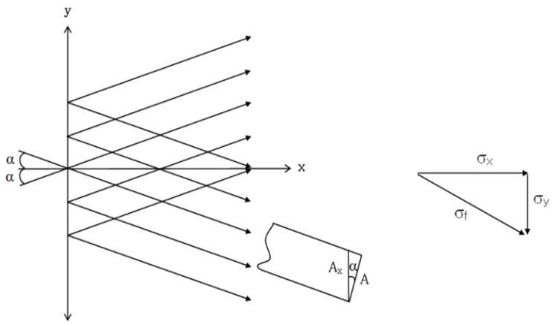

Fig. 2 Definition of wind angle for a netting analysis

spiral composite material can be calculated from Eq. (3) and (6) as follows:

$$t_f = \frac{p\,d}{4\,\sigma_f}\,\frac{1}{\cos^2\alpha} \tag{8}$$

Furthermore, if the thickness and stress of the circumferentially wound composite material are t_θ, and σ_θ respectively, the total load (7) can be calculated by considering Eq. (4) as follows:

$$\frac{p\,d}{2} = \sigma_\theta t_\theta + \sigma_f t_f \sin^2\alpha \tag{9}$$

When Eq. (8) is put in Eq. (9), the thickness of the circumferential composite material is as follows:

$$t_\theta = \frac{p\,d}{2\sigma_\theta}\left(1 - \frac{1}{2}\tan^2\alpha\right) \tag{10}$$

Here, the tensile strengths of the spiral and circumferential fibers are identical $(\sigma_f = \sigma_\theta = \sigma_T)$ and the total thickness of the composite material can be derived from Eq. (8) and (10) as follows:

$$t = t_f + t_\theta = \frac{3\,pd}{4\sigma_T} \tag{11}$$

3. Shape Design and Analysis of ANG Fuel Tank

The finite element model(FEM) of the fuel tank has uniform stress distribution in the longitudinal direction and the fuel tank shape is symmetrical with respect to the center plane. Therefore, only the central part of the fuel tank was modeled, as shown in Fig. 3. Furthermore, an eight-node three-dimensional laminated solid element was used for the central part because there is no geometric nonlinear effect in the central part. For the boundary condition for finite element analysis, the cyclic symmetric condition was applied, and a multi-point constraint was used to implement the behavior of the fuel tank. To predict the liner, which shows plastic behavior due to autofrettage pressure, the material nonlinear analysis method was introduced. Furthermore, the filament winding pattern was applied as shown in Table 3 to calculate the accurate behavior and stress distribution of the composite material fuel tank.

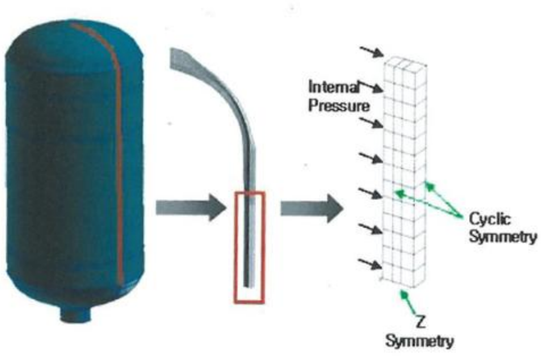

Fig. 3 Finite element model and boundary condition

Table 3 Filament winding pattern for the finite element analysis

Pattern type	Winding angle	Number of strands	Number of laminates	Thickness
Hoop winding	°88	2	3	0.627㎜
Helical winding	°14	2	2	0.513㎜

The autofrettage pressure was set at 125 bar. The stress distribution of the liner when the autofrettage pressure was applied reached the plastic region beyond the yield strength 260 MPa. At the zero pressure condition with the autofrettage pressure removed, the circumferential stress of the liner was – 22.5 MPa. This stress is the compressive residual stress in the liner caused by autofrettage.

The circumferential stress distribution of the fuel tank when the working pressure was applied is shown in Fig. 5. The maximum stress was 332 MPa, which occurred in the outermost circumferential carbon fiber composite material layer. For pressure test, 90 bar was applied, which is 1.5 times the working pressure, stipulated by KGS AC412. The maximum stress was 461 MPa for the circumferentially wound carbon fiber composite material. This circumferential stress appears to be highly safe because it is approximately 18% of 2,550 MPa, which is the tensile strength of the Toray T700S composite carbon fiber material, and the maximum deformation is approximately 0.26 mm.

For the minimum burst pressure test, 180 bar was applied, which is three times the working pressure. Fig. 7 shows the circumferential stress distribution in the fuel tank. Fig. 8 shows the circumferential stress distribution when a pressure of 271 bar was applied to the fuel tank. The maximum stress in the outermost composite material layer of the fuel tank was 2,551 MPa, which is almost the same as the tensile strength of the used composite carbon fiber material. Therefore, the predicted burst pressure of the fuel tank, that is, the design burst pressure can be evaluated as 270 bar.

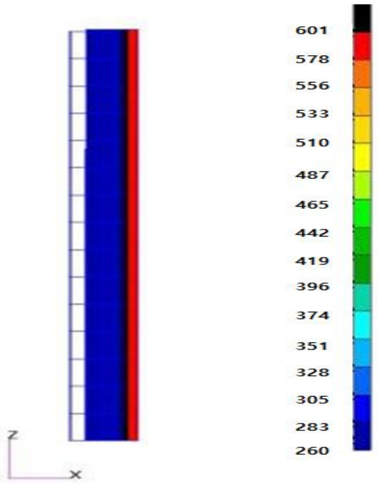

Fig. 4 **Von Mises stress distribution of aluminum liner under autofrettage pressure**

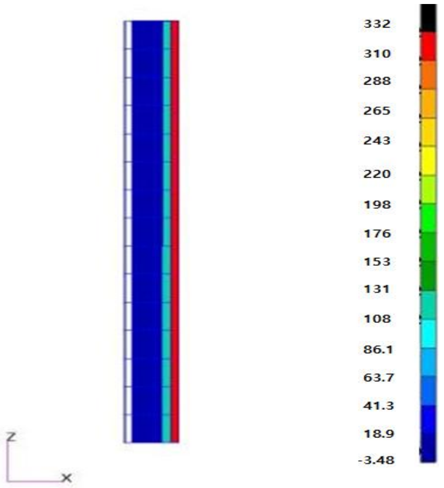

Fig. 5 **Hoop stress distribution of ANG fuel tank under operating pressure**

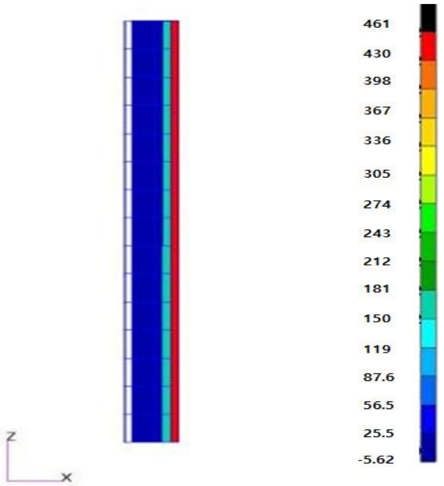

Fig. 6 **Hoop stress distribution of ANG fuel tank under internal test pressure**

4. Results of Stress Analysis through FEM

For the loading condition, a uniform pressure is applied to the inside of the finite element model. The loading sequence is as follows. A plastic deformation

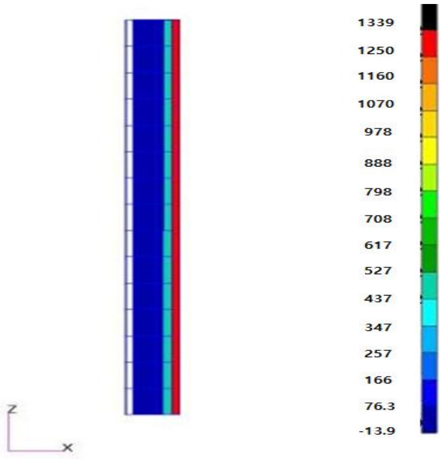

Fig. 7 Hoop stress distribution of ANG fuel tank under minimum burst pressure

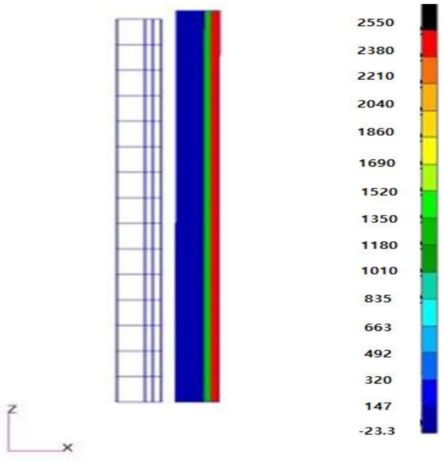

Fig. 8 Hoop stress distribution of ANG fuel tank under internal pressure of 271 bar

Table 4 Stress analysis results for ANG fuel tank

Pressure(bar)		Displacement (㎜)	Liner stress (1) (㎫)	Composite stress (2) (㎫)
Autofrettage pressure	125	0.349	260	609
0	0	0.0447	-22.5 (3)	76.7
Operating pressure	60	0.19	114	332
Internal test pressure	90	0.263	181	461
Min. burst pressure	180	0.775	260	1,339
Design burst pressure	270	1.5	260	2,551

(1) : von Mises stress
(2) : max. hoop stress
(3) : compressive residual hoop stress

of the liner is caused by applying an autofrettage pressure. After removing the pressure, loading is performed in the order of working pressure, pressure test pressure, minimum burst pressure, and design burst pressure. Table 4 shows the stress analysis results of the ANG fuel tank made of a composite carbon fiber material, which was calculated through finite element analysis under various load conditions. The loading sequence is as follows. After plastic deformation is caused in the liner by applying autofrettage pressure, the pressure is removed, and the working pressure, pressure test pressure, minimum disruptive pressure, and design disruptive pressure are applied in that order.

5. Conclusions

The results of the stress analysis for shape design are as follows:

(1) When the autofrettage pressure was set at 125 bar, and the autofrettage pressure was applied, the stress exceeded the yield strength 260 MPa and reaches the plastic region.

(2) The working pressure is a stress that is smaller by approximately 20 MPa than when autofrettage was not performed and can suppress the fatigue cracks due to the reduction of tensile stress following autofrettage. Thus, fatigue cracks can be suppressed to some degree by lowering the tensile stress by autofrettage.

(3) The pressure test pressure is approximately

18% of the tensile strength of the carbon fiber composite material (2,550 MPa), and the maximum deformation is approximately 0.26 mm, which is a safe level.

(4) In the case of minimum burst pressure, the maximum stress was observed at 1,339 MPa in the carbon fiber composite material wound in the circumferential direction, which is approximately 53% of the tensile strength of the Toray T700S carbon fiber composite. The maximum deformation that occurred at this time was approximately 0.78 mm.

(5) The burst pressure of the fuel tank—that is, the design burst pressure—when a pressure of 271 bar is applied to the fuel tank can be evaluated as 270 bar.

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