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Optimal design considering structural efficiency of compressed natural gas fuel storage vessels for automobiles

Myung-Chang KANG[1], Hyung Woo LEE[1], Chul KIM[2]

1. National Core Research Center for Hybrid Materials Solution, Pusan National University, Busan 609-735, Korea;
2. Research Institute of Mechanical Technology, Pusan National University, Busan 609-735, Korea

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Abstract: The shape and thickness of the dome were investigated with the aim of optimizing the type II CNG storage vessels by using a finite element analysis technique. The thickness of the liners and reinforcing materials was optimized based on the requirement of the cylinder and dome parts. In addition, the shape of the dome, which is most suitable for type II CNG storage vessels, was proposed by a process of review and analysis of various existing shapes, and the minimum thickness was established in this sequence: metal liners, composite materials and dome parts. Therefore, the new proposed shape products give a mass reduction of 4.8 kg(5.1%)

Key words: CNG fuel storage vessel; mechanical property; dome part; bursting; structural analysis

1 Introduction

Type II fuel storage vessels for compressed natural gas (CNG) automobiles, which have been successfully introduced into local and overseas markets, are composed of metal liners and composite materials[1]. Type I storage vessels are manufactured by a process of hot spinning, after a continuous execution of deep drawing and ironing, to form the dome[2]. Whereas type II storage vessels are manufactured by wrapping composite materials around the type 1 metal liners in order to reduce the thickness of the metal liners required in the cylinder part of the storage vessel, thereby improving the mileage range of automobiles as the larger pressure vessels can be lighter[3−6].

This research investigates the mechanical properties needed for finite element analysis by testing the basic material properties of fuel storage vessels (type II) for CNG automobiles. An optimal design of the pressure vessels for CNG automobiles was achieved with regard to structural efficiency, based on the thickness of the liners, the composite materials, the dome's shape and the thickness of the metal liners[7−9]. This was verified by using a finite element analysis.

2 Mechanical properties of materials used in finite element analysis

Calculation of product thickness depends upon the following Eqs.(1) and (2), respectively[10].

$$\sigma_1=\sigma_\theta=\frac{pr}{t},\quad \sigma_2=\sigma_z=\frac{pr}{2t},\quad \sigma_3=\sigma_r\approx 0 \tag{1}$$

$$\frac{1}{6}[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2]=k^2,$$

$$\sigma_1=2k,\quad t=\frac{\sqrt{3}pr}{2Y_\mathrm{s}},\quad k\approx\frac{Y_\mathrm{s}}{\sqrt{3}} \tag{2}$$

where p represents bursting test pressure; r represents radius of pressure vessel; Y_s represents yield stress.

In general, composite materials are known to rupture in an elastic region. The strains of fibers and matrices, in the case of the deformation of composite materials in an elastic region, are equal, therefore, the strains can be expressed as shown in Eq.(3), respectively.

$$\sigma_\mathrm{f}=E_\mathrm{f}\varepsilon_1,\quad \sigma_\mathrm{m}=E_\mathrm{m}\varepsilon_1 \tag{3}$$

where ε_f and E_f represent the amount of strain and elasticity modulus of fibers; ε_m and E_m represent the amount

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Corresponding author: Chul KIM; Tel: +82-51-510-2489; E-mail: chulki@pusan.ac.kr

of strain and elasticity modulus of resin; σ, σ_f and σ_m represent the stress in the composite material, fiber and resin.

The resultant force of the composite material can be expressed as Eq.(4), and Hooke's Law can be used to calculate the elastic modulus of composite materials in the fiber direction (E_1) and the vertical direction (E_2) as Eq.(5), of which, V_f and V_m are indicated as Eq.(6).

$$P = \sigma_1 A = \sigma_f A_f + \sigma_m A_m \tag{4}$$

$$E_1 = E_f V_f + E_m V_m, \quad E_2 = \frac{E_f E_m}{V_m E_f + V_f E_m} \tag{5}$$

$$V_f = \frac{A_f}{A}, V_m = \frac{A_m}{A} \tag{6}$$

where A, A_f and A_m represent cross sectional area of the composite material, fiber and resin; E_1 and E_2 represent the elasticity modulus in the fiber direction and its perpendicular direction; P represents the resultant force of composite materials.

The properties of the materials were determined by tensile and anisotropy testing[6], and the numerical expansion described above are shown in Table 1.

Table 1 Mechanical properties of steel liner and composite used in finite element analysis

Mechanical properties	Steel liner	Composite
E_{11}		54.80 GPa
E_{22}	205.00 GPa	950.00 MPa
E_{33}		0.28 MPa
S_{11}		1054.60 MPa
S_{22}	950.00 MPa	28.10 MPa
S_{33}		28.10 MPa
Yield strength	850.00 MPa	
Poisson ratio	0.28	0.25

E_{11} represents longitudinal elastic modulus; E_{22} and E_{33} represent transverse elastic modulus; S_{11} represents longitudinal tensile strength; S_{22} and S_{33} represent transverse tensile strength.

3 Designs

3.1 Design analysis of type II storage vessels

The pressure-resistant structural analysis for Model No. CNG2-026, which is a general form of type II storage vessel, was conducted and its safety was evaluated.

The displacement and load boundary conditions are shown in Figs.1(a) and (b), respectively. The stress status in LS1 and the results of residual stress occurring in LS2 are shown in Fig.2. The maximum stress occurred in the metal liner at 40.0 MPa, whilst the autofrettage pressure was only 400 MPa (approximately 47% of the yield stress) as shown in Fig.2(a), and almost no residual stress occurred, as shown in Fig.2(b). The results of finite element analysis at the working pressure (LS3, 20.7 MPa), test pressure (LS4, 31.1 MPa) and bursting pressure (LS5, 56.9 MPa) are shown in Figs.2(c), (d) and (e), and the actual bursting conditions predicted by trial errors are shown in Fig.2(f). At the minimum bursting pressure of 56.9 MPa, the maximum stress in the metal liner was approximately 675 MPa, or 70.7% of the yield stress.

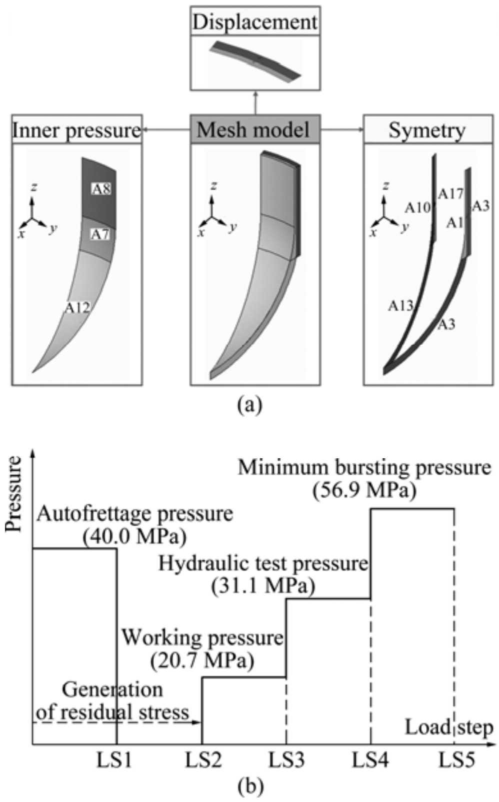


Fig.1 Boundary conditions of displacement (a) and load (b) used in FE analysis of fuel storage vessel (Type II)

3.2 Improvement of storage type II vessels

3.2.1 Determination of thickness of metal liner and composite materials

In order to improve the metal liners, only the relevant parts were modeled, as shown in Fig.3(a), and the axial constraint was given to the upper and lower faces of the model, and the symmetric constraint was given to both sides of the tangential direction. The thickness prior to the yield at 26.0 MPa (the working pressure of the metal liners) was determined through a finite element analysis via trial and error methods. Figure 3(b) organizes the results of the finite element analysis through trial and error methods, and this shows that the optimal thickness of the liners is 4.6 mm.

For this section, only the cylinder and the composite material part of the metal liner were modeled, as shown in Fig.4, and the axial constraint was given to the upper

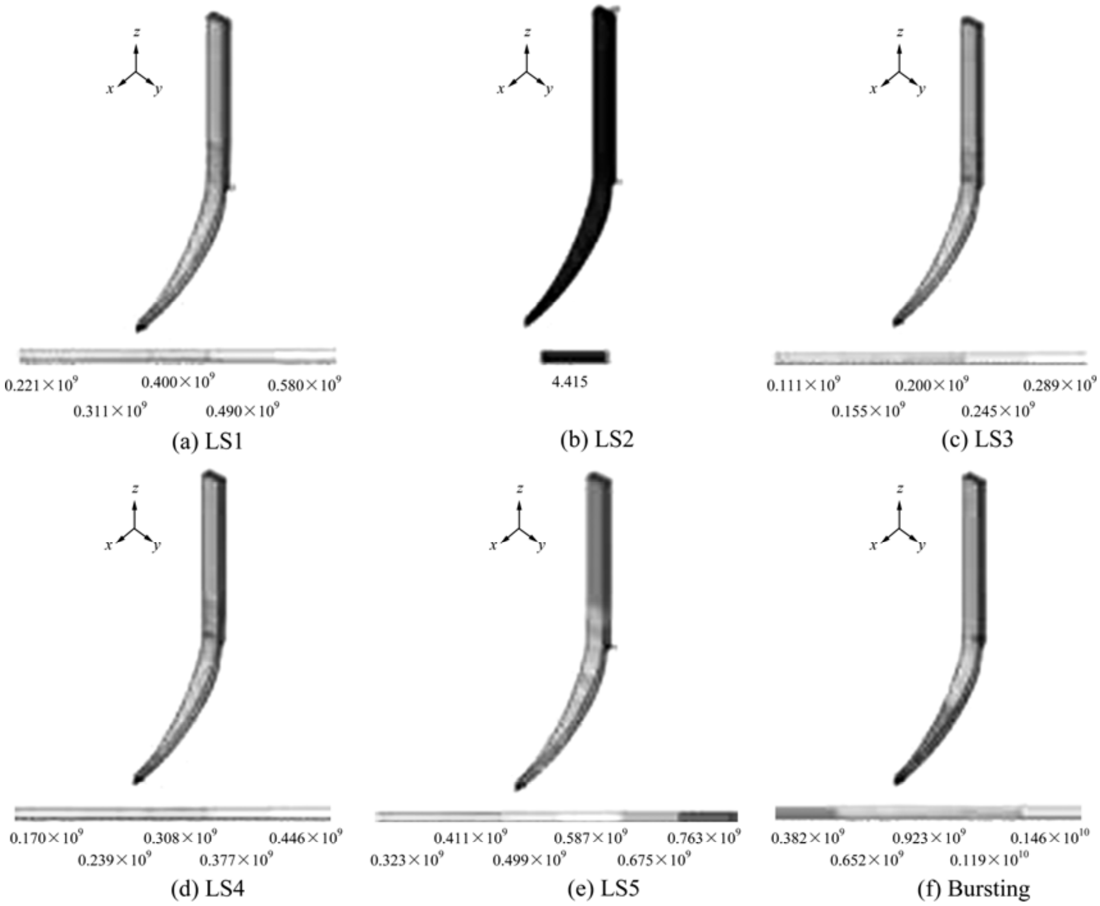


Fig.2 Proposed drawing and equivalent stress distributions from results of FE analysis of Type II fuel storage vessels

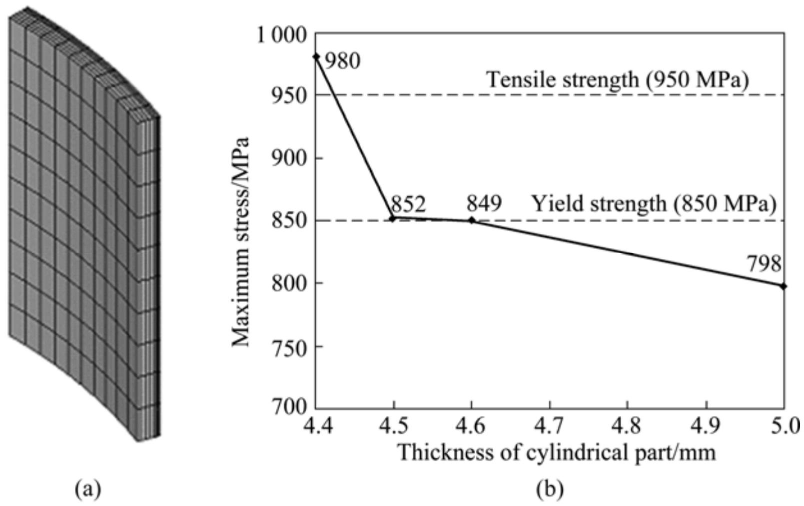
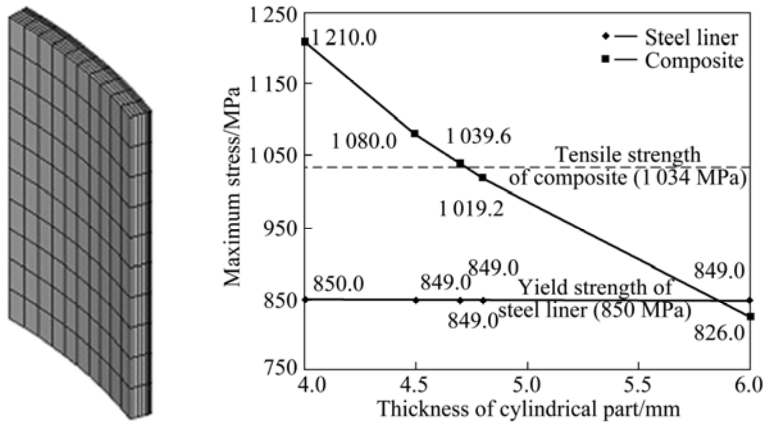


Fig.3 FE model (a) and maximum equivalent stresses (b) according to thickness variation from results of FE analysis of steel liners

and lower faces of the model, and the symmetric constraint was given to both sides of the tangential direction. For the thickness of composite materials, the autofrettage pressure of 40.0 MPa of the type II storage vessel and the bursting pressure of 56.9 MPa were considered.

Figure 4(b) shows the results of the finite element analysis to determine the thickness of the composite material based on bursting pressure. When the thickness of composite material is 4.8 mm, the maximum stress of metal liners appears to be 849 MPa, less than the yield stress (850 MPa), and the maximum stress of composite materials appears to be 1 019.2 MPa, less than the tensile stress (1 034 MPa). The yielding of the metal liners starts to appear at 4.0 mm thickness of composite materials, but the bursting points of composite materials is close to 4.7 mm, therefore the thickness of composite materials is



(a) (b)

Fig.4 FE model (a) and maximum equivalent stresses (b) according to thickness variation resulted in FE analysis of steel liner and composite

determined as 4.8 mm.

3.2.2 Determination of thickness of dome part of metal liner

The model used here was almost identical, and only the dimensions of the dome were revised gradually. The same displacement and load boundary conditions as shown in Fig.1 were used for each condition in the finite element analysis. Changes in the maximum stress in the metal liners and composite materials pursuant to the thickness change in the dome part of metal liners are shown in Fig.5.

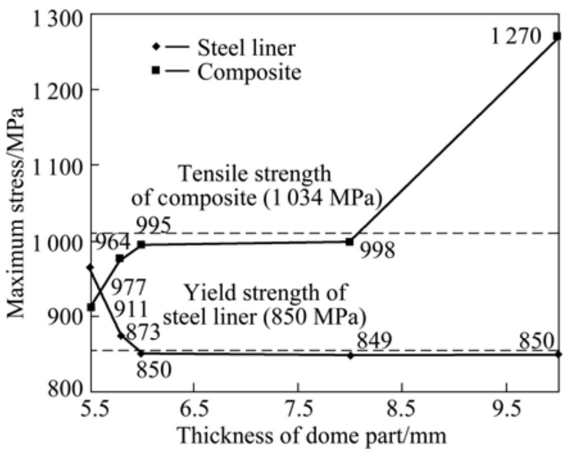


Fig.5 Maximum equivalent stresses according to thickness variation from results of FE analysis of dome part

The thickness of the dome part of metal liners can be divided into less than 6.0 mm, 6.0−8.0 mm, and larger than 8.0 mm, which almost coincides with the metal liner's elastic limit, yield section and work hardening section from Fig.5. Based on the results in Fig.5, the design variable of the thickness of the dome is determined as 6.0 mm. A comparison of the thickness of existing and proposed parts design is shown in Table 2.

Table 2 Comparison of thickness according to each part

Part	Existing design/mm	Suggested design/mm
Cylindrical wall	4.3	4.6
Dome	6.5	6.0
Composite	6.6	4.8

3.2.3 Pressure-resistant structural analysis of improved Type II storage vessels

The optimal thickness, after considering three kinds of design pressures, was determined from Fig.3(b), Fig.4(b) and Fig.5. The schematic drawings of the products using this thickness, and the results of the pressure-resistant structural analysis, are shown in Fig.6(a); and a comparison between the maximum stresses of metal liners and composite materials pursuant to the design pressure condition is shown in Fig.7.

Figure 6 shows the occurrence of similar stress to the cylinder and dome parts of liners at the working pressure, test pressure and bursting pressure, after autofrettage treatment.

Figure 7 shows that a shape transition region of maximum stress occurs in the metal liners between the cylinder and dome parts under the remaining design pressure conditions, except for the bursting pressure.

3.2.4 Lightweight effect due to optimal shape design

A change in mass occurs when adopting the shape of the current product, as shown in Fig.1, to that of the proposed shape as shown in Fig.6(a), and as the proposed type II storage vessels are mainly used for inland transportation, this change in mass is an important issue. The total length of the relevant products, used as a fixed value, is 1 900 mm, and the height results of each dome and cylinder part, based on the designs of Figs.1 and 6(a), are shown in Table 3. The mass results of the steel liners and the composite materials using the same value are shown in Table 4 and Table 5.

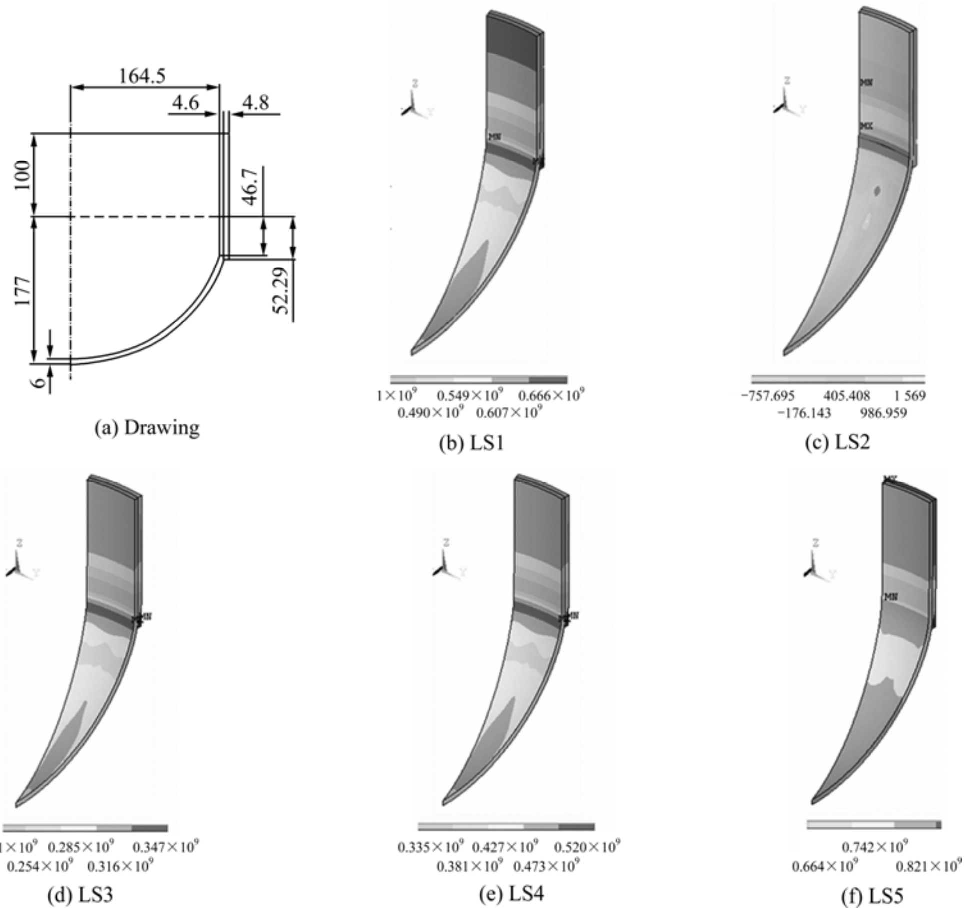


Fig.6 Proposed drawing and equivalent stress distributions from results of FE analysis of Type II fuel storage vessels

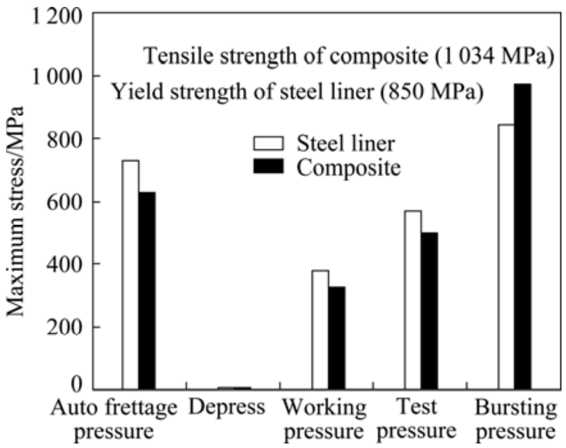


Fig. 7 Maximum equivalent stresses of steel liner and composite in each load step resulting from FE analysis of Type II fuel storage vessels

Table 3 Comparison of length and density between present and suggested dome shape

Part	Length/mm			Density/(g·mL^{-1})
	Dome	Cylinder	Total	
Present dome	67.12	1 765.76	1 900.00	7.85
Suggested	130.30	1 639.40	1 900.00	1.80

Table 4 Comparison of mass between steel liner of present and suggested dome shapes

Part	Volume/mm^3			Mass/kg
	Dome	Cylinder	Total	
Present dome	665 247	7 950 316	9 260 810	72.7
Suggested	830 213	7 903 471	9 563 897	75.1

Table 5 Comparison of mass between composite of present and suggested dome shapes

Part	Volume/mm^3	Mass/kg
Present dome	12 202 811	22.0
Suggested dome	8 247 100	14.8

4 Conclusions

1) In order to satisfy the design conditions, the minimum thickness was established in this sequence: metal liners, composite materials and dome parts. Finite element analysis was then conducted for the entire model by applying the results of the design conditions.

2) In the case of the existing shapes, the bursting of the fuel storage vessels for CNG automobiles occurred in

the dome area, but in the case of the newly proposed shape, it occurred in the cylinder area, therefore it is the case that the composite materials can prevent scattering of the metal liner's fragments and can prevent additional damage to human lives and property.

3) The mass of the existing shape and the proposed shape products are 94.7 kg and 89.9 kg, respectively, giving a mass reduction of about 4.8 kg (5.1%).

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