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Development of Type 4 Composite Pressure Vessel by using PET Liner for Self-contained Breathing Apparatus

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PET 라이너를 적용한 공기호흡기용 타입 4 복합재료 압력용기 개발

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ABSTRACT

In this study, we solved the human hazard problem of aluminum liner by applying plastic PET liner which is widely used as a material for food and beverage containers in the market. In order to reinforce dome area by using low strength / high elongation plastic liner, The aluminum boss was covered on the plastic liner surface. In order to predict the performance of the developed product, the structural analysis was carried out by applying the three - dimensional laminated solid element, and the soundness of the product was verified through the prototype performance test.

Key Words : Composite(복합재), Pressure Vessel(압력용기), Liner(라이너), Self-contained Breathing Apparatus (공기호흡기)

1. Introduction

As a self-contained breathing apparatus (SCBA) is a product that is attached to a human body for a long time, it is important to ensure that it is lightweight and safe. As a result, a Type 3 product, which enables the application of low-specific gravity carbon fiber and the implementation of a leakage mode prior to breakage has been used. However, the aluminum inner liner inside the Type 3 container has the problem of rust generation, as the oxide film contained in the aluminum peels off when the aluminum inner liner is in contact with oxygen for a long period of time. This rust component may cause serious heavy metal problems if introduced to human bodies.

Accordingly, this study solved the problem of hazard to human bodies by applying a polyethylene terephthalate (PET) liner, which has been widely used as a material in food and beverage containers,

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in order to prevent rust generation and hazard to human bodies caused by the aluminum inner liner's corrosion in existing breathing apparatuses. This study applied the thermal curing method of PET materials to improve the strength around the boss, which is responsible for oxygen inflow into the container by contacting the external air flow. In addition, the aluminum boss was covered on the plastic liner surface to reinforce the area around the dome, due to the use of low-strength and high-elongation plastic liner. To predict the performance of the developed product designed with the above method, three-dimensional (3D) additive solid elements were applied to conduct the structural analysis, and the product integrity was proven through the prototype performance test.

2. Design and structural analysis of Type 4 composite cylinder used in SCBA

2.1 Design theory of liner

The liner, which plays a role in preventing internal gas leakage, and the mandrel, which winds the fiber in the composite container, were designed based on the isotensoid dome theory. This theory started with two assumptions: that the fiber content is constant and that the number of fibers that pass through the cross-section is constant when the dome is cut in the vertical direction of the meridian as shown in Fig. 1.

Based on these assumptions, a relationship between the dome's radius and fiber angle is derived as presented in Eq. (1) to calculate the curved shape of the dome[1~3].

$$rsin\alpha = r_b \tag{1}$$

where r_b refers to the radius of the boss.

2.2 Design theory of winding

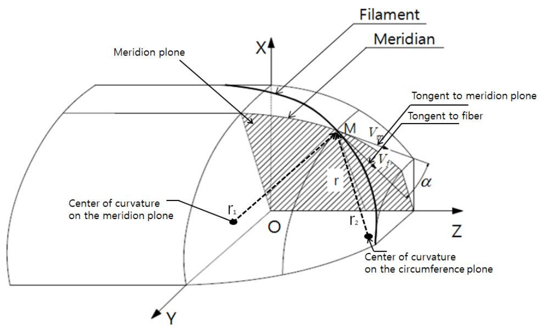


Fig. 1 Geometry of dome part for Type4 composite pressure vessel

The winding layer that supported most of the inner pressure inside the composite container was designed based on the nominal theory. This theory starts from the assumption that the fiber supports the entire inner pressure, and the pattern design in the winding layer is performed through Eq. (2), which is a relationship equation between the winding angle and dome's final curve shape [4~6].

$$2 + \frac{rr''}{1 + r'^2} = \tan^2\alpha \tag{2}$$

where r refers to the radius of the area around the dome, and α refers to the fiber angle.

2.3 Conceptual design of the composite container

A total of four design cases were compared and analyzed, as shown in Fig. 2, to derive an excellent structural shape based on the isotensoid dome theory described in Section 2.1 and the nominal theory described in Section 2.2. First, in Case 1, 5 t was applied as the plastic liner thickness, which was the same as that used in existing Type 3 aluminum liner. Furthermore, 14° and 30° of the helical winding layers and 90° of the hoop layer in the outermost side were arranged. Second, in Case 2, the winding pattern of the composite was the same as in Case 1, but the liner thickness was reduced to 0.6 t, which was suitable to the blow molding condition. Third, in Case 3, the liner thickness was 0.6 t, which was the same as in Case 2; 14°, 30°, and 45° of the helical winding layers were arranged; and the hoop layer was present between the helical layers. In addition, the hoop layer was characterized by applying a metal boss to additionally reinforce the strength around the boss neck according to the plastic liner application. Finally, in Case 4, the liner thickness and helical winding pattern were the same as those in Case 3, but the difference was that the hoop layer was arranged on the outermost side.

A finite element analysis (FEA) was conducted to investigate the performance of the above concept designs. The product had a shape that was rotated 360° around the center axis. Thus, only part of the center angle in the entire model was modeled, as shown in Fig. 3, and a periodic symmetry condition was assigned in the circumferential direction in the model's cross-section due to the presence of the helical layer that had a repetitive pattern on a regular cycle. In addition, 20-node second-order displacement solid elements, provided by ABAQUS (a commercial finite element program) were applied to predict the anisotropy of the filament winding structure and the local stress distribution in the cylindrical dome part accurately[7].

For the load, a path incremental procedure that increased internal pressure step-by-step as shown in Fig. 4 was applied[8].

The structural analysis results in the conceptual design draft were derived, and they are presented in Table 1. The stress concentration area, by which the bursting mode could be predicted, was analyzed, and the analysis results exhibited that the stress was concentrated in the fiber layer around the dome in Cases 1, 2, and 4 so that dangerous failure mode at the dome area would be plucked out during the bursting, whereas the stress was concentrated in the fiber layer at the cylinder side in Case 3, so that a safe failure mode where the cracks occurred around the cylinder was expected. The analysis results of safety factor at 900 bar, which was the minimum bursting pressure of the next container, revealed that the lowest stress occurred in Case 3, which was the best in terms of the safety. Accordingly, Case 3, which showed the safe failure mode and the best safety among the concepts, was selected as the final conceptual design.

2.4 Optimal design of the composite container

In the cylinder area, during the container winding, the dimensions in the container’s radial direction maintain a certain value along the container's longitudinal direction, which makes winding convenient.

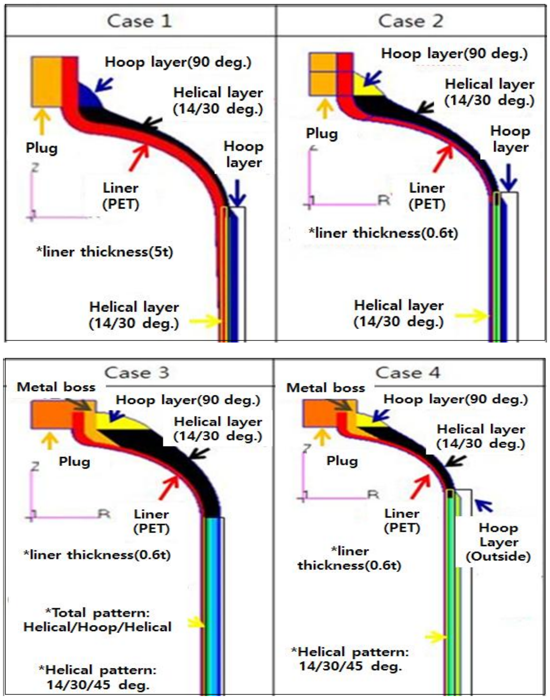


Fig. 2 Conceptual design of type 4 composite pressure vessel

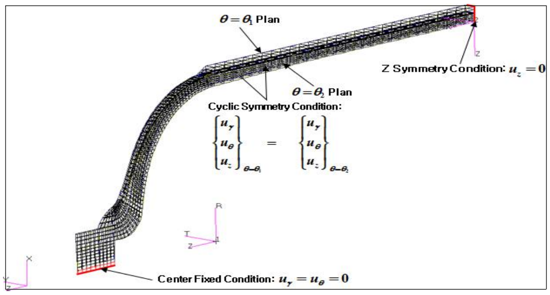


Fig. 3 Finite element modeling of type 4 composite pressure vessel

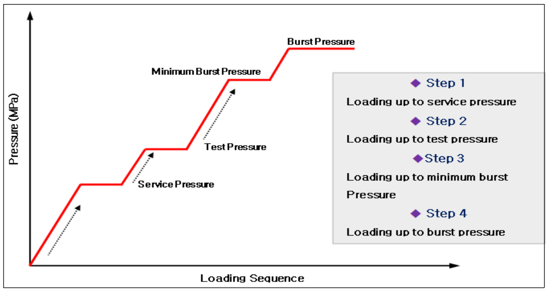


Fig. 4 Loading sequence of type 4 composite pressure vessel

Table 1 Finite element analysis results of conceptual concept

	Case1	Case2	Case3	Case4
Applied Material	Liner: PET(tensile strength: 57MPa) Winding: Carbon fiber T700(tensile strength: 2548MPa)			
Service pressure (300bar)	Liner: 51MPa Winding: 839MPa	Liner: 42.9MPa Winding: 710MPa	Liner: 28.5MPa Winding: 607MPa	Liner: 50.9MPa Winding: 775MPa
Test pressure (300bar)	Liner: 56.8MPa Winding: 1430MPa	Liner: 56.6MPa Winding: 1190MPa	Liner: 47.5MPa Winding: 1020MPa	Liner: 57MPa Winding: 1330MPa
Min. burst pressure (900bar)	Liner: 57MPa Winding: 1790MPa	Liner: 57MPa Winding: 1590MPa	Liner: 54.6MPa Winding: 1360MPa	Liner: 57MPa Winding: 1650MPa
Stress concentration part	Liner: boss neck Winding: dome	Liner: boss neck Winding: cylinder and dome	Liner: boss neck Winding: cylinder	Liner: dome knuckle Winding: dome knuckle
Estimation	danger failure mode	danger failure mode	safe failure mode	danger failure mode

In this regard, this study compared and analyzed three cases: an isotensoid dome (Case 1 based on the conceptual design Case 3), a length-increased non-isotensoid dome (Case 2), and a length-decreased non-isotensoid dome (Case 3) as shown in Figs. 5 and 6. The structural analysis was conducted to investigate the performance of the conceptual designs and the results are presented in Table 2.

In Cases 2 and 3, failure occurred at the flat portion of the fiber layer under failure mode 1 (assuming stable conditions) thereby deriving a safe

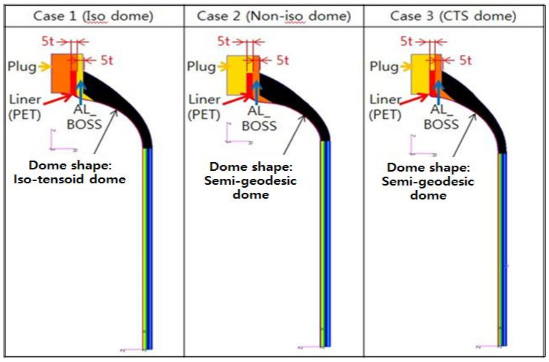


Fig. 5 Optimum design of type 4 composite pressure vessel

Table 2 Finite element analysis results of optimum concept

	Case1 (Iso dome)	Case2 (Non-iso dome)	Case3 (Non-iso dome)
Applied material	Liner: PET(tensile strength: 57MPa) Winding: Carbon fiber T700(tensile strength: 2548MPa)		
Applied pressure	Burst pressure: 1100(target: 1000bar ↑)		
All part analysis	Stress generation above fiber strength in hoop layer → Failure		
Composite part analysis (except hoop layer)	Max. stress in cylinder → second failure part	Max. stress in dome → second failure part	Max. stress in dome knuckle → second failure part
Liner part analysis (except boss)	Max. stress in cylinder → first failure part	Max. stress in cylinder and dome → first failure part	Max. stress in cylinder → first failure part
Estimation	safe failure mode	danger failure mode	danger failure mode

failure mode, whereas failure occurred at the dome area of the fiber layer under failure mode 2 (assuming unstable conditions), thereby deriving an unsafe failure mode. That is, these two concepts had inconsistent failure modes, and, as such, they could not be selected as the optimal structural concept. In contrast, a failure occurred at the flat portion of the fiber layer under both modes 1 and 2 in Case 1, thereby deriving a constant safe failure mode. Case 1 was selected as the optimal structure. In summary, the isotensoid dome shape derived the safest failure mode, whereas the non-isotensoid dome shapes revealed structural instability due to an unstable failure mode.

3. Evaluation of Type 4 composite cylinder prototype for SCBA

3.1 First bursting test

The container bursting test was conducted after fabricating a prototype. The results exhibited a performance above 1,000 bar, which was the design bursting pressure in the specification as presented in Table 3. However, in this bursting mode, a failure occurred in that the dome area was pulled up, rather than the container's cylinder area, which was predicted in the structural analysis. Accordingly, the fabrication process was analyzed, and the analysis results verified that the fiber was tangled at the junction between dome and cylinder during prototype winding.

Thus, the structural analysis was conducted by setting up the fiber angle to be tangled at the junction during structural analysis modeling to analyze the container's bursting mode. The analysis results verified that the maximum stress occurred at the junction as presented in Table 4, verifying that the cause of the first bursting test was due to the fiber tangles at the junction.

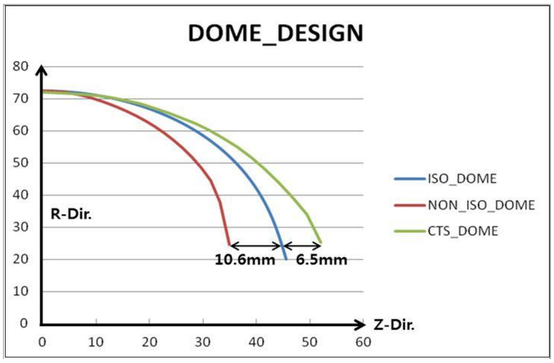


Fig. 6 Dome shape of optimum design

Table 3 1st burst test result of type 4 composite pressure vessel

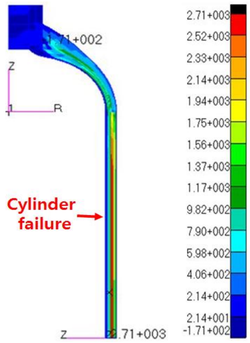
	Spec.	Test	Structural analysis
Burst press.(bar)	1000	1st: 1158 2nd: 1100	1231(error: 6%)
Burst mode		 Dome junction failure (Danger failure mode)	

Table 4 Finite element analysis results for analysis of 1st burst test

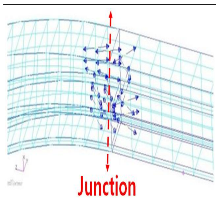
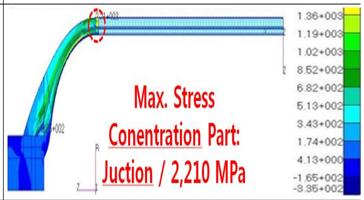
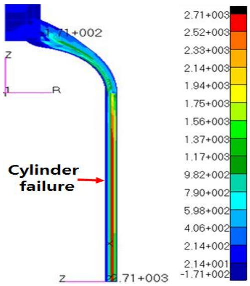
Structural analysis condition	Structural analysis result
	
√ Set the fiber angle to blend in the dome knuckle	√ Strength: 92% level of fiber strength(2400MPa) → Predict burst pressure: 1004bar(Similar to test results) √ Burst can occur when fiber blend occurs in dome knuckle

Table 5 2nd burst test result of type 4 composite pressure vessel

	Spec.	Test	Structural analysis
Burst press.(bar)	1000	1170	1231(error: 5%)
Burst mode			

3.2 Second bursting test

The second prototype was fabricated to conduct a container bursting test. The test result revealed an excellent performance above 1,000 bar, which was the pressure specification as presented in Table 5, and the stable failure mode where the bursting mode occurred at the container's cylinder area predicted in the structural analysis was also derived.

4. Conclusions

This study solved the problem with existing SCBAs of potential hazard to human bodies by applying the PET material used in the food and beverage fields to the liner of the composite pressure container. Furthermore, this study solved the fatigue accumulation problem when using the SCBA for a long time by using lightweight PET materials.

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