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Development of a Type 4 Composite Cylinder for Self-contained Breathing Apparatus

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공기호흡기용 타입 4 복합재료 용기 개발

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ABSTRACT

Aluminum liners used in cylinders are hazardous for human health. In this study, we use a plastic PA liner inside cylinders to solve this problem. Plastic PA liners are widely used in the manufacturing industry in the production of food and beverage containers. We covered the aluminum boss with a plastic liner material and wound the composite fibers over the liner material. To reinforce the dome area, we used low strength / high elongation plastic liner. To predict the performance of the developed product, we conducted structural analyses utilizing the 3D laminated solid element. We verified the soundness of the product by testing the prototype.

Key Words : Composite(복합재), Cylinder(용기), Liner(라이너), Self-contained Breathing Apparatus(공기호흡기용)

1. Introduction

In case of life-saving or extinguishing activities in fire, various toxic gases from fire should be breathed without filtration. Therefore, the air respirator is a personal equipment that is designed to accumulate air in a high pressure cylinder and to send it to the mask so that fresh air can be breathed. cylinders for self-contained breathing apparatus need to be lightweight and safe to use as users wear them on their body for a long periods. So, lightweight carbon fiber full-wrapped composite cylinders capable of implementing the “leak before burst” design principle are commonly used for this purpose. However, the aluminum liner used inside these cylinders is prone to rusting because of the peeling of the oxide layer due constant contact with oxygen for extended periods. The rust particles thus produced can cause serious harm to the user. In addition, the aluminum

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liner increases the overall weight of the cylinder which puts additional strain on the user who has to carry it on his back.

Therefore, in order to solve the problem of rust generation and the additional weight associated with the use of aluminum liners, we have used the ultra-light nylon material developed for gas blocking in the food and beverage field. We have applied a tow preg to obtain uniform performance through a constant fiber to resin volumetric ratio. In addition, during development, we analyzed the structural strength and load distribution factor of each part according to the length of the boss, and improved the structural stability of the part by deriving a suitable boss structure for the corresponding cylinder.

A prototype of the developed cylinder was manufactured and its performance was tested. The cylinder had a minimum bursting pressure of 1,100 bar, and has a good rupture mode starting at the center of the cylinder and forming a fracture profile in the longitudinal direction of the cylinder. Excellent repeatability without leakage or rupture was derived for 8,000 repetitions.

2. Design and Analysis of Type 4 Composite Vessel for Self-contained breathing apparatus

2.1 Liner Design

Liner for preventing leakage of gas and winding the fibers in the composite cylinder were designed using iso-tensoid dome theory. The theory originates from the assumption that the fiber content is constant if the number of fibers passing through the section is constant when the dome part is cut in the vertical direction of the meridian, as seen in Fig. 1. Based on this assumption, we can derive the shape of the dome by using the relation between the radius of the dome and the angle of the fiber as shown in Eq. (1)[1-6].

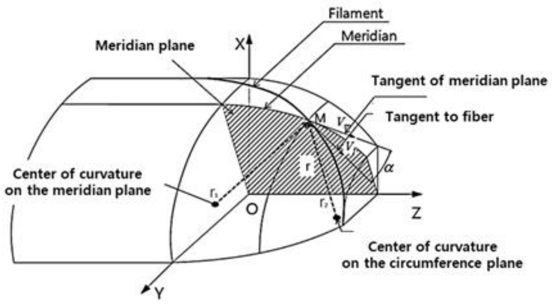

Fig. 1 Schematic diagram of iso-tensoid dome theory

$$r sin\alpha = r_b \quad (1)$$

Here r_b is the radius of the boss.

2.2 Boss Design

The boss is responsible for the inflow and outflow of the gas and connects the cylinder to the outside through a valve or an adapter. Usually the boss in Type 4 cylinder with polymer liner is made of a high rigidity metal material. Therefore, in Type 4 composite cylinder, the performance of the interfacial structure that provides sealing and assembly between the boss and the liner determines the performance of the cylinder. Due to the importance of this key component, numerous patents reporting different designs have been filed and registered. Thus, in this research, a boss structure suitable for a composite cylinder for self-contained breathing apparatus was also developed. The concept of the boss structure is shown in Fig. 2. The inner and outer parts of the plastic liner injection hole are tightened with a metal boss. The outside of the liner and the inside of the outer metal boss are threaded, and so can be screwed together. An O-ring used between the liner and the inner metal boss provides sealing by putting a pressing force on the liner. Threading of the liner has been made possible by the use of high strength nylon material. In order to ensure secure fastening of the liner and the outer metal boss, a concave shape has been provided on the liner as shown in Fig. 3.

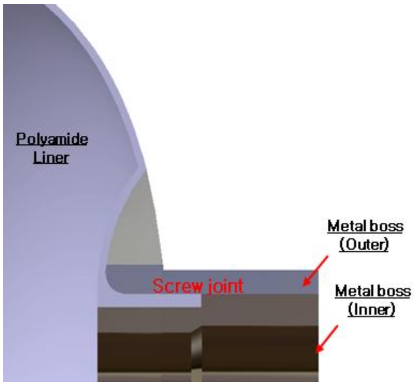

Fig. 2 Tightening structure of liner and boss for Type4 composite vessel

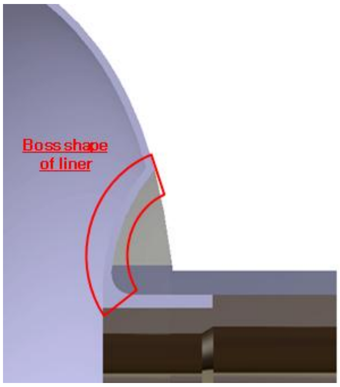

Fig. 3 Inlet structure of liner for Type4 composite vessel

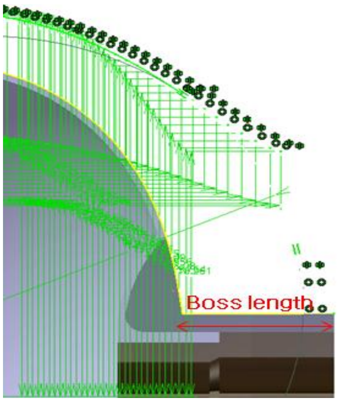

Fig. 4 Winding path line of composite layer for Type4 composite vessel

2.3 Winding Design

The winding layer which supports most of the inner pressure of the composite cylinder was designed based on the netting theory. In this design, the fiber sustains the entire inner pressure. The pattern design of the winding layer was derived using equation (2), which is the relationship equation between the winding angle and the curve of the dome[7-11]. Based on these, the winding path was constructed as shown in Fig. 4. The boss length was calculated considering the thickness of the composite material on the boss part.

$$2+\frac{rr''}{1+r'^2}=\tan^2\alpha \qquad (2)$$

Here r is the radius of the dome and α is fiber angle.

2.4 Knob Design

The knob part that is fastened to the tail stock of the winding machine and transmits the rotational force to the liner is required to support for a long time the compressing force exerted by the metal shaft during the winding of the cylinder. Thus, a metal material of high rigidity is used for this part. In order to maintain the shape of the cylinder, the wing shape is applied to the knob to realize the dome shape of the liner, as shown in Fig. 5.

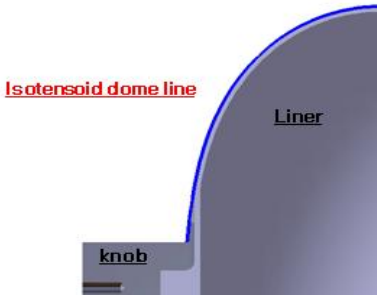

Fig. 5 Isotensoid dome line of knob part for Type4 composite vessel

2.5 Structural Analysis of Composite Vessel

Structural analysis was performed to predict the structural performance of the developed cylinder. First, the cylinder was rotated 360 degrees about the center axis. As shown in Fig. 6, only some central angles of the whole structure were modeled, and cyclic symmetry conditions were given circumferentially to the cross section of the model due to the presence of the helical layer that has cyclic repetitions of the same shape. In order to predict accurately the orthotrophy of the filament winding structure and the local stress distribution of the cylindrical-dome part, a 20-node secondary displacement solid element provided with the commercial finite element software ABAQUS was applied[12].

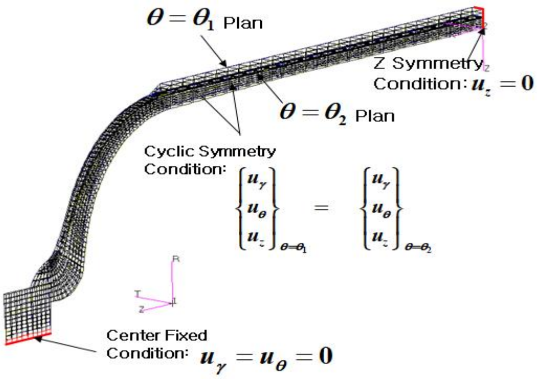

Fig. 6 Finite element modeling of type 4 composite vessel

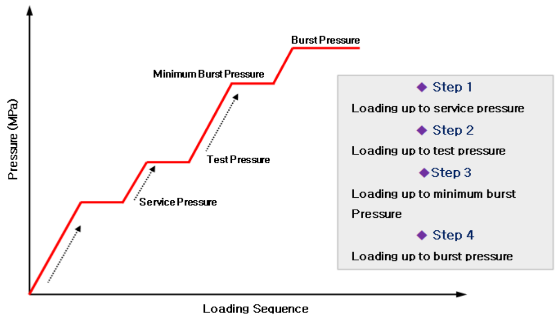

Fig. 7 Loading sequence of type 4 composite vessel

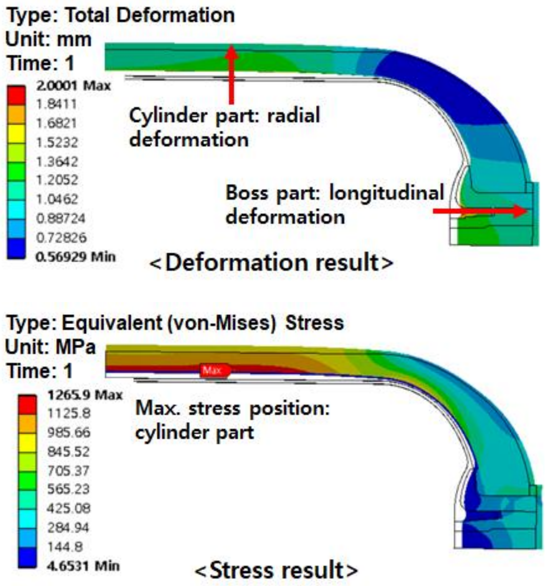

Fig. 8 Finite element analysis result of type 4 composite vessel

As shown in Fig. 7, the load pressure was increased in a stepwise manner.

As shown in Fig. 8, the structural analysis was carried out from two perspectives, i.e. rigidity and strength. First, the deformation of the cylinder during the stiffness analysis shows that the cylinder portion of the cylinder is swollen in the radial direction while the internal pressure is applied, and the boss portion has moved in the longitudinal direction. This is a typical deformation mode caused by to the application of an iso-tensoid dome, which is deformed in the longitudinal direction due to the characteristic of the iso-tensoid dome shape having a relatively shorter length in the radial direction. Accordingly, when the composite material is wound, its thickness in the dome is increased relative to the cylinder part so as to suppress the longitudinal movement. The results of the strength analysis show that most of the stresses under the action of the applied pressure are concentrated in the cylinder portion. This is the result of the difference in diameter of different parts of the composite cylinder as the stress concentrates on the cylinder part having a greater diameter than the boss part.

3. Tests of Type 4 Composite Vessel for Hydrogen Gas Transportation

3.1 Burst Test

The prototype was tested according to the KGS AC418 2017 (Facilities, Technology and Inspection Standards for the Manufacture of Nonmetallic Liner Composite Containers for High Pressure Gas) testing standard. The cylinder was pressurized by applying water pressure until the cylinder bursted at a rate of 1 MPa/s. In the test, the cylinder failed at a pressure of 1,100 bar. As shown in Fig. 9, an excellent burst mode that started at the center of the cylinder and formed a fracture surface in the longitudinal direction of the cylinder was induced.

3.2 Cycling Test

In accordance with the KGS AC418 2017 (Facilities, Technology, Inspection Standards for the Manufacture of Nonmetallic Liner Composite Containers for High Pressure Gas) testing standard, the manufactured prototype was tested to evaluate the cyclic performance of the cylinder. The cylinder is to be subjected to repeated pressurization from a pressure lower than 10% of test pressure to test pressure. The prototype exhibited excellent cyclic performance without leakage or burst during 8,000 repeated pressurization. As shown in Fig. 10.

Fig. 9 Burst mode of liner for type 4 composite vessel

Fig. 10 leakage mode of type 4 composite pressure vessel

4. Conclusions

In this study, light nylon material developed for the purpose of gas shielding in the food and beverage field was applied to solve the problem of rust generation and increased cylinder weight caused by the presence of aluminum liners in the gas storage tanks used in conventional air respirators. The tow preg was applied to obtain the uniform performance based on the constant fiber to resin volumetric ratio. In addition, during development, we analyzed the structural strength and load distribution factor of each part according to the length of the boss, and improved the structural stability of the part by deriving a suitable boss structure for the corresponding cylinder.

The developed product has undergone performance testing after prototyping. During testing, an excellent burst mode starting at the center of the cylinder and forming a fractured surface in the lengthwise direction of the cylinder was obtained at a minimum burst pressure of 1,100 bar. The prototype exhibited excellent cyclic performance without leakage or burst during 8,000 repeated pressurizations.

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