STUDY ON BEHAVIOR OF AMBIENT HYDRAULIC CYCLING TEST FOR 70 MPA TYPE-3 HYDROGEN COMPOSITE CYLINDER

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ABSTRACT

Hydrogen used in hydrogen fuel cell vehicles is the flammable gas which has wide flammable range and flame propagation speed is very fast. This fuel cell vehicle equipped with high-pressure vessel in the form of fuel to supply the high pressure hydrogen storage system needs to be checked carefully about a special safety design and exact weak point for high pressure repeated fatigue. 70 L liner and 70 MPa Type-3 vessel were tested using the equipments which can perform ambient hydraulic cycling test and burst test in the Korea Gas Safety Corporation. And it was performed to identify the internal external behavior through the Finite Element Analysis (FEA) and real leakage mode for high pressure repeated fatigue when subjected to be pressurized in vessel. 70 L liner and 70 MPa Type-3 vessel were tested using the equipments which can perform ambient hydraulic cycling test and burst test in the Korea Gas Safety Corporation. And it was performed to identify the internal external behavior through the Finite Element Analysis (FEA) and real leakage mode for high pressure repeated fatigue when subjected to be pressurized in vessel. Through this study, liner of type-3 hydrogen vessel is ruptured first on cylindrical (body) part than Dome part in 8.5 MPa. Also the same Phenomena are confirmed through the Finite Element Analysis (FEA). External composite leakage mode in ambient hydraulic cycling test was occurred in different area such as the Dome, Dome knuckle and cylindrical (body) parts. But cracks of inner liner for gas tight were occurred in only cylindrical (body) parts. Also in FEA results, when vessel is pressurized, Dome knuckle and cylindrical (body) parts is weakest among all parts because of expansion of cylindrical (body) parts.

1. INTRODUCTION

As the interest in environment issue such as global warming and air pollution increases, a lot of effort is being put into earlier development for mass production of Hydrogen FCV which produces neither harm exhaust gas nor carbon dioxide causing global warming.

The equipment at Korea Gas Safety Corporation is to verify the safety reliability by evaluation of the system and the parts of high-pressure hydrogen storage system composed of various kinds of valves and hydraulic cycling test of pressurized cylinder used for Hydrogen FCV. There has not been any unified standard/regulation/test method for Hydrogen FCV and its parts yet only with the introduction system at markets and its standard being made. In addition, since the experience of using hydrogen as fuel is meager yet, there are not a few uncertainties about the behavior and feature of cylinder. Accordingly, it is necessary to carry out the test of cycling fatigue for cylinders which are very important parts of Hydrogen FCV in order to accomplish safety and durability of high-pressure hydrogen storage system for Hydrogen FCV [1]. In particular, even though there have been plenty of reports on safety and durability of Type-3 cylinder in the field of composite cylinder, how much more performance it has compared with others has not been substantially verified yet in Korea. Therefore, the hydraulic cycling test for Type-3 cylinder was carried out by the utilization of the systemized hydraulic cycling equipment at Korea Gas Safety Corporation for the purpose of examining the behavior of hydrogen cylinder [2] [3].

2. TEST EQUIPMENT AND METHOD

One of the design verification tests for high-pressure cylinder is to create the condition of hydrogen charge or release for simulation of the environment with real fatigue properties of cylinder for the verification of cylinder integrity. Since the properties of hydrogen may cause risk and makes it difficult to find the exact position of leakage when it is charged or released, the test is to detect any leakage which may be caused by accumulated fatigue and to determine whether it satisfies the regulation for durability. Water is used as test medium for visual and image check.

Table 1. Specifications of high pressure pump

Content	For 35 MPa	For 70 MPa
Flow Rate	84 LPM	71 LPM
MAX. Pump Pressure	55.5 MPa	111 MPa
Required Suction Pressure	0.3-0.4 MPa	0.3-0.4 MPa
Stroke Length/Stroke Per Minute	105mm/435	105mm/ 435
Fluid/ Max. Temp	Clean Water/ 60℃	Clean Water/ 60℃

Today, since hydrogen cylinder is charged to 35 MPa and 70 MPa for use, the equipment dedicated to each kind of cylinders which have different performance and capacity is furnished at Korea Gas Safety Corporation for hydraulic cycling test. There is the equipment which can adjust the velocity per minute to the average of 6 cycles so that the time spent on tests can be reduced and there are other apparatuses each of which has its own pressure to match each demanded velocity per minute.

Figure 1. High Pressure Pump and Chamber

3. INTERNATIONAL STANDARD FOR HYDROGEN CYLINDER

An international standard for safety confirmation of hydrogen cylinder which is extremely pressurized is being developed. In Korea, since there are very few testing facilities to examine the safety of extra-high pressure cylinder, the domestic manufacturers have had a lot of difficulty in developing any products. However, in recent years, owing to the increased interest in and grown capability of hydrogen fuel, a safety standard for hydrogen cylinder named UN ECE No.406 has been established.

Table 2. International Regulation for Hydrogen Cylinder

Item	**ANSI/NGV2-2007 (Regulation of North America)**	**UN ECE R No.406 (Regulation of Europe)**
AMBIENT HYDRAULIC CYCLING TEST	Name: Room-temperature Cycling Test	Name: Room-Temperature Pressure Cycle Test
	Cylinder Used: 2	Cylinder Used: 2
	Test Method: Operating Pressure X 1.25, Repeat less than 10 cycles/m	Test Method: (a) Lower Cycling Pressure: 2 MPa (b) Higher Cycling Pressure: Operating Pressure X 1.25 (c) Less than 10 cycles/m
	Outcome: Leakage is allowable but not burst at more than Design Life x 750(11,250 cycles) Any burst at more than 45,000 cycles is allowable (NGV2000) Any burst is allowable at more than Design Life x 2,250 (33,750 cycles) (NGV2007)	Outcome: There should not any leakage or burst at less than the first cycle 4,000(Basic Charge Times for at least 15 years) X 3 (12,000 cycles) Leakage is allowable but not any burst between 12,000 and 36,000

Before, all cylinders were tested according to the modified details of the regulations for hydrogen cylinders specified at ANSI/NGV2 2007, North America CNG Industrial Standard, which, called Modified ANSI/NGV2 2007(HGV) in Korea, is applied to the tests of cylinders for Hydrogen FCV. The following is the test standard for Permeability Test Equipment and Hydraulic Cycling Test Equipment which have been made at Korea Gas Safety Corporation.

4. ST RESULT AND REVIEW

4.1 Test of Liner Burst and Ambient Hydraulic Cycling Test of Composite Cylinder

In general, at the test of cylinder burst, the manufacturers design and make the cylinders whose bodies are supposed to burst. The reason is to minimize the impact on other external parts by burst of the body which can absorb some of the impact. The frame for winding carbon fiber and the liner preventing any gas from being released should be checked if the body has stable burst and there is any defects inside the liner. Figure 2 shows the test of burst at the liner made in Korea, which was found to have the burst beginning at the body.

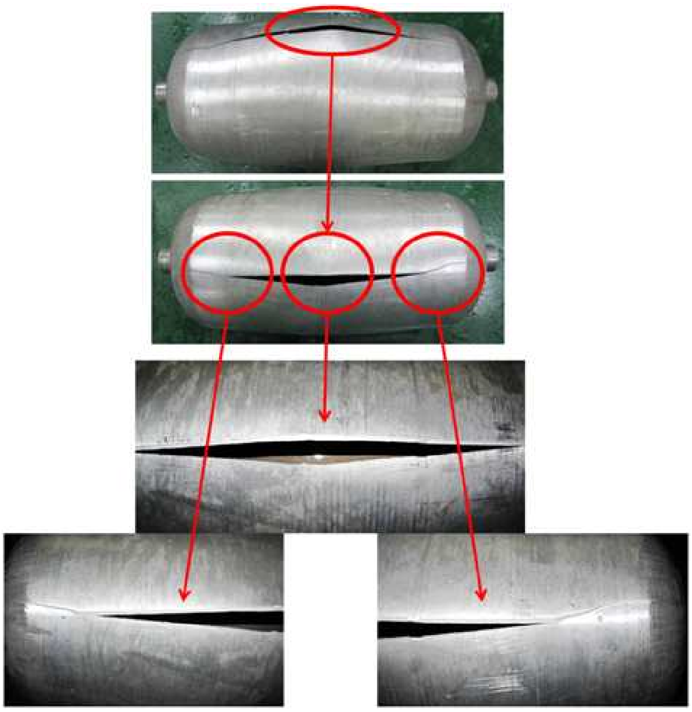

Figure 2. Burst Test of AL Liner

The picture below is about the hydraulic cycling test of foreign-made 40-liter 70 MPa. In general, the composite made of a bundle of fiber is solidified into resin, and if it has no sealing, the fluid inside, on being pressurized, is leaked to outside through small holes. The leakage to outside at the final stage when the liner comes to have internal cracks due to fatigue after it has had more cycles than those guaranteed by the manufacturers. It is necessary to find out what part of the inside of the liner has the leakage which can be visible with that.

Figure 3. Leakage of Type -3 Cylinder

4.2 Check of Leaking Part

A Penetration Test was carried out inside the liner with cut liner and composite material in order to find the exact position of the defected part in the cylinder which was found to have leakage by hydraulic cycling test, which showed long damage on the cylinder (body) as suggested at Fig. 4. What has to be noted at this point is that the leaking part on the liner was the center of cylinder while that of composite cylinder was dome knuckle and dome area, which can be thought as the following: the fluid did not leak directly into the top of composite material but to the part which is vulnerable to leakage (the parts of composite with the thinnest thickness or the area of insufficient impregnation).

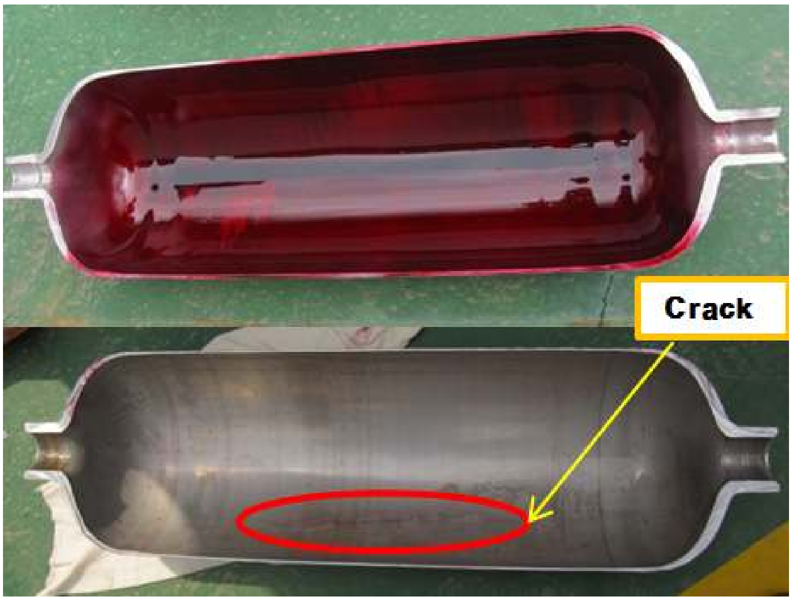

Figure 4. Penetration Test for Inner Liner of Type-3 Cylinder

5. ANALYSIS OF FINITE ELEMENTS

Hydraulic cycling tests and penetration tests were carried out to find leaking positions at the certified composite cylinders. The results of them were applied to structural analysis to determine which area moved to generate the fatigue of liner when it is pressurized

At the modeling of finite elements, the three-dimensional laminated solid elements were used for precise prediction of anisotropy of filament-winding structure and the distribution of local stress at cylinder and dome areas. In addition, multi-point constraint and boundary condition using periodic symmetry condition were applied. The techniques of Geometric Non-linear and Material Non-linear Analysis were adopted for analysis to predict non-linear behavior at the interface of cylinder/dome and liner's plastic behavior[4].

In particular, since the helical angle at the dome area is very likely to continuously change and wind, the technique of designing only with the existing fixed angle causes the accuracy of modeling to drop[5].

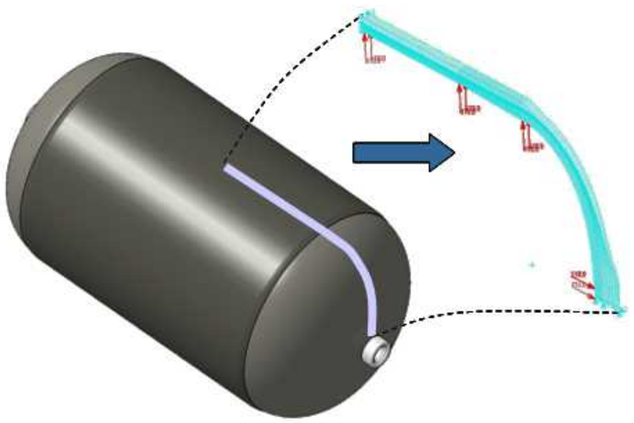

Figure 5. FE Analysis Model

Table 3. Material Properties of AL Liner

Material / Property / Raw Material	Yield Strength (MPa)	Tension Strenth (MPa)	Elongation (%)	Shearing Strength (MPa)
Liner	290 or more	320 or more	14.0 or more	-
Resin	-	-	-	13.8 or more

Table 4. Material Properties of Carbon Fiber

Elastic Modulus	E1(GPa)	192
	E2(GPa)	3.9
Poisson's Ratio	V12	0.38
	V23	0.008
Shear Modulus	G12(GPa)	1.262
	G23(GPa)	1.262
Fiber Volume Fraction	Vf(%)	0.453

Consequently, the technique was utilized which made possible the analysis with the consideration of helical angle changing continuously in order to determine the accurate prediction of behavior at dome area and the stress distribution.

The quality of fatigue was kept from being increased by the design of winding pattern minimizing any excessive deformation such as bending at the boundary point (part of knuckle) of dome area which occurs at the times of repeated charging.

A variety of detailed structural analyses were carried out for the evaluation of the effect of such design variables as carbon fiber and liner shape on the structural behavior of cylinder along with the application of the above various analysis and design elements, which produced the below results as seen at Fig 6 through the examination of cylinder's structural behavior depending on the change of design variables.

For the structural analysis of composite pressure cylinder, the commercial software of MSC/PATRAN was used for 3-D modeling of liner, hoof layer and helical layer and then the stress and the deformation were analyzed by FEA commercial software of ABAQUS to show the stress and the deformation under the representative maximum charging pressure.

This shows that the composite cylinder has vertical motion around dome knuckle and that the parts of dome and boss horizontal motion. Accordingly, it was found that when pressurized, the cylinder (body) gets bigger stress than the dome area and gets swollen as being pressurized, which makes dome knuckle and cylinder (body) vulnerable to fatigue.

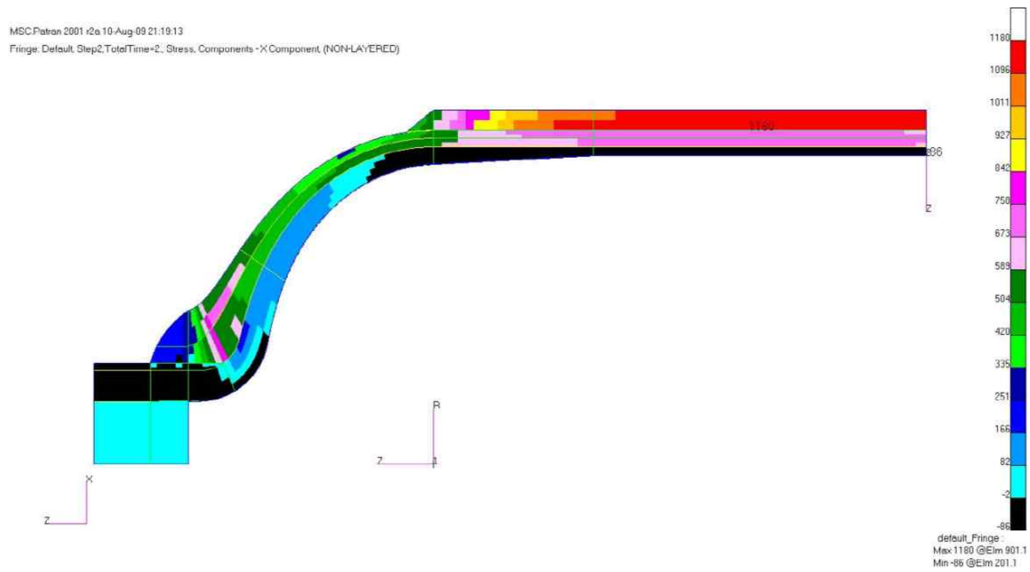

Figure 6. Stresses and Strains at Max. Fill Pressure

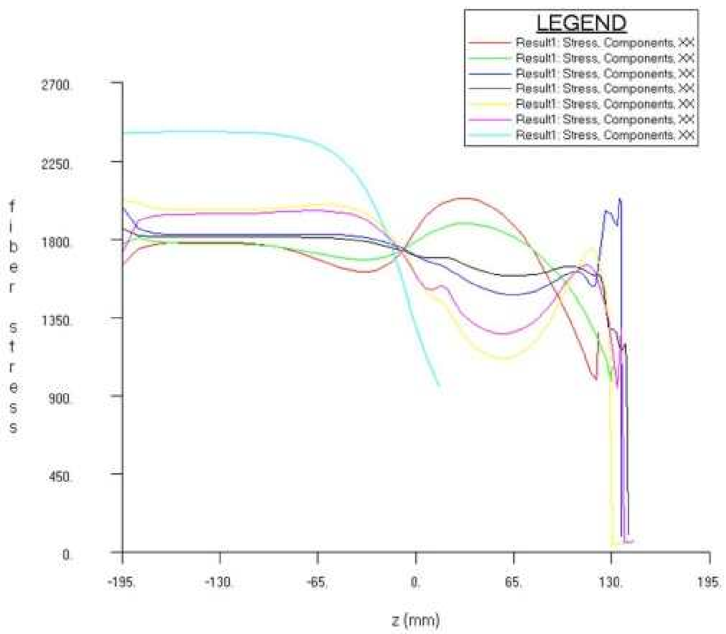

Figure 7. Distribution of Stress for Each Layer

6. CONCLUSION

This study has carried out the test for 70 MPa Type-3 Hydrogen Cylinder and Finite Element Analysis to reach the following conclusion:

1) The burst at cylinder (body) begins first at the test of liner burst, which causes the stress concentrated more at the cylinder (body) that at the dome area.

2) In the case of leakage at the liner due to fatigue at Hydraulic Cycling Test of Composite Cylinder, the surface of the composite comes to have several areas of leaking. However, the Penetration Test revealed that the defect inside the liner occurs at the cylinder (body).

3) The Structural Analysis showed that the stress of cylinder is concentrated on the body. Accordingly, the deformation of cylinder shown by structural analysis revealed that the cylinder has vertical motion while the boss area horizontal motion. Consequently, it was found that when pressurized, the cylinder (body) gets bigger stress than the dome area does and gets swollen as being pressurized, which makes dome knuckle and cylinder (body) vulnerable to fatigue.

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