SAFETY EVALUATION AND STRESS ANALYSIS OF FILAMENT WOUND GAS CYLINDERS WITH A SURFACE DAMAGE

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Abstract

This paper reports on the results of experiments and numerical simulations about the effect of the surface damage on the strength of a filament wound (FW) gas cylinders. The tested cylinders were fabricated by winding of epoxy resin impregnated S-glass fibers on an aluminum liner. The cylinders were of diameter 178 mm and of length 511 mm. The thickness of cylinders was total 7.3 mm and consisted of 2.3 mm aluminum liner and 5.0 mm of composite overwrap in four layers: two helical winding and two hoop-winding. Prior to service, all the cylinders were submitted to the treatment of autofrettage, an overpressuring in order to produce compressive residual stresses in metallic liner, and thus to increase the fatigue strength of liner.

Burst tests were carried out for virgin cylinders and two damaged cylinders: one with a notch at central part of a cylinder, one with close to the dome. In order to simulate the tests, FEM calculations have been conducted by using the procedures of MARC with 4-node axisymmetric elements. The damage was assumed to have propagated in circumferential fiber direction in earlier stage of test and modeled as an axisymmetric gouge. This model gave a good estimate of the cylinder burst pressure. The influences of damages upon the fatigue strength of the liner were discussed as well in relation with the stress distribution around the damages.

1. Introduction

Filament wound (FW) gas cylinders are now widely used as firemen's air containers, medical oxygen containers, fuel gas tanks for natural gas vehicles, etc. FW cylinders of the most popular type are fabricated by winding of resin impregnated high strength fibers on a metallic liner. For a fully wrapped cylinder, windings are generally conducted in two modes; (1) "helical winding" to strengthen mainly in length direction", and (2) hoop winding" to strengthen in circumferential direction of the cylinder. These two winding layers are sometimes divided into a number of alternatively piled layers in order to moderate the discontinuity at the ends of different winding layers. These cylinders might be damaged by any shocks or collisions in service. The safety evaluation against damages is an important task for these cylinders.

This paper presents a set of pressuring tests conducted for fully wrapped gas cylinders with metallic liners; damaged and non-damaged cylinders. A numerical analysis on stress and strain distribution was conducted for these cylinders. The modelling of damages is important to establish good estimation methods of the burst pressure and fatigue strength of cylinders. Most damages are initiated by exterior shocks or collisions in a form of "cut" or "gouge". The detailed paths of damage growth are generally very complicated and difficult to pursue the whole ways. In the present study, damages were analyzed by using a simplified axisymmetric model with reference to several results of pressuring tests of real FW gas cylinders 1, 2). The influences of damages upon the burst pressure and the fatigue strength of the liners were discussed in relation with the stress distribution around the damages.

2. Experimental

2.1 Cylinder and material properties

A commercially available composite cylinder with an aluminum liner (6061-T6) wound by 4 layers (2 helical winding and 2 hoop winding) of S-glass fiber impregnated in epoxy type of resin was used.
for experimental tests. The working performance of the cylinder and mechanical properties of the Al and S-glass fiber are given in Table 1 and 2, respectively.

The exterior geometry of the cylinder was 178mm x 511mm. Fig. 1 shows the general dimensions of the gas cylinder. At the cylindrical part, the aluminum liner was 2.3 mm thick and the composite overwrap layers were 5 mm thick in total. At the dome pan, the aluminum liner was 4.0mm thick, and thicker than that in the cylindrical pan. Fig. 2 shows four layers of S-glass FRP, two hoop winding and two helical, wound on the Al liner with the different thicknesses.

Prior to usage, composite cylinders were once pressurized up to 1.83 times of the service pressure in order to produce compressive residual stresses in the aluminium liner for longer fatigue life. The service pressure is 15 MPa and designed to be in service, keeping the safety factor larger than 3.0.

2.2 Experimental procedure

A set of strain gages were mounted to measure strains on the outer part of composite cylinder in the longitudinal and circumferential direction. The location of the strain gages are shown in Fig. 1. The strain values were recorded by a personal computer. A pressuring equipment was used for pre-pressurization and burst test. A motor pump with maximum water pressure capacity of 150 MPa was employed to generate necessary internal pressure. Composite cylinders were put in a metal chamber and internal water pressure was applied gradually up to burst pressure.

Several cylinders without damage were tested to burst to obtain the ultimate strength of the cylinder. A couple of cylinders with a mechanical notch on the surface of overwrapped composite layer are as well subjected to the pressurizing tests. The mechanical notches of 8x1.2mm, and 20x1.2 mm were introduced by a precision hand type rotating cutter with a blade of 259x1.5mm on the cylindrical pan of two cylinders; one at the center and the other near the dome boundary. The results of the burst tests and the notch location are shown in Table 3.

3. FEM Simulations

A commercial FEM code, MARC K6.1-Mentat 2.1r was employed to simulate the internal pressure tests of composite cylinders. A mesh corresponding to a quarter of the cylinder for axisymmetric modelling was generated by using Mentat preprocessor. The calculation was conducted with 747 nodes with two degrees of freedom and with total 623 of 4-node axisymmetric elements; 126 elements in aluminum liner and 497 elements in four FRP layers. The mesh and boundary conditions are shown in Fig. 3. By the condition of symmetry, the nodes on the center line of the cylinder were fixed in the length (z) direction and in the radial (r) direction. Figure 4 (I) shows the notches entered the simulation program using rezoning which made to generate the damaged mesh easily. Figure 5 shows pressure loading steps in the

<table>
<thead>
<tr>
<th>Table 1. Performance of the tested gas cylinders</th>
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<tbody>
<tr>
<td><strong>Service Pressure (MPa)</strong></td>
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<tr>
<td><strong>Vol. (Liter)</strong></td>
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<tr>
<td><strong>Filling gas vol. (N Liter)</strong></td>
</tr>
<tr>
<td><strong>Test pressure (MPa)</strong></td>
</tr>
<tr>
<td><strong>Min. burst pressure (MPa)</strong></td>
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<thead>
<tr>
<th>Table 2. Mechanical properties of the Al liner and S-glass</th>
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<tbody>
<tr>
<td><strong>Aluminum Liner</strong></td>
</tr>
<tr>
<td>$\sigma_y = 250$ MPa</td>
</tr>
<tr>
<td>$E = 70$ GPa</td>
</tr>
<tr>
<td>$\nu_{LT} = 0.27$ GPa</td>
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Fig. 1 Schematic view of FRP gas cylinder

Fig. 2 The detailed section of the FRP layers and Al liner near the dome

Fig. 3. Mesh and boundary conditions of FEM model and details of the layers
Table 3 Results of the experimental tests and REM simulations.

<table>
<thead>
<tr>
<th>Damage location</th>
<th>No notch (at the center)</th>
<th>20 mm notch (at the center)</th>
<th>20 mm notch (near the dome)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burst pressure (Exp.)</td>
<td>62</td>
<td>55</td>
<td>54.5</td>
</tr>
<tr>
<td>Place of the burst (Exp.)</td>
<td>50 mm from dome</td>
<td>at the notch place</td>
<td>at the notch place</td>
</tr>
<tr>
<td>Circumferential stress in hoop layer at 15 MPa(Sim.)</td>
<td>280</td>
<td>302</td>
<td>150</td>
</tr>
<tr>
<td>Circumferential stress range in Al liner at 15 MPa (Sim.)</td>
<td>270</td>
<td>285</td>
<td>223</td>
</tr>
</tbody>
</table>

FEM calculation. The first step of pressurizing at 27.5 MPa corresponds to the autofrettage treatment to produce compressive residual stresses in aluminium liner at the second step of the depressurization to zero. An axisymmetric damage was introduced at the third step of calculation by displacing the mesh lines. The service pressure of 15 MPa was applied at the forth step and increased gradually up to 75 MPa. A special subroutine named Elevar was linked to main program to obtain stress and strain values of each element.

4. Discussion

For comparison, a brief results of the experimental tests and simulations are given in table 3. From table 3, it is seen that the cylinder which had a notch close to the dome got burst at the lowest internal pressure, although the circumferential stress of the cylinder which had notch at the center of cylinder is highest. This inconsistency is considered to be due to the bending effect and enhancement of longitudinal stresses.

Figure 6 and 7 shows the stress and strain distribution of a virgin cylinder under service pressure of 15 MPa, respectively. In Fig. 6, the circumferential stress of aluminum liner is a third of the yield stress of aluminium ($\sigma_y=230$ MPa) around the center of cylinder part. This

![Fig. 5 Pressure steps for FEM simulations](image)

![Fig. 6 Distribution of hoop stresses in Al liner and FRP fiber near the cylinder surface under the service pressure, 15 MPa](image)

Fig. 4 Geometry of notches for FEM (I) simulations and real experiments (II)

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shows that a one-time over pressure of 27.5 MPa is also results a useful residual compression stress on the aluminum liner. Figure 7 shows an acceptable agreement between experimental and FEM simulation in case of present modeling.

The stress situation of hoop layer with damage or without damage was checked by using FEM simulations. Figure 7 shows the simulation results. At the service pressure of 15 MPa, a notch of 8x1.2mm and 20x1.2 mm at the center of cylinder resulted an increase in the circumferential stress 3.5% and 7% respectively. The effect of notch was more clear when the pressure was increased to the near the burst pressure. Circumferential stress of 1155 MPa at the near burst pressure of a cylinder with no damage was increased to 1245 MPa and 1145 MPa by a 20 mm notch-like damages at the center and near the dome, respectively.

The effect of the notches (small notch = 8x1.2mm and big notch =20x1.2 mm) on the aluminum liner also checked by FEM simulations, since any stress increase in Aluminum liner is effecting directly to the fatigue life of the composite cylinder. Figure 10 shows a comparison the stress range of the aluminum liner with damage and without damage. The stresses shown here are the difference between autofrettaged liner stress and service pressure stress. As seen in Fig. 10, the liner with no notch has approximately 270 MPa circumferential stress difference at the central part under the service pressure, whereas a notch of 8x1.2mm or 20x1.2 mm resulted 285 MPa and 305 MPa, respectively. Figure 11 shows how the stress difference is changing if the same size notch-like damages were done at an area close to the dome. The maximum difference was seen around the vicinity which is located approximately 148 mm from the center of vessel. The stress range was 216 MPa at this vicinity for the cylinder with no damage. The same stress range was increased to 223.11 MPa by small notch and 234.15 MPa by big notch. Comparing Fig. 10 to Fig. 11, it is seen that the same size notch results more bigger damage at the central area of cylinder. In another word, a damage in the central part of the composite cylinder is more effective to shorten the fatigue life of the aluminum liner than the one close to the dome area. This was also confirmed by strain distribution of a cylinder under service pressure. Figure 12 also shows that the central part of the cylinder gets higher straining even if the cylinders had the same size of the damage.

5. Conclusions
Stress analysis of a filament wound cylinder with damage or without damage were evaluated by experimentally and simulations.

1- In the experimental part of this study cylinder without notch or
yith notch at the center or near the dome were pressurized up to burst pressure. A damage (20x12 mm) on the outer FRP hoop layer caused the burst pressure to reduce by approximately 7 MPa. This shows that a damage near the dome of the cylinder can be equally effective as a notch at the center of the cylinder.

2- FEM simulations for a virgin cylinder under service pressure of 15 MPa revealed that circumferential stress of aluminum liner is a third of the yield stress of aluminium (σ_y=230 MPa) around the center of cylinder part. This shows that a one time over pressure of 27.5 MPa is also results a useful residual compression stress on the aluminum liner.

3- Simulations were conducted to see how the stress distribution of aluminum liner changes if any damage occurs in the surface of the cylinder. With damages of the same size, straining was much higher at the central part of tested cylinders for present study which reveals that a notch at the center of the cylinder is more influencing to reduce the fatigue life of the Al liner.

REFERENCES


MARC-MENTAT Manuals, 1995, Marc Analysis Research Corporation, Polo Alto, USA