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Pressurization test on CFRP liner-less tanks at liquefied nitrogen temperature

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Abstract—Two liner-less CFRP concept tanks were prepared for internal pressurization tests at liquefied nitrogen (LN_2) temperature. The tanks were designed in two patterns of eight-ply UD quasi-isotropic lay-up, in the shape as a cylinder of 600 mm in diameter and 1200 mm in length, covered with an aluminum flange at one end and with a CFRP hemisphere dome at the other. The maximum strain was applied as the damage onset condition so that the internal pressurization at LN_2 temperature did not damage them up to 1.1 MPa. Damage onsets, such as transverse cracking and leak path formation, were monitored during the tests using helium flow detection, acoustic emission, and pressure-strain monitoring. The CFRP concept tanks showed no damage in the 1.1 mm thick cylindrical gauge section under pressurization up to 1.1 MPa at LN_2 temperature. The design was thus shown to be successful in keeping the CFRP tanks intact.

Keywords: Cryogenic tank; CFRP; damage evaluation; pressurizing test; liquefied nitrogen.

1. INTRODUCTION

The structural safety margin increases the weight of aerospace vehicles, so a smaller safety factor would provide an advantage on the payload weight. In designing expendable launch vehicles, engineers thus often apply a safety factor of 1.25, although 1.5 is commonly used for commercial aircrafts. For reusable launch vehicles (RLVs), however, a larger safety factor may be essential for repeated usage. Thus, materials of excellent specific weight such as carbon fiber reinforced plastic (CFRP) are indispensable for realizing RLVs [1–4].

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The fracture process of CFRP, however, complicates the design condition as the fracture completes in several steps, such as matrix transverse cracking, drastic increment of the crack density, then the linkage of the dense cracks that leads to the final collapse. The dense cracking is detrimental to the CFRP out-of-plane strength, which imposes restrictions on the buckling margin of pressure vessels. Furthermore, the drastic increment of the crack density leads to 'leak path' formation, or crack connection through the CFRP tank wall. This implies that a CFRP tank may not need a liner, which keeps the contents from through-wall leakage, if the dense matrix cracking is prevented. In addition, the final collapse may be prevented due to the pressure release through the leak path in the same manner as the 'leak-before-fracture' of metallic pressure vessels. So the condition of dense cracking may be the rationale for the design of RLV propellant tank. Thus, matrix cracking has been a topic on which interest has been focused in CFRPs. Aoki *et al*. have studied CFRPs with different types of epoxy matrices, bismaleimide matrix and PEEK matrix at room temperature (R.T.), LN_2 temperature, and liquefied helium (LHe) temperature with regard to matrix cracking, delamination propagation, and final collapse or the static strength [5, 6]. Yokozeki *et al*. have evaluated the process of transverse crack propagation on a CFRP, IM600/#133 (Toho Tenax Co. Ltd.) using a coupon type specimen and tubular specimen [7–9]. In these works, the free edge was found to have a significant effect in lowering the strain level of transverse crack initiation. The experiments also revealed that maximum strain provides an acceptable insight on the matrix dense cracking of thick-ply specimens. Kumazawa *et al*. have evaluated the cracking conditions of several CFRPs at R.T., LN_2 temperature, and LHe temperature [10–12]. The fracture strength of the CFRPs at LN_2 temperature was reported in these papers to be about 20% lower than R.T. strength. The experiments and analyses on cruciform bi-axial specimens revealed that the mass flow rate through the leak path increases at LN_2 temperature condition compared to the R.T. condition.

Based on the data of these previous works [5–12], the authors have prepared and evaluated concept tanks made of IM600/#133 toughened epoxy resin containing high strength carbon fiber. Large dispersion of CFRP material parameters may be unavoidable on large-scale structures such as launch vehicle tanks. Although there are theoretical conditions on the damage onset, maximum strain may thus provide an acceptable estimation of the matrix dense cracking and the leak path formation. Thereby the maximum strain has been selected as the transverse cracking condition for the tank design. The tanks were designed so that (i) LN_2 temperature does not harm the tanks without the internal pressurization (ii) internal pressurization at R.T. does not damage them up to the maximum hoop strain of 0.65%; (iii) internal pressurization at LN_2 temperature does not damage them up to 1.1 MPa, which provides 0.45% of maximum hoop strain with linear elastic estimation, and (iv) the leak path forms due to the dense cracking at the maximum hoop strain of about 0.55% at LN_2 temperature. The authors have evaluated the tanks on conditions (i) and (ii) in previous work [13–18] showing that the tanks remained intact; thus

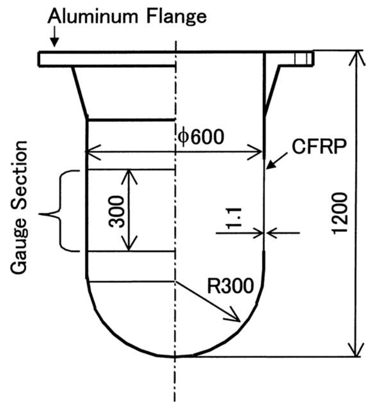


Figure 1. Configuration of CFRP tank (Unit: mm).

the design condition of maximum strain has increased the credibility for the CFRP cryogenic tank of RLV. Thereby the authors evaluate the tanks in this work on the condition (iii) to assess if 1.1 MPa of internal pressure will damage the CFRP tank wall at LN_2 temperature.

2. TANK CONFIGURATION

Two liner-less tanks were produced by Fuji Heavy Industry Co. Ltd. comprising an eight-ply UD quasi-isotropic lay-up in two different patterns, Type A $(45/0/-45/90)_S$, and Type B $(45/90/-45/0)_S$. Each tank was designed as a cylinder of 600 mm in diameter and 1200 mm in length, covered with an aluminum flange at one end and with a hemispherical CFRP dome at the other end. The gauge section was set to the central 300 mm cylinder wall of a reference thickness 1.1 mm. Figure 1 shows a schematic diagram of the tank configuration.

3. EXPERIMENTAL PROCEDURE

Each tank was installed inside of a vacuum chamber after setting acoustic emission sensors of MISTRAS AE testing system (Physical Acoustics Corp.) surrounding the gauge section and attaching strain gauges, as shown in Fig. 2. The vent pipeline was connected to a helium flow detector MSE-3000 (Shimadzu Corp.) in order to monitor the through-crack leakage.

The tanks were filled with LN_2 and pressurized internally with gaseous helium up to 0.98 MPa in steps of 0.2 MPa. Figure 3 illustrates an example of the LN_2 filling process. Note that the outside of the tank was kept in the experiment at low pressure such as 6 Pa; atmospheric air pressure was thus superimposed on the internal pressure. Thus, the maximum internal pressure, 0.98 MPa, was equivalent to 1.1 MPa.

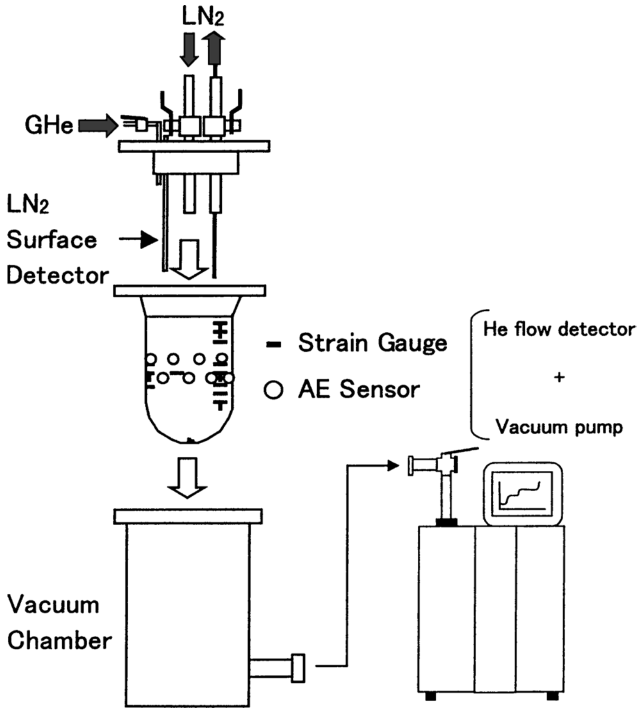


Figure 2. Schematic diagram of the test configuration.

Figure 3. A photograph of the cryogenic test.

Gaseous helium does not diffuse into LN_2, so through-crack leakage was limited to the region above the height of the LN_2 surface. Therefore, the surface was monitored during the LN_2 draining process, in order to detect the position of through-crack leakage.

4. RESULTS AND DISCUSSION

The source data of AE in the LN_2 filling process provided two kinds of information: (1) the hit rate of total signals and (2) the locations of the signals. Figure 4 shows an example of the (1) AE hit rate during the LN_2 filling process. The hit rate represents the total AE numbers per 30 seconds and the '0 second' was set to the starting period of the LN_2 filling process. The LN_2 surface reached to the level of gauge bottom AE sensors around 600 s, and the LN_2 surface reached to the gauge top AE sensors level around 1000 s. As may be seen in the figure, the AE signals were detected during the LN_2 filling process, but the hit-rate decreased to a level in some 500 s, which is long enough to stabilize the tank wall temperature to the temperature of the LN_2 contents. This implied that LN_2 evaporation emits a pattern of noise, which is equivalent to AE signal, and the noise emission rate decreases to a level as the tank wall temperature approaches the temperature of the LN_2 contents. Figure 5 shows an example of the second factor (signal locations) during the LN_2 filling process at the threshold level of 70 dB. As may be seen in the figure, the LN_2 evaporation noise uniformly covered the gauge section, so the damage onset signal was expected to be seriously disturbed on the location by the noise. However, the hit-rate of total signals (factor 1) provided an insight into the CFRP damage as the drastic increment of the hit-rate arises from CFRP dense cracking. Thus, AE measurements were applied during the pressurization tests following the LN_2 filling into the CFRP tanks.

Figure 6 illustrates an example of the strain data on the internal pressurizing up to 0.98 MPa plus initial strain due to the vacuum chamber evacuation and the thermal

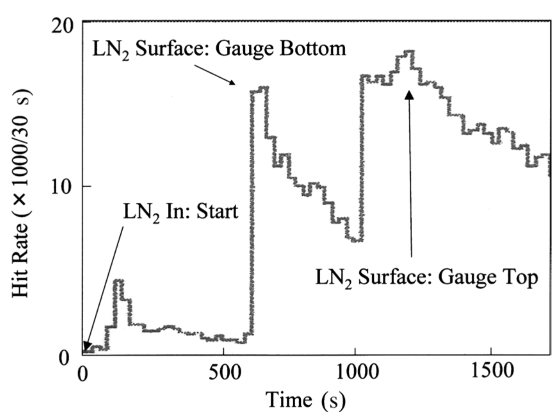


Figure 4. An example of AE hit rate in LN_2 filling process.

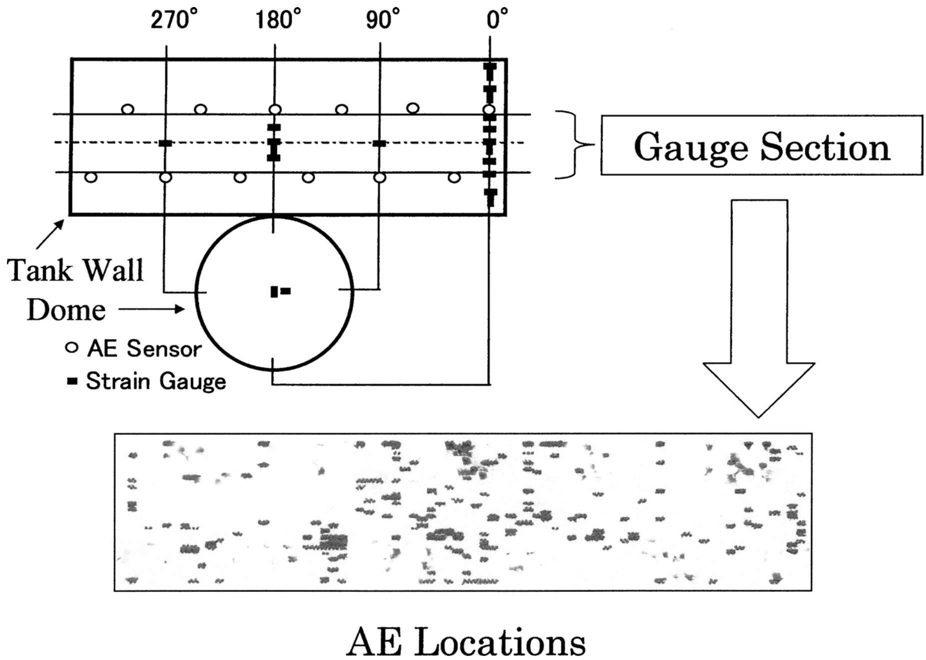


Figure 5. An example of AE locations in LN_2 filling process.

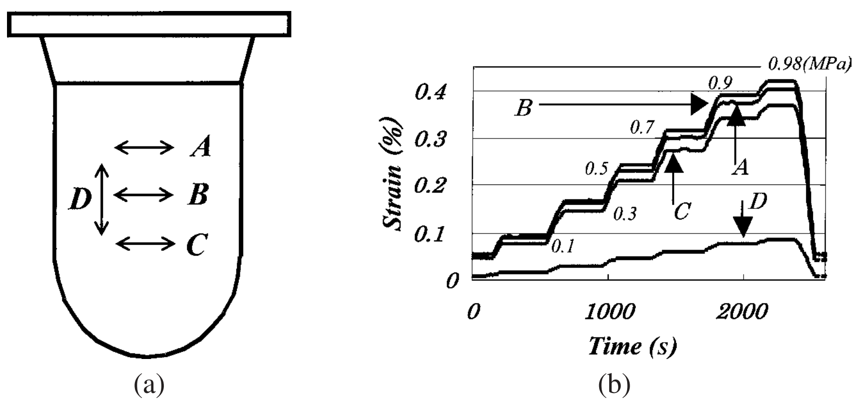
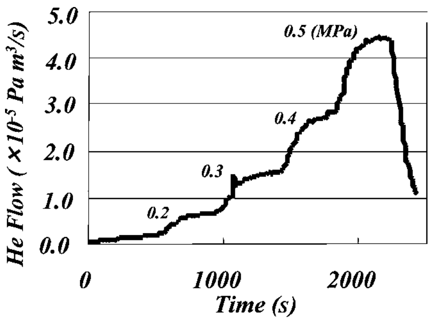
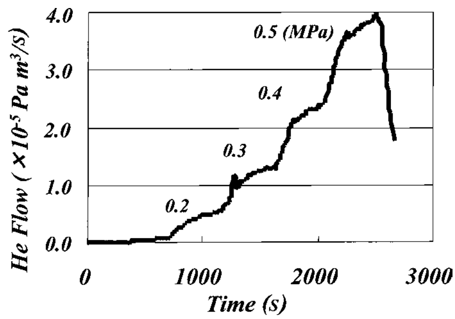


Figure 6. An example of data showing the strain in cryogenic pressurization (Type A). (a) Measurement directions. (b) Strain measurement results.

strain by the internal LN_2. The maximum hoop strain data, 0.42% of Tank A and 0.46% of Tank B at the middle of the gauge section, showed good agreement with the estimated linear elastic strain of 0.45%. The AE hit-rate remained at the evaporation noise level during the pressurization. Thus, AE signals were expected due to the LN_2 evaporation and not due to the CFRP cracking. In addition, the helium leak had remained within error level during the LN_2 draining process. Thus it was concluded that there was no leak path present on the tanks A and B. In order to



(a)



(b)

Figure 7. An example of data showing the helium permeability (Type A). (a) Before a cryogenic pressurizing test. (b) After a cryogenic pressurizing test.

confirm this fact, helium flow detection tests were conducted at R.T. before and after the cryogenic pressurizing tests. The helium flow has shown consistent patterns as is shown in Fig. 7. Therefore, tanks were confirmed intact through the test condition of LN_2 temperature and the internal pressure. Thus, the tanks A and B have passed the design condition (iii) that internal pressurization at LN_2 temperature does not damage them up to 1.1 MPa, which provides the maximum hoop strain of 0.45% with linear elastic estimation. Although there still remains the evaluation of design condition (iv), that the leak path forms due to the dense cracking at the maximum hoop strain of about 0.55% at LN_2 temperature, the CFRP IM 600/#133 with the design concept of maximum strain on the damage onset has so far increased the possibility for the realization of CFRP cryogenic propellant tanks that might be used for future launch vehicles.

5. CONCLUSION

Composite concept tanks, which were made of IM600/#133 toughened epoxy CFRP, were pressurized internally up to 1.1 MPa at LN_2 temperature and the damage was assessed with helium flow detection method, AE method, and pressure-strain monitoring.

The three methods concluded that the tanks were operational at LN_2 temperature for detecting the onset of CFRP damage. However, LN_2 evaporation noise was found detrimental to the AE method on the signal source location.

The CFRP tank design with maximum strain condition for the damage onset was shown successful in keeping the tank gauge sections intact from the leak path formation by matrix cracking.

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