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Y. Morino , T. Shimoda , T. Morimoto , T. Ishikawa & T. Aoki

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Applicability of CFRP materials to the cryogenic propellant tank for reusable launch vehicle (RLV)

Y. MORINO [1], T. SHIMODA [1], T. MORIMOTO [1], T. ISHIKAWA [2] and T. AOKI [3]

[1] *National Space Development Agency of Japan, 2-1-1 Sengen, Tsukuba, Ibaraki 305-8505, Japan*
[2] *National Aerospace Laboratory, 6-13-1 Ohsawa, Mitaka, Tokyo 181-0015, Japan*
[3] *Department of Aeronoutics and Astronautics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan*

Abstract—It is essential to utilize carbon fiber reinforced plastics (CFRP) for main structural materials of cryogenic propellant tanks in order to realize the drastic weight reduction needed for efficient reusable space transportation systems. Recently developed toughened CFRP materials, which are expected to show good cryogenic properties, are considered promising candidates for these kinds of applications. The present study investigates cryogenic properties of candidate materials and structural elements, including Y-joint structural models. 300 mm diameter filament wound tank and 600 mm diameter lay up tanks were fabricated and tested. Based on these experimental data, the feasibility of a CFRP cryogenic tank is discussed and future research tasks are proposed. This research is being conducted under the cooperation contract between NASDA and NAL.

Keywords: Composites; cryogenic tank; RLV.

1. INTRODUCTION

Drastic weight reduction of propellant tanks is needed for realization of the practical reusable space transportation vehicles because the large propellant tanks occupy a primary part of the airframe. Figure 1 shows some of the RLV concepts, which are investigated in Japan. Utilization of carbon fiber reinforced plastics (CFRP) for cryogenic propellant (liquid hydrogen and liquid oxygen) tanks would be one of the most promising enabling technologies for this purpose. So far there has been very little information or data to verify the feasibility of this technology, although some very ambitious demonstrations like DC-XA and X-33 have been carried out in USA.

We started this research three years ago aiming to assess the feasibility of the cryogenic composite tanks and to evaluate the degree of weight reduction compared with conventional aluminum tanks. Before that time we had very little

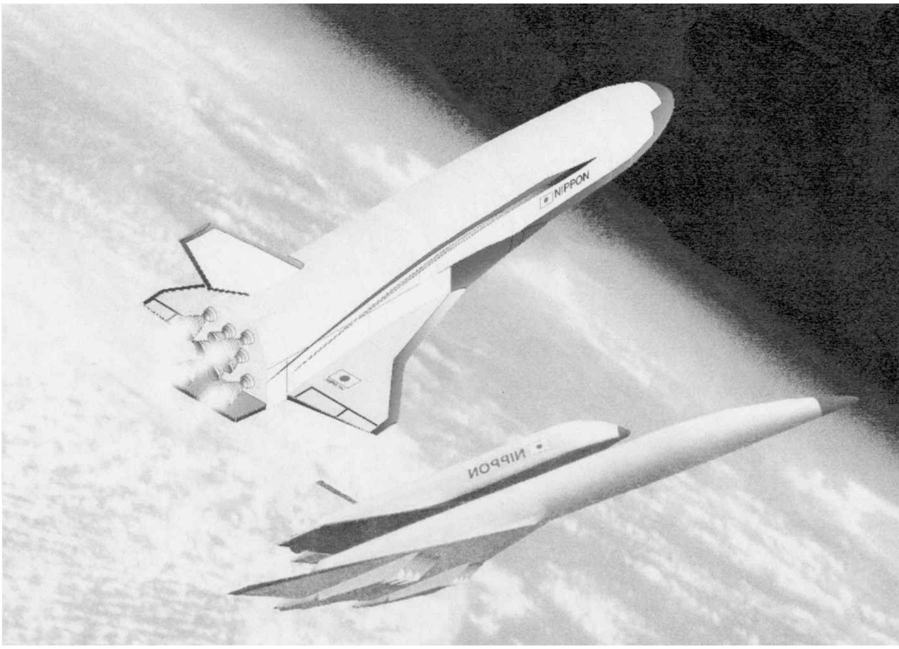


Figure 1. Typical RLV concepts studied in Japan.

material data on composite materials at cryogenic temperatures. Consequently, we started by obtaining fundamental material characteristics at various temperatures and conducted some preliminary structural element testing. Recently we initiated small tank testing to detect potential technical problems related to application to the cryogenic pressure vessels. At present we are dealing with tanks with no inner lining for structural simplicity. From the data obtained so far, we discuss applicability of the CFRP cryogenic tank and future research directions.

2. MATERIAL PROPERTIES

The expected weight reduction of popular aerospace primary structures by using composite materials would be 20% to 30% if compared with conventional aluminum materials. This ratio would be contributed by improvement of specific strength and specific stiffness together with introduction of one-piece forming technology that reduces the number of assembly interfaces. This is assuming that CFRP has the same specific strength/stiffness and heat resistance properties as typical aerospace aluminum alloys. Cryogenic environments will impose additional severe requirements concerning leak tightness and low temperature toughness.

Candidate materials include high temperature cured epoxy systems, bismaleimide systems, PEEK systems and others. Several kinds of CFRP materials were tested at temperatures from room temperatures down to liquid helium temperatures [1]. As a result of this testing, we found that the static tensile strength of the quasi-isotropic laminates decreases with temperature decrease in most cases and matrix cracks develop at relatively low stress level at the cryogenic temperatures. The latter phenomenon is important in view of propellant sustainability against leaking. The relationship between cracks and leak was observed by experiments with respect to applied loads [2]. This result seems to suggest that existence of open cracks and connection of these cracks is essential to create a serious leaking path. An analytical explanation of these phenomena is being tried in order to identify critical parameters in view of the material selection. From these material data we selected the Toho IM600/#133 for the reference material to be used in the following research because of its overall good properties and available database, particularly at cryogenic temperatures. However, systematic selection of the best material for RLV tanks should be made in future based on well-defined requirements and more comprehensive material data that also should be obtained in future.

3. STRUCTURAL ELEMENTS

There are many complex structural elements in the actual rocket tanks, such as stiffened structures, openings for propellant inlet/outlet, attachment of low/high temperature insulation systems, and junctions to the neighboring structures. Composite materials/structures that are used in these portions have complex stress distributions and relatively low production quality, therefore they are susceptible to local defects or insufficient performance. It seems very important to design the tank at sufficiently high reliability even in these complex structural portions. So, it is necessary to take into account these issues in the early R&D phase. In accordance with this consideration, the following basic structural element tests were conducted to identify important technological problems in this area.

3.1. Y-joint model testing

A rocket propellant tank usually consists of a cylindrical section and dome sections. The joining part at the cylinder/dome interface also connects to the neighboring structure and therefore is called a ‘Y-joint’ after its cross-sectional shape. Complex loads including internal pressure, external forces and thermal gradients are imposed on this part. In addition, the quality of the complex layered portion can be worse than that of the simple structural portion. In this respect, Y-joint structural models were fabricated and tested in order to identify potential technical problems concerning design and production for these kinds of structural elements.

The assumed tank geometry is a cylinder of 8 m diameter with elliptical domes of 2 m height (minor radius ratio 0.5). Cross-sectional geometry of fabricated specimen is shown in Fig. 2. Here, thickness of the tank around the Y-joint is assumed as 6 mm. The width of the specimen is 50 mm (straight). The material is IM600/#133 from Toho-rayon (180°C cured toughened epoxy system). The narrow space between the two branches is filled with 90°C layered materials. Three kinds of

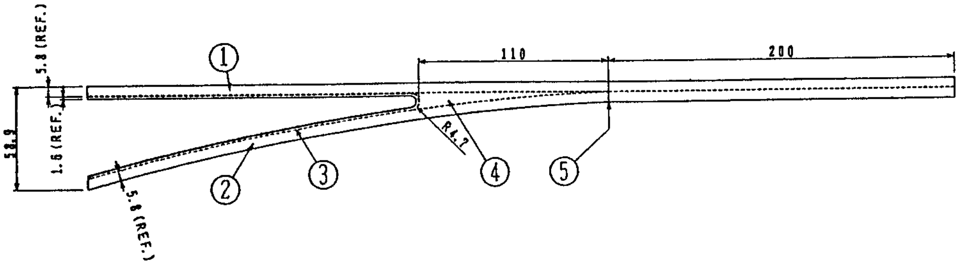


Figure 2. Geometry of the Y-joint.

Figure 3. Deformation of the Y-joint.

specimens were made: Type A, quasi-isotropic lay-up with unidirectional prepreg, Type B, same as Type A except for 1 mm over-plying inside surface of the branch portion, Type C, quasi-isotropic lay-up with cloth prepreg, 1 mm over-plying.

Finite element analysis (FEM) was conducted to calculate stress distribution around the Y-joint of the full-scale tank. Elastic properties of the material are assumed to be orthotropic in the in-plane direction and uniform along the thickness direction. Internal pressure of 300 MPa was assumed as a reference load. Calculated deformation around the Y-joint is shown in Fig. 3 where the displacements are not scaled. One can see that the lower branch of the Y-joint is pulled down by the dome caused by mismatch of deformation between the dome and cylinder. As a result of this deformation, tear-like loads are imposed on the Y-joint portion. Maximum shear stress in the Y-joint is 65 MPa at the filled area between the Y branches.

Referring to this calculation, tearing loads were imposed on the Y-joint model specimens. Tests were conducted at room temperatures and near liquid nitrogen temperatures. In the latter case, specimens were covered with insulation materials and cooled with liquid nitrogen before imposing loads. The measured fracture loads (tearing force) were shown in Fig. 4. Specimens without over-ply were fractured at the interface plane between the straight portion and filled portion. Specimens with over-ply were initially fractured at considerably lower loads by the separation of over-ply (shown by black columns) and then fractured in the same mode as the specimen without over-ply. The fracture loads at the straight interface plane were between 300 N and 400 N. No significant differences were observed for different test temperatures and materials.

For the purpose of fracture stress comparison with the full-scale model analysis, FEM analysis of the Y-joint model specimens was conducted corresponding to the test conditions. For the Type A specimen, the calculated maximum shear stress

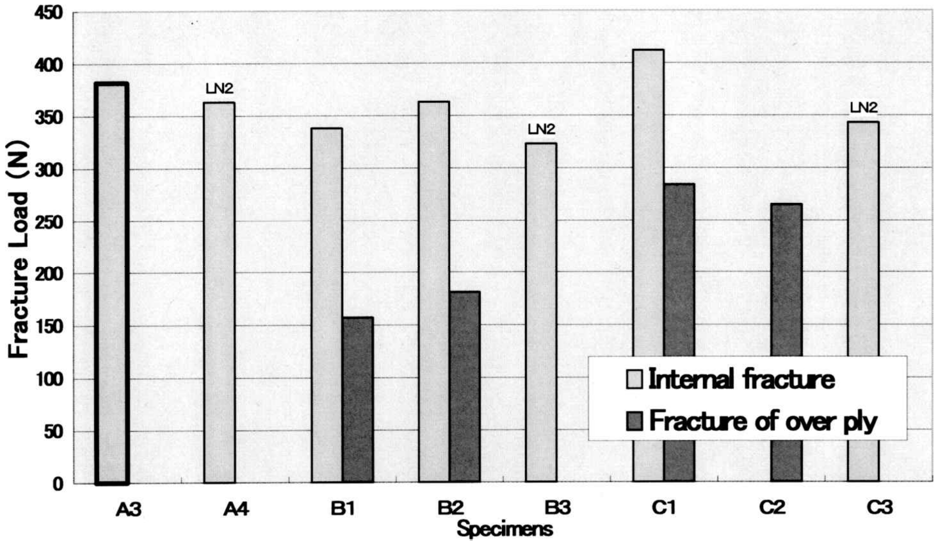


Figure 4. Fracture loads of the Y-joints.

at the fracture was 77 MPa and calculated location of the fracture agreed with the experimental observation (interface between the straight branch and filled portion). This value is a little higher than the previously mentioned stress for the supposed propellant tank. However, considering accuracy of the analysis, variation of material quality and necessary margin for design flexibility, etc. it seems that the design arrangements supposed in this study was inappropriate for the assumed internal pressure. Accordingly, improvement of Y-joint geometry or application of stronger weaving methods has to be considered in order to establish a feasible tank design.

3.2. Cryogenic insulation materials

Cryogenic insulation is needed inside or outside of the tank wall in order to prevent excessive boiling off of the cryogenic propellant. The thermal contraction of the insulation material is generally much larger than CFRP substrates and therefore large thermal strain is induced at the adhesive plane of the insulation layer. In addition, large strain induced by the internal pressure is repeatedly imposed on the tank wall during the duty cycle of the RLV. In this respect, low temperature characteristics of insulation materials and CFRP/insulation adhesion are very important for evaluation of insulation systems. As a preliminary evaluation of the insulation materials, several typical plastic foam materials have been tested at low temperatures. Figure 5 shows fracture strains of two typical insulation materials at from room temperature to -150°C. Airex foam shows better elongation properties than Rohacell foam, particularly at low temperatures. From this result, it seems unwise to use the latter as cryogenic RLV rocket tank insulation, although additional cryogenic tests are needed to finalize the conclusion.

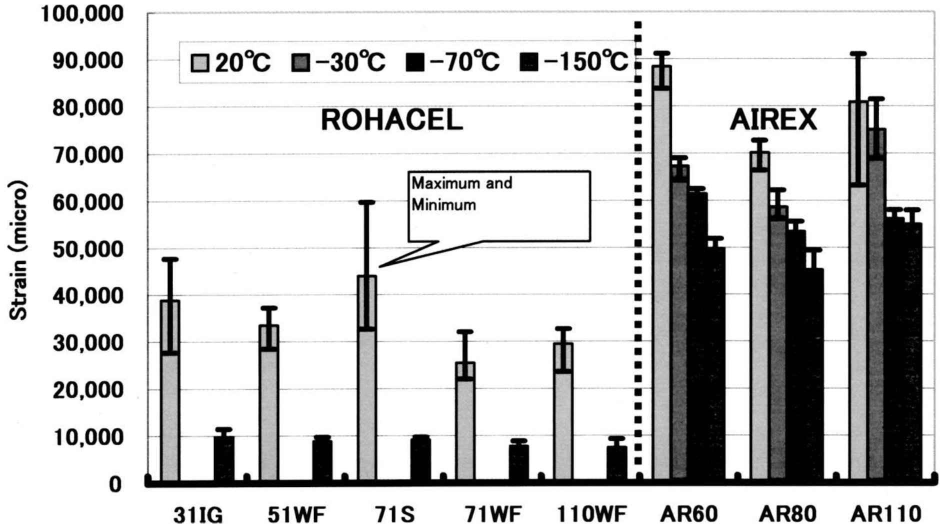


Figure 5. Fracture strains of the various insulation materials.

4. SMALL TANK TESTING

4.1. Filament winding method

The filament winding (FW) method is a very efficient method for producing pressure vessels that require low weight and cost. The application of this method to cryogenic propellant tanks is very attractive in spite of possible difficulties in quality control due to tape alignment and cross-plying. Usually this method is used together with liners inside. However we first try no lining tank in order to seek drastic weight/cost performance and structural simplicity. In order to examine the feasibility of FW methods, a small FW tank of 30 cm in diameter was fabricated by use of 1 cm width prepreg tape (IM600/#133) the same as in the lay-up tank. The cylinder section is 30 cm long and layer construction is (90°, ±30°, 90°)s, resulting in a thickness of about 1.1 mm. The domes are spherical shape and helical wound with 4 plies. An aluminum boss flange is attached to the center of the dome. This boss is a part of the mandrel. The bulk of the mandrel is made of plasters in order to put out the FW tank after winding and thermosetting.

An adhesive film liner (FM300) was added inside the tank in order to prevent leaking which was observed after the fabrication. The cause of the leak was supposed due to vapor coming out from the mandrel degrading the quality of the materials and producing the defects such as voids that would become leak passes. The film liner prevented the leaking at room temperature. Then the tank was filled with liquid nitrogen under no internal pressure as, shown in Fig. 6. After this cryogenic testing, leaks were detected in most parts of the tank. This means that a lining of FM300 was not effective for sealing at liquid nitrogen temperature. The tank was cut into pieces to inspect cross-sectional microstructures. The microscopic picture of a defective portion is shown in Fig. 7. These defective portions were

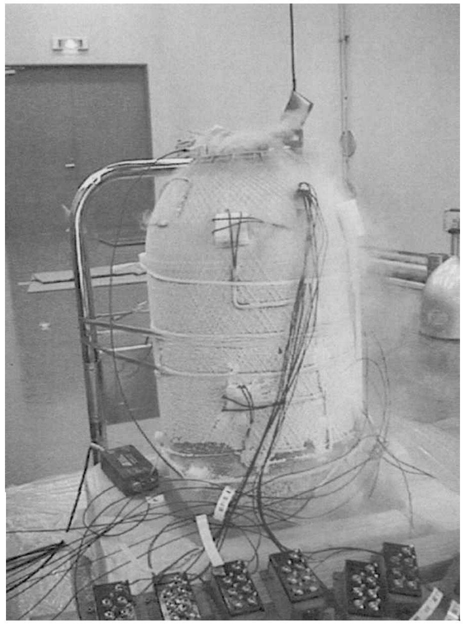
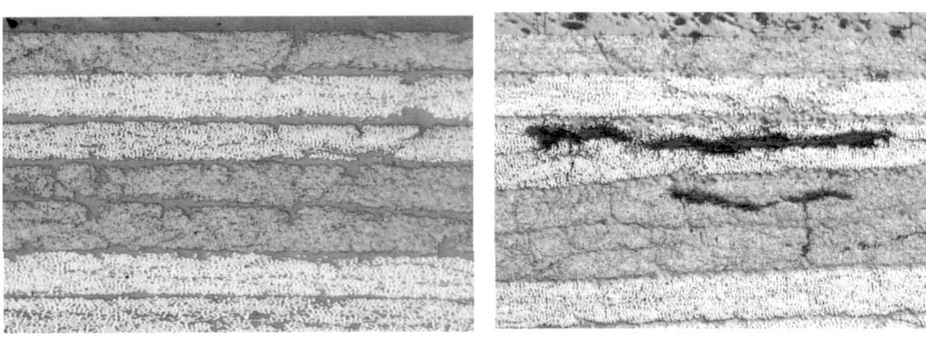


Figure 6. Cryogenic testing of the small FW tank.



(sound portion) (defective portion)

Figure 7. Cross-section of the FW materials.

located at the portion where the leaks were observed. We suppose that, through these voids or defects, internal gas leaked outside when the internal lining layer was destroyed by the internal thermal stresses. Based on these results, improvements of fabrication were made and the fabrication of the second phase tank is being conducted.

4.2. Lay up methods

As shown in Refs [1, 2], we found that micro-cracks are formed in typical candidate CFRP materials at very low stress level at cryogenic temperatures. However, it is not clear if this phenomenon occurs similarly in actual pressure vessels and if this is

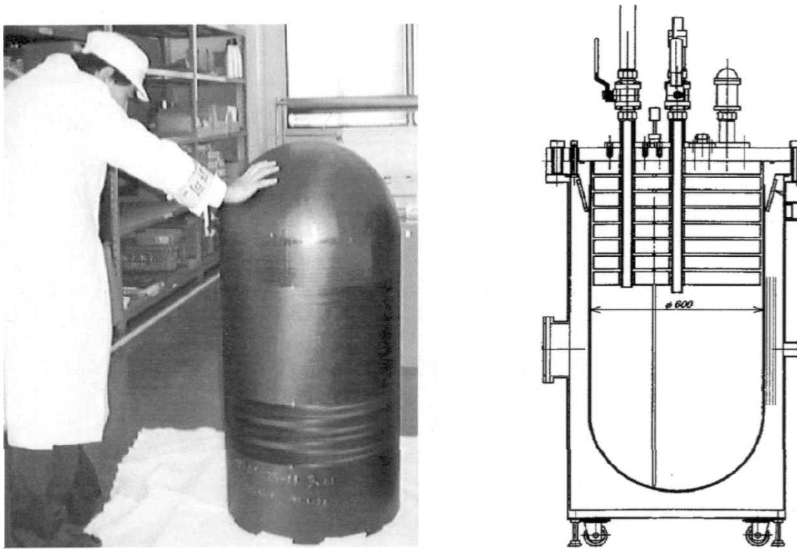


Figure 8. 60 cm lay-up and cryogenic test configuration.

critical in the sense of leakage or strength. To solve this problem, we are preparing cryogenic pressurization tests of small CFRP tanks made of a typical toughened epoxy system (IM600/#133). Specimen and testing apparatus are shown in Fig. 8. The tank is composed of a 60 cm diameter cylinder and spherical dome of same diameter. Total length is about 1.2 m and an aluminum flange is bonded to the top of the CFRP tank. A part of the cylinder (0.3 m length) has minimum thickness of about 1.1 mm and this part is used for crack evaluation. Three specimens were made. They are different in lay-up configuration of the crack evaluation part. The dome portion is made of cloth prepreg and the part of the tank in in-plane directions is quasi-isotropic.

The specimen with the upper flange is installed in a vacuum chamber, which has a top disk to close the tank and chamber at the same time. The top disk has various piping systems for loading of cryogenic liquid, pressurization and measurements. The flange of the specimen is kept at room temperature by electric heaters to avoid unexpected failure of bonding at the cryogenic temperatures. The planned maximum internal pressure is 1.5 MPa at the liquid nitrogen temperature. The maximum hoop stress expected in the crack evaluation portion is about 40 MPa. A helium detector connected to the vacuum chamber will monitor leaking. Damages of the specimen including micro-crack formation will be confirmed by destructive inspection after the cryogenic tests.

5. CONCLUSIONS

In this paper, we have described an overview of the RLV cryogenic tank research, most of which has been conducted under cooperation between NASDA and NAL.

The research is still in the phase of the preliminary material characterization and much more material and structural element testing is needed in future before proceeding to the next intensive research phase, such as sub-scale tank testing or flight testing. We believe that such a step-by-step approach will finally reach the realization of practical Reusable Launch Vehicles.

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