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Influence of stacking sequence on leakage characteristics through CFRP composite laminates

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Abstract

In this paper, gas leakage characteristics of damaged carbon fiber reinforced plastic (CFRP) laminates for three stacking sequences were obtained experimentally with the use of in-plane biaxial tests. Permeability through the laminates was measured under biaxial loadings, and the damages induced by mechanical loads were identified with using ultra-sonic C-scan to acquire relationships between damage and permeability. The results of the experiments imply that onset of leakage due to development of damage is dependent on stacking sequences, and permeability under tensile loadings is an increasing function of biaxial loads. From these findings, leakage characteristics would be dominated by crack density, leak path complexity which depends on stacking sequences, and crack opening displacements which attribute to thermal and mechanical loadings.

Keywords: A. Carbon fibers; A. Polymer–matrix composites (PMCs); B. Matrix cracking; C. Laminates; B. Gas permeability

1. Introduction

Lightweight characteristics in vehicle operations are highly desirable for cost and emission reductions. Carbon fiber reinforced plastic (CFRP) composite fuel tanks have an advantage over metallic ones in weight as well as cost. It is well known that CFRP high pressure fuel tanks installed in compressed natural gas (CNG) buses have already been in operation. Recently, application of CFRP cryogenic propellant tanks to reusable launch vehicles (RLV) is considered to be one of the effective methods to increase payload and decrease cost as the results of weight reduction of the vehicle structures. In case of the composite cryogenic propellant storage tanks of the RLV, the defects induced by manufacturing process and by operational cryogenic temperature lead to fuel leakage and may become a cause of structural fracture such as the X-33 liquid hydrogen tank failure through the accumulation of hydrogen gas in the honeycomb cores [1]. Metal or polymer liners have been considered for preventing leakage through the defects in CFRP composite tanks. However these liners for the liquid hydrogen or oxygen tanks do not only decrease the efficiency of weight reduction, but also cause problems due to difference of thermal contraction between the liner materials and the CFRP composites under cryogenic conditions. Therefore the feasibility of the CFRP propellant tanks without liners has been examined. Several studies [2,3] have shown that severe thermal strain at cryogenic temperature of liquid hydrogen might induce matrix cracks at relatively low mechanical loads. Even though the CFRP laminates are not mechanically loaded, thermal cycle between room temperature and cryogenic temperature induce matrix cracks in carbon fiber/toughened epoxy resin composites [4]. The continuous chain of connected matrix cracks in the CFRP laminates would cause the gas leakage [5], and the leak rate through damaged laminates is significantly higher than the diffusion rate through undamaged laminates [6,7]. The leakage through composite

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laminates under mechanical loads and cryogenic condition was experimentally investigated [8,9], and permeability through the damaged laminate changes with not only temperature variation but also with applied loads. Leakage analysis scheme was also developed in consideration of the relationships between damage and gas permeation, and good agreement with experimental data were shown [10–13].

In this study, leakage properties of damaged CFRP cross-ply and quasi-isotropic laminates under biaxial loads were investigated at room temperature. Cruciform specimens were prepared to evaluate the leakage properties of the laminates under in-plane biaxial loadings. Development of matrix cracks in the CFRP laminate was evaluated through the use of ultrasonic C-scan. The laminates were fabricated with three different stacking sequences to clarify the effects of stacking sequences on damages. Leak experiments were conducted with the cruciform specimens following the development of cracks at room temperature, and permeability of helium gas through the laminates was measured in relation to applied loads and their biaxial load ratios.

2. Measurement of leakage properties

2.1. Biaxial test setup and cruciform specimen

The leak measurement system for the composite laminates had been developed to measure permeability through a cruciform specimen under biaxial loadings. The system consisted of the cruciform type biaxial testing machine, leak measurement cell and a helium leak detector [13].

The biaxial testing machine consisted of four hydraulic actuators of 250 kN (tension/compression) capacity arranged horizontally as shown in Fig. 1. These four actuator assemblies made two pairs, and were rigidly mounted diagonally in an octagonal box-shaped frame. Each loading axis was named x- and y-axis, which coincided with 0° and 90° directions of the laminate, respectively.

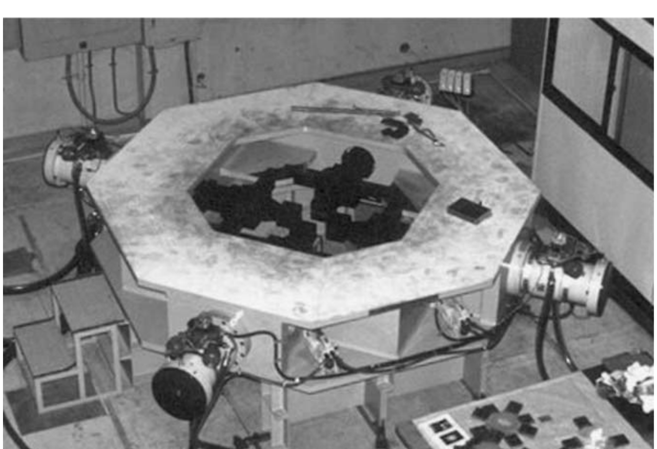

Fig. 1. Biaxial testing machine.

The material system used in this study was PAN-based intermediate-modulus carbon fiber/180 °C cured epoxy, Besfight IM600/#101 ($T_g = 252$ °C) made by Toho Tenax Corp. Stacking sequences of specimens were $(0/0/90/90)_S$, $(0/90/0/90)_S$ and $(45/0/-45/90)_S$. Glass fiber reinforced plastic (GFRP) tabs were bonded on the laminate and the geometry of the biaxial cruciform specimens is shown in Fig. 2. Two specimens per each stacking sequence were prepared. $(0/0/90/90)_S$, $(0/90/0/90)_S$ and $(45/0/-45/90)_S$ specimens were labeled as specimen An, Bn and Cn ($n = 1, 2$), respectively. Thickness of the laminates was 1.2 mm, and gauge area for leak measurement was 45 mm × 45 mm on the center of the biaxial specimen as shown in Fig. 3. The relationships between biaxial loads and strains in the gauge area were experimentally measured with strain gauges before damage development. In this experiment, the strain gauges were detached from the cruciform specimen after the strain measurements so that they would not have obscured the leakage measurement.

Prior to leak experiments, the laminate specimens were subjected to several cyclic loadings to induce matrix cracks. The cracks in the laminates were measured using ultrasonic technique, and C-scan images were obtained using 25-MHz transducer and glass reflector plates.

2.2. Leak test of damaged laminates under biaxial loadings

The permeability through the damaged CFRP laminate under biaxial loadings was measured with two stainless steel cups padded on the laminate as shown in Fig. 4. These cups for gas supply and its detection were fixed on the center portion of the cruciform specimen with outer frames. Helium gas was fed to the laminate surface from a feed port of the gas supply cup and released from an exhaust port to the atmosphere. Helium gas flowed through the gas supply cup at very low rate to keep atmospheric pressure inside the

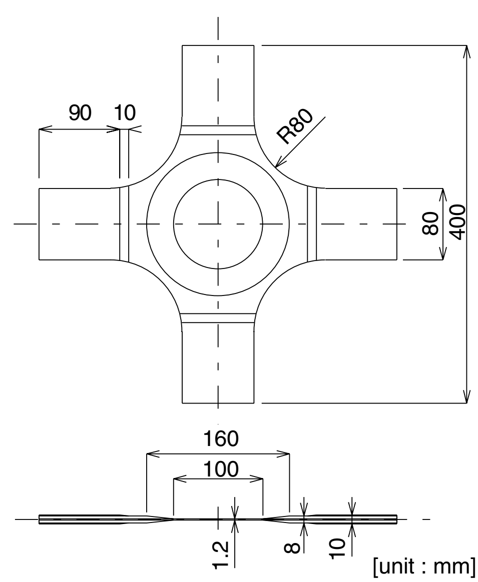

Fig. 2. Configuration of cruciform specimen.