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Effect of autofrettage on durability of CFRP composite cylinders subjected to out-of-plane loading

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ABSTRACT

The objective of this study is to evaluate effects of autofrettage on durability of composite cylinders subjected to impact loading. Impact tests and damage observation were performed on the composite cylinders with and without autofrettage. Internal pressure tests were also conducted on the cylinders after impact tests. Simulated cycle tests were conducted on the rectangular plate specimens simulated as composite cylinders after impact tests. For the composite cylinder with autofrettage, absorbed energy became smaller, which was due to suppression of the damages, such as delamination. As a result, residual strength became larger and fatigue life became longer. It was clarified that CFRP composite cylinders with proper autofrettage were superior in the impact resistance.

1. Introduction

Generally, fiber reinforced plastic (FRP) composite cylinders with metallic liners are subjected to the autofrettage to reduce average stress induced in a liner during operations. Autofrettage is a pressure application procedure, used in manufacturing composite cylinders with metallic liners. An applied pressure strains the liner past its yield point sufficiently to cause permanent plastic deformation which results in the liner having residual compressive stress and the FRP having residual tensile stresses at zero internal pressure. This compressive stress in the liner reduced average stress in working condition, which results in larger fatigue life. In order to estimate residual stress distribution and residual properties of composite cylinders after autofrettage, analytical investigations have been conducted. Su and Bhuyan conducted stress analysis on steel-lined hoop-wrapped cylinders including semi-elliptical cracks using 3-dimensional finite element method [1]. They also conducted the analysis on aluminum-lined composite cylinders [2]. Hu and Chandrashekhara developed a model using fracture mechanics and global–local finite element technique considering autofrettage [3]. These are analytical works and investigations based on the real experiments have been limited.

On the other hand, FRP lamination structures, such as FRP composite cylinders have problems, which include lower damage tolerance for out-of-plane loading. In such FRPs, glass fiber reinforced plastics (GFRP) has relatively higher impact resistance. Therefore, they have been used for composite cylinders. Alderson and Evans [4] conducted impact and static indentation tests on filament-wounded (FW) GFRP composite pipes in two support conditions. Gning et al. [5] also reported the response of thick GFRP composite cylinders to static and impact load. Doyum and Altay [6] conducted low-speed impact tests on S-glass and E-glass FRP tubes. Curtis et al. [7] conducted similar lateral indentation in quasi-static and low speed impact tests on GFRP tubes and also conducted internal pressure tests to determine their residual burst strength.

Recently, carbon fiber reinforced plastics (CFRP) composite cylinders have also been used to reduce the weight of cylinders. As the investigations about CFRP tubes, Will et al. [8] investigate the effect of laminate stacking sequence of CFRP filament wound tubes on the ability to dissipate kinetic projectile energy. Zuraida et al. [9] conducted quasi-static indentation tests on hybrid and non-hybrid glass and carbon/epoxy composite tubes. In order to improve impact resistance, Wakayama et al. [10] proposed the hybridization method with low modulus carbon fiber. Kobayashi et al. [11] proposed elasto-plastic multi-layer analysis to predict residual burst strength for post-impact hybrid composite vessels.

Many experimental studies exist. However, effect of residual tensile stress in FRP wall induced by an autofrettage on the damage initiation and progress due to out-of-plane loading has not been clarified. In the present study, in order to clarify effects of autofrettage on the damage progress in CFRP composite cylinders due to out-of-plane impact loading, impact tests were conducted on fully-wrapped CFRP composite cylinders with and without autofrettage. Surface and cross-sectional observation were

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Table 1
Angle and thickness of materials.

		Inner	←	→	Outer
Material and angle	A6061-T6	0°	±70°	0°	±35°
Thickness (mm)	1.96	0.82	0.93	0.94	0.62

Table 2
Material properties.

	A6061-T6	T700SC-12000
Young's modulus (GPa)	68.6	230
Yield strength (GPa)	274	–
Tensile strength (MPa)	308	4900

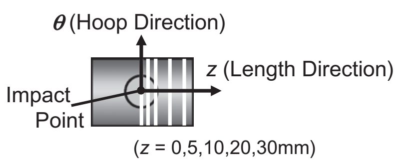

Fig. 1. Schematic view for the location of cross-sectional observation.

conducted after impact tests. From the internal pressure tests, damage progress and residual bust strength was also measured. In order to evaluate the fatigue life of the composite cylinders impacted, simulated cycle tests were conducted on the rectangular plate shape specimens including simulated impact damages.

2. Experimental procedure

2.1. Composite cylinder

In this study, CFRP composite cylinders (JFE Container Co.) were used. The cylinder was an aluminum alloy liner covered by CFRP layers fabricated with a FW method. The aluminum alloy used was A6061-T6 and the carbon fiber was T700SC-12000 (Toray Co.). The resin system used was bisphenol A type epoxy for base resin and an amine compound for cure agent. The dimension of the cylinder was 328 mm long and 110 mm of outer diameter. Thickness of a liner and the lamination of CFRP at the center of the cylinder were shown in Table 1. In Table 1, 0° means hoop direction. Mechanical properties of the material used are shown in Table 2. This composite cylinder was designed as the use of maximum fill pressure, 19.6 MPa.

2.2. Autofrettage

In order to investigate the effect of autofrettage on the damage behavior induced by impact and the fatigue properties after impact, autofrettage were conducted. In this study, the autofrettage was to keep internal pressure 37.0 MPa for 30 s. The pressurizing media was water. After the autofrettage, the pressure test keeping internal pressure 30.7 MPa for 30 s was also conducted to confirm no leakage in the cylinder.

2.3. Impact test [10]

Impact tests were conducted on the cylinders using a drop-weight type apparatus. A 7 kg impactor with the tip radii of $r = 3$ and 20 mm was dropped from the height of 450 mm, which resulted in 30 J potential energy of the impactor. A high-speed video camera was used to measure the velocity of the impactor before and after the collision, v_1 and v_2 respectively. Absorbed energies to the specimen were calculated as

$$E_A = \frac{1}{2} m (v_1^2 - v_2^2) \quad (1)$$

where m is mass of impactor. After the tests, the surface of the cylinder was observed using a digital camera. Some cylinders were sectioned and polished for sectional observations using a video microscope, which gave the information of the internal damage state. In order to observe the damage distribution, sectioning was conducted as shown in Fig. 1.

2.4. Internal pressure test

In order to measure the residual strength of the cylinder after impact, the internal pressure test was done. The internal pressure test used the water pressure by manual pump of the capacity of 100 MPa. Internal pressure was measured using a pressure gauge. In addition, to observe the damage behavior during the internal pressure test, the test was periodically terminated every 10 MPa and the surface of the specimen was observed around the impact point by fluorescent penetrant inspection.

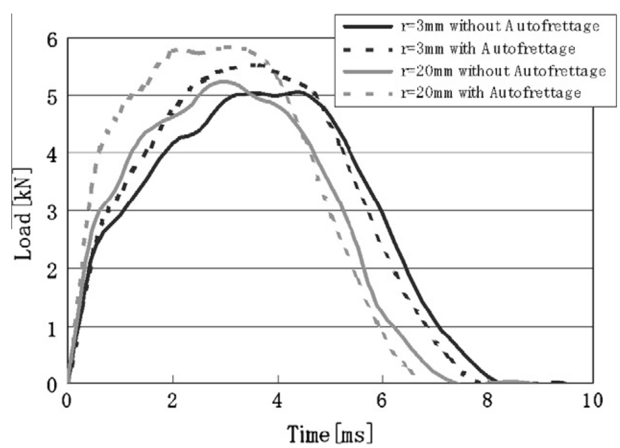

Fig. 2. Load–time curves during collision.

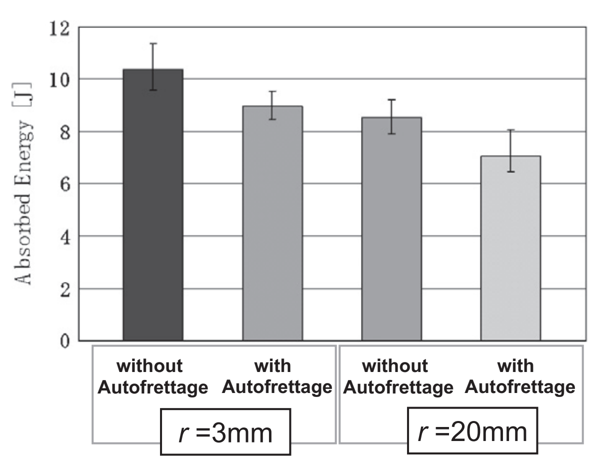

Fig. 3. Absorbed energy to the cylinder during collision.