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A simplified method for predicting burst pressure of type III filament-wound CFRP composite vessels considering the inhomogeneity of fiber packing

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ABSTRACT

The present study proposes a method to predict the burst pressures (BPs) of type III filament winding carbon fiber-reinforced plastic (CFRP) composite pressure vessels considering the inhomogeneity of carbon fiber packing through experimental work and simplified mechanical models reflecting the evolution of local damage in the CFRP layers. Vessels that had different carbon fiber volume fractions (Vfs) were prepared and tested to measure their BPs. The inhomogeneity of carbon fiber packing was evaluated using Weibull probability based on the microscopic observation of CFRP cross-sections in the virgin vessels. Detailed stress analyses of pressurized composite vessels considering the carbon Vf were conducted. Unstable fracture of the hoop layer was demonstrated by a simplified mechanical model combined with the inhomogeneity of the carbon Vf and de-bonding between the fiber and matrix. About 20% difference in the BP was measured between tested vessels with and without glass fiber-reinforced plastic layers over CFRP layers. The proposed method for predicting the BP based on the constant stress model enables consideration of the development of local fiber breaking prior to catastrophic fracture and to quantitatively estimate the change in the BP due to the difference in Vf.

1. Introduction

Type-III filament winding (FW) composite vessels are used for high pressure hydrogen containers in fuel cell vehicles because of their high strength-to-weight ratios [1–5]. The vessels are composed of a metallic liner wound with continuous fiber-reinforced plastic (FRP) materials. A high strength-to-weight ratio is also required to reduce the sizes of containers [6].

Technical standards have set basic requirements for the ratio between the marked service pressure and the minimum required burst pressure of fully wrapped carbon fiber-reinforced aluminum lined cylinders [7,8]. To increase the strength-to-weight ratio within the requirements, improvement in the quantitative prediction techniques for the burst pressure of FW composite vessels is necessary. One approach for improving the prediction method is by considering evolution processes of local failures that affect the estimation of burst pressure in carbon fiber-reinforced plastic (CFRP) such as transverse cracking, delamination between CFRP layers that have different fiber orientations, and fiber/matrix de-bonding or fiber breakage. Though the final burst occurs when unstable successive carbon fiber breakages occur, the evolution processes of local failures change the pressure at which it happens. Quantitative methods for predicting burst pressure based on the fracture mechanisms of FW CFRP layers are required for the development of composite vessels. Many multi-axis failure criteria have been proposed for the failure of FRP materials (i.e. specimen level) and simple structures composed of FRP [9–17]. Continuum damage mechanics models on the global fracture of laminated and wound FRP plates considering de-lamination, matrix cracking, fiber/matrix debonding and fiber breakage with their probabilistic behaviors were investigated to predict the failure of composite plates. Strength evaluation models for unidirectional FRPs have been proposed related to the Weibull distribution of fiber strength, fiber packing, and boundary effects [11,13]. In addition to the simple tension tests of plate specimens, tests using tubular specimens have been widely performed to investigate the effects of FW parameters on the strengths of FW FRP structures under pressure loads [18–25].

A combination of burst tests of FW composite pressure vessels and analysis of stress is a direct way to clarify the validity of prediction methods for estimating the burst pressure of FW composite pressure vessels [2,4,26–39]. The relationship between the fiber volume fraction and the failure pressure has been investigated in FW graphite-epoxy composite pressure vessels [2,4]. The effects of winding parameters

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such as winding tension, number of winds, and lay-up on the burst pressure of the composite pressure vessels have been demonstrated. The simulation method for predicting burst pressures of FW composite pressure vessels and the optimum design method have also been developed using continuum damage mechanics models of FRP materials and 3D finite element simulations [37–39].

Although the evolution of local damage in CFRP layers during the increase in pressure within FW-CFRP composite vessels is a critical factor for predicting the burst pressure during the design process of composite vessels, detailed simulations considering continuum local damage evolution in 3D finite element models are time consuming calculations. It is necessary to develop a method to predict the burst pressure with reasonable precision based on the detailed stress analysis of undamaged composite vessels and using simplified mechanical models considering local damage evolution in the CFRP layers. The present study proposes a method to predict the burst pressure of type III FW CFRP composite pressure vessels considering the inhomogeneity of carbon fiber packing through experimental work and simplified mechanical models reflecting local damage evolution in the CFRP layers.

2. Experimental procedures

2.1. Tested composite vessels

A drawing of the composite vessel tested is shown in Fig. 1. The vessel was made of aluminum liner covered with FRP layers. The liner used in the present study was AA6061-T6. The size is listed in Table 1

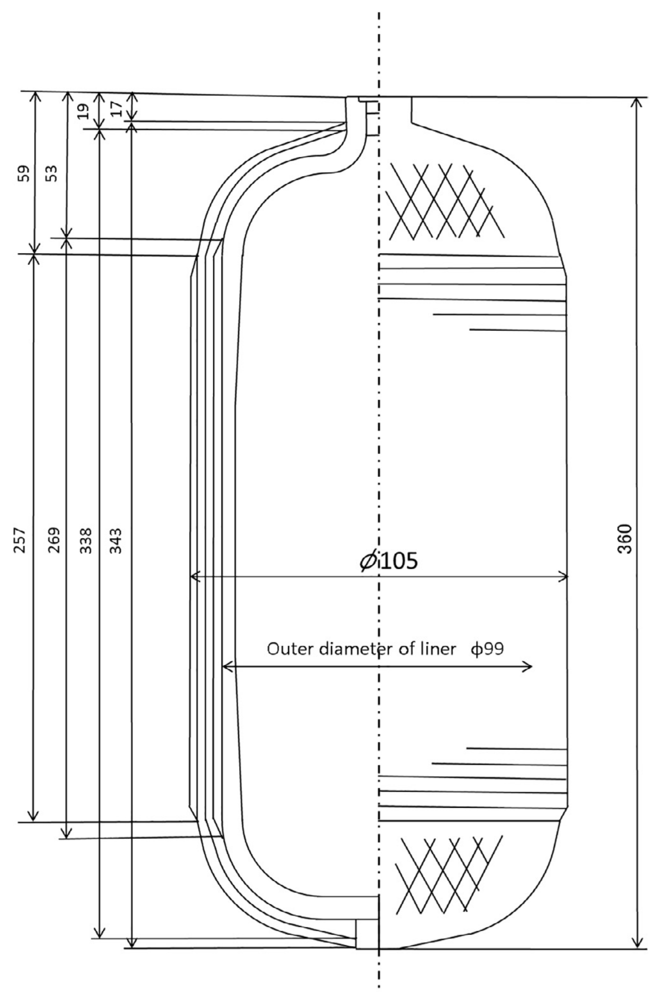

Fig. 1. Drawing of tested vessel (unit: mm).

Table 1
Configurations of Al alloy liner.

Volume [L]	OD [mm]	TL [mm]	MT [mm]
2.1	99	349	1.5

OD: Outside diameter, TL: Total length, MT: Minimum thickness.

Table 2
Mechanical properties of AA6061-T6.

E [GPa]	ν	σ_{ys} [MPa]	E_p [MPa]	σ_B
68.9	0.33	286	520	303

E: Young's modulus, ν: Poisson's ratio, σ_{ys}: Yield stress, E_p: Plastic modulus, σ_B: Tensile strength.

and the mechanical properties of AA6061-T6 are listed in Table 2. The CFRP and glass fiber-reinforced plastic (GFRP) layers in the composite vessel were manufactured using the FW method. The layer is denoted the 'hoop layer' when the fiber direction is normal to the axial direction of the vessel and the 'helical layer' when the fiber direction is not normal to the axial direction, as shown in Fig. 2. A coordinate system is also set as shown in Fig. 2 where the origin is at the center of the cylinder section and the positive z is directed toward the nozzle. The lay-up order, nominal thicknesses, and fiber angles of CFRP and GFRP layers are listed in Table 3.

The diameter and mechanical properties of a polyacrylonitrile-based carbon fiber tow (TRH50 18M, Mitsubishi Chemical Carbon Fiber and Composites, Inc.) and a type S glass fiber tow (S-2 Glass fiber 463, AGY) are listed in Table 4. The mechanical properties of epoxy resin (jER827, Mitsubishi Chemical Co., Ltd) are also listed in Table 4 [40,41]. To prepare vessels having different microstructures of CFRP layers, the FW tension (from 1 N to 42.7 N) and laminate constructions (with/without GFRP over CFRP layers) were varied. To investigate the effect of microstructure of CFRP on the burst pressure of the vessel, these sample vessels had not been autofrettaged. Two vessels for burst tests and one vessel for observation of microstructure of CFRP were manufactured at each condition.

2.2. Burst tests and observations

The burst test adhered to the standard test procedure KHK-S0121(2005) [8]. The medium to apply pressure was water and the pressure rate 1.4 MPa/s. The values of strain at the surfaces of CFRP

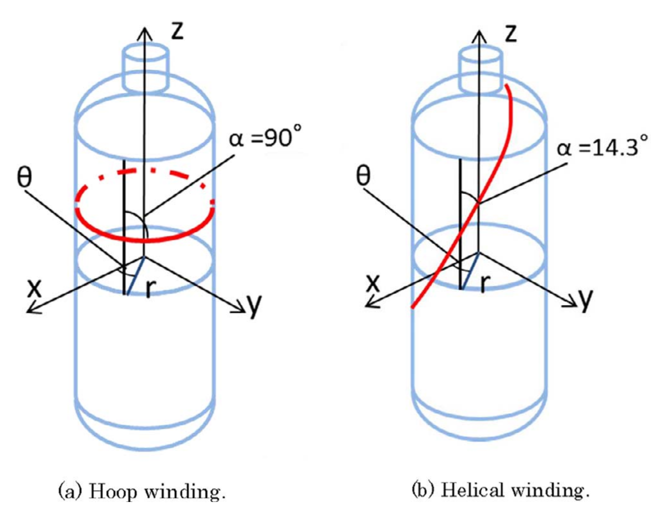

Fig. 2. Filament winding geometry and coordinate systems. (a) Hoop winding. (b) Helical winding.