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Failure analysis of carbon fiber/epoxy composite cylindrical laminates using explicit finite element method

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ABSTRACT

Based on continuum damage mechanics, the progressive failure analysis using explicit finite element method is performed to predict the failure properties and burst strengths of aluminum–carbon fiber/epoxy composite cylindrical laminate structures in terms of three composite pressure vessels with different geometry sizes. The failure analysis employs the Hashin damage initiation criterion and the fracture energy-based damage evolution law for composite layers. The numerical convergence problem is solved by introducing viscous damping effect into finite element equations for strain softening phenomenon. Effects of the calculation time and mesh sizes on the failure properties of composite laminates are explored. In addition, the predicted failure strengths of composite laminates using explicit finite element analysis are also compared with those by experiments and implicit finite element analysis.

1. Introduction

Currently, high pressure hydrogen storage vessel as a commonly recognized hydrogen storage structure has been widely used to provide hydrogen energy source in fields of the hydrogen fuel cell vehicles because they exhibit many advantages such as high strength/stiffness-to-weight ratio, excellent resistance to fatigue and corrosion as well as satisfactory durability [1,2].

Lightweight high pressure composite hydrogen storage vessel is a complex system and its design includes mainly two parts: one is the prediction of load-carrying capacity of composite vessel and the other is the weight reduction for optimized composite vessel [3]. Previous to the structure optimization which aims to achieve the minimum weight of composite vessel, an initial exploration of the damage and failure behavior of composite vessel is required for the reliable and economical design of composite laminates [4–7].

In China, carbon fiber/epoxy composites are now being used to manufacture the composite vessels with winding structure by deploying each unidirectional composite layer in angled orientations in order to achieve high stiffness and strength. Therefore, the composite vessel can be considered as the aluminum–carbon fiber/epoxy composite laminated structure. Various failure modes may be provoked under internal pressure and these failure modes continue to evolve with load conditions. Specially, an important response to the failure evolution of carbon fiber-reinforced polymer matrix composites is stiffness degradation, which poses a strong challenge to the prediction of load-bearing ability of composite laminates [8–10]. In this case, the progressive failure analysis which is developed to account for the continuous stiffness degradation and load-bearing ability of composite structure becomes necessary. Since Kachanov [11] first used the continuum damage mechanics (CDM) to study the creep rupture of metals, progressive failure analysis using CDM has been proved to be an excellent tool in acquiring the damage initiation and accumulation information of composite laminated structures [12,13]. In the CDM theory, the loss of stiffness can be physically considered a consequence of distributed microcracks and microvoids. Over the past five decades, the CDM theory has been widely used to predict the isotropic/anisotropic stiffness degradation and failure strengths of composite laminates by introducing the phenomenological damage variables associated with various damage modes such as the fiber breakage, matrix cracking and shear failure in fiber-reinforced composites [14,15]. Recently, Garnich and Akula [16], Liu and Zheng [17–19] gave comprehensive reviews on the popular methodologies which deal with the progressive failure analysis of fiber-reinforced polymer composites with respect to the failure criteria, stiffness degradation models and damage evolution laws as well as the failure strengths for composite laminates.

For composite laminates, Kam et al. [20], Chapelle and Perreux [21], Cohen et al. [22,23], Hwang et al. [24], Onder et al. [25], Zheng and Liu [26] derived the stress solutions using the classical laminate theory and proposed different solution algorithms for predicting the failure strengths of composite cylindrical laminates. However, the damage evolution properties and different failure mechanisms have not been deeply studied. Associated with the finite element analysis, Perreux et al. [27,28], Liu and Zheng

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Fig. 1. (a) 15 L composite vessel-A, (b) 74 L composite vessel-B and (c) 150 L composite vessel-C.

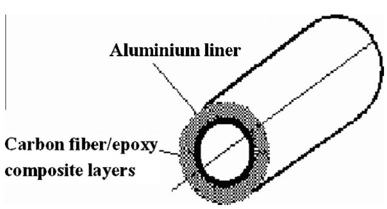

Fig. 2. Schematic diagram of winding carbon fiber/epoxy composite vessel.

[29,30], Doh and Hong [31], Tzeng [32] and Minnetyan et al. [33] used the CDM and the fracture mechanics to study the damage constitutive relationships and failure strength of composite vessels. These models proposed different damage evolution laws for different failure modes in order to explain different failure mechanisms of composites. Yet, the numerical convergence problem emerges when the finite element method is employed to predict the limit load-bearing ability of composite structures. The failure analysis was performed using implicit finite element analysis and the arc-length algorithm was used to solve the numerical convergence problem [29,30,34–38]. However, the calculation cost is relatively large since the arc-length algorithm requires more calculation resource than the Newton–Raphson algorithm for the failure analysis of complicated structures.

Alternatively, the quasi-static progressive failure analysis of aluminum–carbon fiber/epoxy composite cylindrical laminates can also be solved using explicit finite element analysis and those

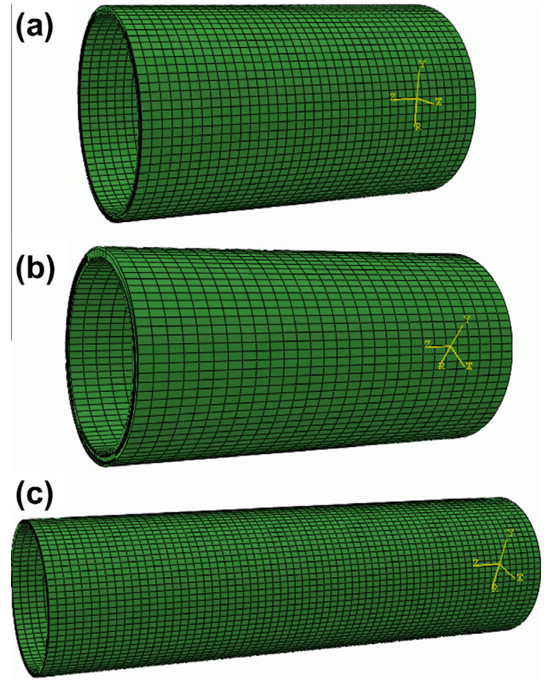

Fig. 3. Finite element models for (a) 15 L composite vessel-A, (b) 74 L composite vessel-B and (c) 150 L composite vessel-C.

snap through problems can be solved by introducing viscous damping effects into the ill-conditioned finite element equations after the stiffness properties of the failed composite elements are degradated. The Hashin damage initiation criterion and the fracture energy-based damage evolution law are employed for composite layers. The finite element code ABAQUS/EXPLICIT is used to predict the damage evolution properties and failure strengths of composite laminates. The failure strengths predicted using explicit finite element analysis are also compared with those using experiments and implicit finite element analysis. This work provides a theoretical foundation for safe and economical design as well as practical application of composite vessels in fields of the hydrogen fuel cell vehicles.

2. Finite element analysis of composite cylindrical laminates

2.1. Finite element modeling

Fig. 1 shows the hydrogen storage vessels with 15 L, 74 L and 150 L capacity applied to the hydrogen fuel cell vehicles. In the following, the finite element modeling concentrates on the cylindrical part of hydrogen storage vessel. The cylindrical part is shown in Fig. 2, which is composed of a 6061-T6 aluminum liner layer and several carbon fiber/epoxy composite layers. The aluminum liner is considered to be isotropic and elastic–plastic, and the multi-linear material hardening property is adopted to simulate the plastic deformation. The carbon fiber/epoxy composites are considered to be transversely isotropic and linear-elastic. The physical and mechanical properties of materials are listed in Table 1.

Table 1
Mechanical properties of materials.

	E_1 (GPa)	E_2 (GPa)	υ_{12}	υ_{23}	σ_s (MPa)	σ_b (MPa)	τ (MPa)	ρ (kg/m^3)
6061 Al	70	70	0.33	0.33	246	324	600	2700
T700/epoxy	154.1	10.3	0.28	0.49	–	–	–	1550

where E is elastic modulus and υ is Poisson's ratio, σ_s and σ_b are the yielding and tensile strengths respectively, τ is the hardening modulus in the bilinear plastic hardening mode, ρ is the density.