Composite Structures 130 (2015) 29–36

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Delamination failure of composite containment vessels subjected to internal blast loading

Jinyang Zheng *, Yang Hu, Li Ma, Yang Du

Institute of Process Equipment, Zhejiang University, Room 101, Teaching building 4, No. 38, Zheda Road, Hangzhou 310027, PR China

ARTICLE INFO

Article history:
Available online 22 April 2015

Keywords:
Delamination
Finite element analysis
Vibration
Dynamic behavior evolution

ABSTRACT

Delamination failure of composite vessels subjected to internal blast loading was studied in this paper. Experiments were conducted on several e-glass/epoxy vessels with aluminum lining. Micro observation and fracture analysis indicated that delamination failure occurred under a wide range of explosive loadings. A finite element model was also established to explore the delamination initiation mechanism and the evolution of dynamic behavior. Delamination simulation was achieved using a tiebreak contact model and a cohesive criterion. Numerical results from the finite element analysis were compared with experimental data, which indicated that both dynamic response and delamination failure are in good agreement. An analysis of dynamic response highlighted the amplitude and phase inconsistency between neighbor layers during the vibration process, which is considered the main cause of delamination failure. The dynamic behavior evolution of delamination under different explosive loading conditions was investigated by setting a small pre-delamination in the numerical model. Results showed that the pre-delamination ignited continuous delamination in different scales of length. With the increment of explosive charge, pre-delamination extended more rapidly with many new delamination appearing and several delamination fusing with the bigger one during the extension.

1. Introduction

Explosive containment vessels (ECVs) are widely used in national defense, science research, and manufacturing industries because they can contain shock waves and other products of internal high explosions. With the advent of fiber-reinforced composite materials, interest in composite materials used in ECVs has increased as these materials have a number of attractive material properties characterized by high strength and stiffness to mass ratios, damage tolerance, and corrosion resistance [1]. Delamination failure (separation of two adjacent composite layers) is one of the most common types of damage in composite structures. Delamination may initiate and propagate inside in a manner that remains undetected during manufacture because of incomplete curing or the introduction of a foreign particle. It may also from impact damage, interlaminar stresses, cyclic loading, and so on. Delamination redistributes the stress in composite structures and can weaken strength and stiffness, thereby reducing the life of a structure [2,3]. Thus, the analysis of delamination continues to be a focus of studies.

Delamination failure is sometimes treated as an extension of the fracture problem. In general, there are three modes of fracture: opening (Mode I), shearing (Model II), and tearing (Mode III) [4,5]. However, the anisotropy and heterogeneity of composite structure mean all three modes may be present during the initiation and propagation of delamination, making it very difficult to analyze [6]. A detailed review of the mechanics of composite delamination, including experimental observations and analysis methods, was presented by Tay [6]. Compared with the experimental observations, the numerical simulation method showed huge superiority as it can reduce the cost, save the time, and the results are more convenient to analyze. The two most common methods to simulate delamination are Virtual Crack Closure Technique (VCCT) [7–12] and cohesive interface elements. VCCT is computationally effective but does not incorporate the prediction of delamination initiation and propagation directions. The use of the cohesive zone model can overcome these difficulties. The origin of the cohesive zone model can be traced to Dugdale [13] and Barenblatt [14]. The model can be easily incorporated into a finite element code by implementing the so-called interface elements. Therefore, numerous authors [15–20] have used this method to deal with delamination problems.

In related literature, the research objects have focused mainly on laminated composite plates; very few analyses have been

* Corresponding author. Tel.: +86 571 879 52 110.
E-mail addresses: jyzh@zju.edu.cn (J. Zheng), yanghu@zju.edu.cn (Y. Hu), mali@zju.edu.cn (L. Ma), du.yang.0918@163.com (Y. Du).

http://dx.doi.org/10.1016/j.compstruct.2015.04.013
0263-8223/

dedicated to the investigation of revolving bodies, such as cylindrical composite structures or composite vessels. The loadings applied on these laminated plates are mostly from the punch or bullet impact, and very few are from explosions. In the current paper, the delamination failure of composite ECV under internal blast loading was investigated. Experiments were conducted on several e-glass/epoxy vessels with aluminum lining. Micro observation and fracture analysis indicated that delamination failure occurred under a wide range of explosive loadings. A finite element model was also established to explore the delamination initiation mechanism and the evolution of dynamic behavior. Numerical results from the finite element analysis were compared with experimental data. Several suggestions on the use of reusable composite ECVs are given based on the results of the investigation.

2. Experiment procedure

2.1. Experiment vessels

Several e-glass/epoxy composite vessels with a 6061 aluminum liner were designed as shown in Fig. 1(a). The aluminum liner which can provides a sealing surface to prevent gas leakage and supports the composite layers was constructed firstly. A through hole with an inner diameter of 30 mm was set on the head of liner to enable placement of the explosive into the vessel during the experiment. After the aluminum liner was completed, 18 composite layers which provide the primary structural resistance against the internal blast forces wound alternately in a double spiral and annular of equal thickness ($[-30/30/90]_6$) on the out surface using an epoxy wet lay-up process. In order to eliminate a gap to appear between composite and the aluminum liner because of thermal expansion, the epoxy cured at a relatively stable room temperature. The total length of the experiment vessel was 278 mm and the inside diameter was about 104 mm. The total thickness of the composite layers was about 3.21 mm. The material parameters of aluminum and e-glass/epoxy were listed respectively in Tables 1 and 2. These vessels were anchored in the vertical-up direction with a buffer substance such as rubber at the bottom during the experiments to eliminate the influence of recoil force from the ground as much as possible.

2.2. Explosive

In the current study, TNT is selected for explosive charge as shown in Fig. 1(b). A series of cylindrical TNT with different weights (i.e., 10 g, 15 g, etc.) were prepared in advance to ensure convenient adjustment during the experiments. The density of the TNT was about 1.59 g/cm^3. An auxiliary structure was designed as shown in Fig. 1(b) to ensure that the explosives were located at the center of the vessel and to eliminate the effect of explosive location on the experiment result. An interference fit between the plastic flange and aluminum pipe was placed, with the pipe clamped by the plastic flange. The pipe could still be moved through the hole of the plastic flange at the same time. The position of the explosive was adjusted by changing the stretching length of the pipe [L in Fig. 1(b)]. The value of L when the explosive was at the center was calculated using Eq. (1):

$$L = L_a + L_e/2 - L_v/2 - L_f \tag{1}$$

where L_a and L_e are the length of aluminum pipe and explosive respectively, L_v is the length of vessel which is 278 mm as shown in Fig. 1, L_f is the thickness of plastic flange edge.

Table 1
Material parameters of TNT and constants of JWL EOS [21].

Material parameters of TNT		Constants of JWL EOS	
Density, ρ, g/cm^3	1.590	A, GPa	371.213
Detonation velocity, D, cm/μs	0.693	B, GPa	3.23
Chapman-Jouget pressure, P_{CJ}, GPa	21.0	R1	4.15
Initial internal energy, e_0, MPa	7.0	R2	0.95
		ω	0.30

Table 2
Parameters of Johnson–Cook material model for 6061 aluminum alloy [22].

ρ (g/cm3) m	G (Mpa) T_m	υ D_1	A (MPa) D_2	B (MPa) D_3	n D_4	c D_5
2.7	6980	0.3	324	114	0.42	0.004
1.34	1790	0.071	1.248	−1.142	0.147	0.0

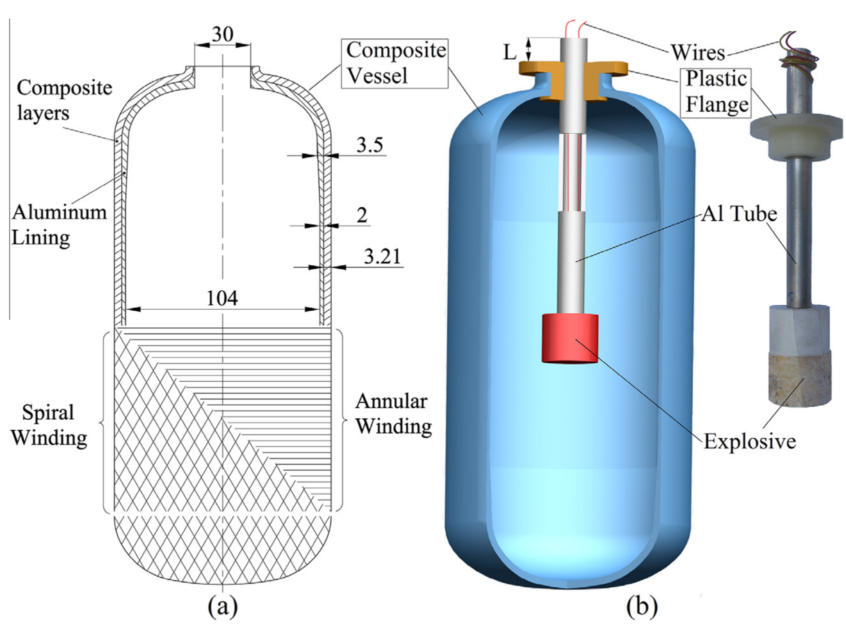

Fig. 1. Structure schematic drawing of composite ECV and the auxiliary structure to fix explosive (length unit: mm).