International Journal of Impact Engineering 102 (2017) 16–26

Contents lists available at ScienceDirect

International Journal of Impact Engineering

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

Dynamic failure of basalt/epoxy laminates under blast—Experimental observation

Xin Li[a,b], Mohd Yazid Yahya[a,*], Amin Bassiri Nia[a], Zhihua Wang[b], Jinglei Yang[c], Guoxing Lu[d]

[a] Centre for Composite, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, Johor, 81310, Malaysia
[b] Institute of Applied Mechanics and Biomedical Engineering, Taiyuan University of Technology, Taiyuan, 030024, PR China
[c] School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore, 639798, Singapore
[d] Faculty of Science, Engineering and Technology, Swinburne University of Technology, Hawthorn Vic 3122, Australia

ARTICLE INFO

Article History:
Received 16 December 2015
Revised 27 May 2016
Accepted 4 December 2016
Available online 5 December 2016

Keywords:
Basalt/epoxy laminate
Blast loading
Experimental investigation
Dynamic failure

ABSTRACT

The dynamic failures of flat and single-curved woven basalt/epoxy laminates subject to blast loading were investigated experimentally. Number of fiber layers ($(0/90)_9$, $(0/90)_{18}$ and $(0/90)_{28}$) and radii of curvature (infinity, $R = 500$ mm and $R = 250$ mm) were considered for the laminates in the experiment. A four-cable ballistic pendulum system was utilized to measure the impulse from the blast loading applied to the specimens. The tests were primarily conducted to characterize the deformation and failure modes of the laminates subject to blast loading, followed by a series of postmortem macroscopic and microscopic examinations to analyze the failure mechanism of laminates. The results showed that the blast-resistance of basalt/epoxy laminates was greatly enhanced through increasing the thickness. By decreasing the radius of curvature, the deformation mechanism of laminates under blast impact changed from flexural modes to indentation modes. Optical and scanning-electron (SEM) micrographs showed that the macroscopic delamination was mainly caused by matrix failure and debonding between fiber and matrix. Meanwhile, extensive fiber breakage led to the further macroscopic fracture of the laminates.

1. Introduction

With excellent strength and stiffness, composite materials such as glass fiber reinforced composites have been extensively used in military and civilian industries, especially in aircraft structures and marine vehicles [1–3]. With the recent increase of terrorist threats, the design of composite structures has to be reassessed to withstand extreme blast loadings. Due to the reduced ductility of fiber reinforced composites, the dynamic behaviors of the composites are much different from the traditional metallic materials. Thus, a basic problem for composite structures is the blast-resistance that needs to be deeply understood.

In the past few decades, numerous investigations were conducted to study the dynamic failure of composites under blast loadings [4–12]. For instance, Yazid et al. [4,5] investigated the blast-resistance of carbon fiber reinforced thermoset and thermoplastic laminates. Similar blast resistance between them showed that studied matrix materials do not have significant influence on the blast behavior of these laminates. Besides, Langdon et al. [7] and Lemanski et al. [8] examined the dynamic behaviors of aluminum alloy–glass fiber-reinforced polypropylene-based FMLs under localized blast loading. Two failure modes were defined as follows: Mode I: Large inelastic deformation of the back face, and Mode II: Complete tearing of the back face. By using the fluid–structure interaction (FSI) experimental apparatus, Latourte et al. [10] tested the performance of composite monolithic and sandwich panels subject to underwater impulsive loads. It was noted that the peak deflections of composite monolithic and sandwich panels have a linear relationship with the applied impulse. To produce comparable levels of damage, the applied impulse for the sandwich panel has to be much higher than that for the monolithic panel. Schiffer and Tagarielli [12] presented an experimental study on the response of circular carbon fiber/epoxy and glass fiber/vinylester composite plates. The results indicated that the blast-resistance of GRP plates is better than that of CRP plates owing to the higher tensile ductility of the GRP materials.

Besides flat panels, curved panels have been widely used as well, for example, as the fuselage of an airplane. Thus, an understanding of dynamic behaviors of the curved panels is also essential. Several researchers studied the blast response of curved structures including sandwich shells [13–15] and composite shells [16–20]. Türkmen [16,17] studied the structural response of laminated composite shells subject to blast loading and found that the maximum deflection of panel increases with the radius of curvature. Also, Kumar et al. [19,20] conducted an experiment to study the effect of plate curvature on blast response of carbon composite panels by utilizing

---

[*] Corresponding author.
E-mail address: yazid.utm@gmail.com (M.Y. Yahya).

http://dx.doi.org/10.1016/j.ijimpeng.2016.12.001
0734-743X/

a shock tube apparatus. It was found that by reducing the radius of curvature, the flexural deformation decreases while indentation deformation increases. Meanwhile, the panel with 112 mm radius of curvature has the best energy dissipation property compared with those panels with infinite and 305 mm radii of curvature.

As mentioned above, the fibers chosen in composites are either carbon or glass. However, some environmental-friendly fibers, such as basalt fiber, also have good mechanical properties [21–24] and perform well in resisting impact [25–30]. Farsani et al. [25] tested the Charpy impact behaviors of basalt fiber reinforced laminates. It was found that the basalt fiber reinforced epoxy offers better energy absorption capability than that of E-Glass fiber reinforced epoxy. Research carried out by Spagnuolo et al. [26] showed that basalt composites perform in terms of the ballistic resistance just as well as the S-2 glass system. These researches all showed that the basalt fiber based composites have significant potential in engineering applications. However, to the authors' knowledge, few blast tests have been conducted to investigate the dynamic failure of basalt/epoxy laminates.

The aim of the current study is to investigate the dynamic failure of basalt/epoxy laminates subject to blast loading. Flat laminates with different thicknesses (1.47 mm, 2.9 mm and 4.45 mm) and single-curved laminates with different radii of curvature (500 mm and 250 mm) were studied in this paper. Influences of thickness and curvature on the deformation/failure modes of laminates are discussed. The post-mortem analyses by using the optical microscope and the FE-SEM were conducted to evaluate the failure mechanisms of laminates.

2. Experimental procedure

2.1. Material and specimen

Woven basalt fiber fabrics (supplied by INCOTELOGY GmbH, Germany) with the thickness of 0.14 mm and the fiber orientation of 0/90 were used to fabricate the composite panels. The properties of basalt fibers are as follows: Density: 2.6–2.8 g/cm^3, Tensile Strength: 3200 MPa, Elastic Modulus: 90–94 GPa. The epoxy (type: 1006) was mixed with hardener to produce the matrix materials. Woven fibers were firstly laid up on the mould with the same stacking sequence. Subsequently, the vacuum infusion process was used to fabricate the samples. Through changing the numbers of fiber layer ($(0/90)_9$, $(0/90)_{18}$ and $(0/90)_{28}$), three different thicknesses (t = 1.47 mm, t = 2.9 mm and t = 4.45 mm) of flat laminates were fabricated. With single-curved moulds, laminates with 18 fiber layers and different radii of curvature (R = 250 mm and R = 500 mm) were also fabricated. A tensile test of flat $(0/90)_{18}$ woven basalt/epoxy laminate with thickness of 2.9 mm was carried out on a universal testing machine, Instron 5982. The load was applied along the fiber direction, as shown in Fig. 1. The testing method complied with the standard ASTM D3039 and the obtained tensile stress–strain curve is presented in Fig. 1. Fiber directions $(0/90)_n$ and dimensions of specimens are given in Fig. 2.

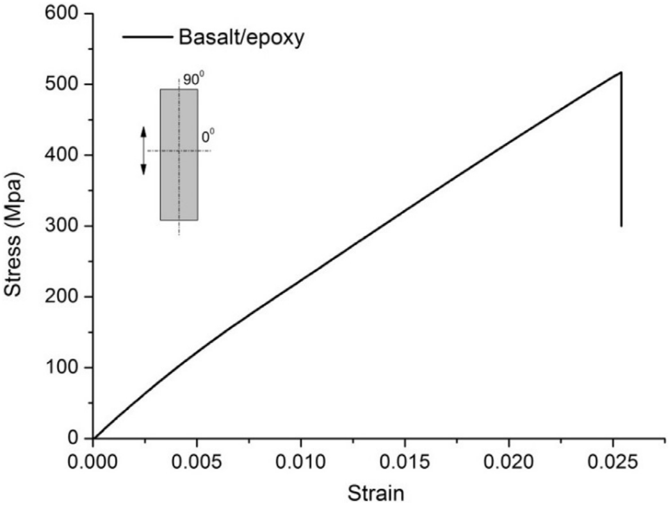

Fig. 1. The tensile stress-strain curve of woven basalt/epoxy laminates along fiber direction.

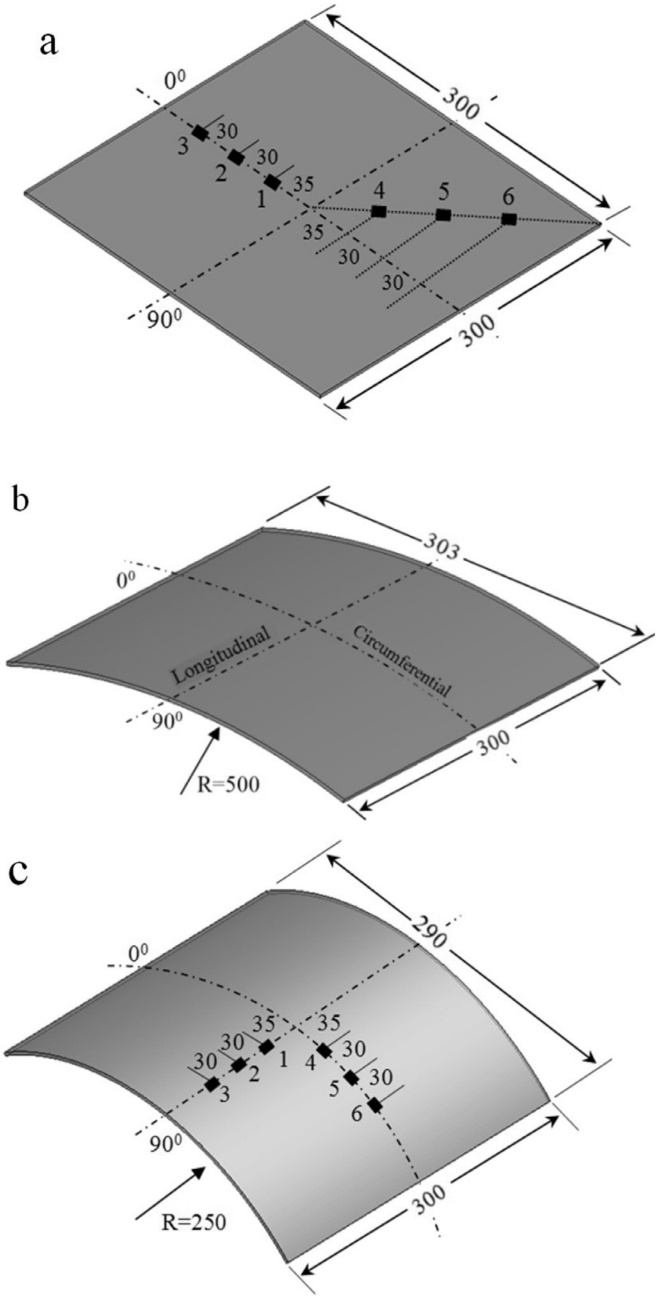

Fig. 2. Dimensions of specimens and gauge positions, (a) Flat, R = infinity, (b) R = 500 mm, (c) R = 250 mm. Unit: mm.

2.2. Experimental set-up

Fig. 3 shows the schematic set-up of the four-cable ballistic pendulum system applied in the blast impact test. The system