Aerospace Science and Technology 54 (2016) 23–40

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Thermo-mechanical numerical modeling on impact compressive damage of 3-D braided composite materials under room and low temperatures

Zhongxiang Pan, Baozhong Sun, Bohong Gu *

College of Textiles, Donghua University, Shanghai, 201620, China

ARTICLE INFO

Article history:
Received 4 February 2016
Received in revised form 30 March 2016
Accepted 31 March 2016
Available online 12 April 2016

Keywords:
3-D braided composites
Low temperature
Impact compression
Thermomechanical behavior
Finite element analysis (FEA)

ABSTRACT

This paper presents an approach to simulate the high strain-rate compression of 3-D braided basalt/epoxy composite materials under room and low temperatures. A microstructure model of 3-D braided composite was established to characterize a fully coupled thermo-mechanical response during the fast deformation. High stress state and low heat generation have been found in braided reinforcement. For out-of-plane compression, adiabatic heat concentration is along single diagonal direction at −100 °C, while a cross-shape heat concentration region is found along two crossed diagonal directions at 26 °C. There are fewer cracks among fiber tows at low temperature. Once the single diagonal shear failure occurs at low temperature, the 3-D braided reinforcement can not keep structure integrity and will be separated into two parts. For in-plane compression, the damage morphology at −100 °C is similar to that at 26 °C. Under the influence from the fiber tows, the adiabatic heating develops the zigzag-shape damage with veins and stripes along the braiding angle in composite, while the 3-D braided reinforcement still keeps its structural integrity.

1. Introduction

Three-dimensional (3-D) braided structure composites have been studied since 1970s for their prominent advantages of high impact resistance, high damage tolerance and excellent net-shape formability compared with traditional laminates [1]. 3-D braided composite materials could be used for components in liquid nitrogen tanks of launch vehicles or used for structures of satellites in the outer space, effect of low temperature should be taken into consideration in structure design. Li et al. [2] conducted quasi-static compressive experiments on 3-D braided composites at room and liquid nitrogen temperature. They found that compression properties at liquid nitrogen environment were improved significantly. Moreover, damage and failure patterns of composites varied with the loading directions and testing temperatures. At liquid nitrogen temperature, brittle failure feature became more obviously and the interfacial adhesion capacity was enhanced significantly. However, few reports focus on high strain-rate properties of 3-D braided basalt fiber composites in low-temperature field. Pan et al. [3] experimentally investigated dynamic compression of 3-D braided basalt/epoxy composite specimens at 26 °C, −50 °C, −100 °C and −140 °C under strain rates from 1300 s^{-1} to 2100 s^{-1}. They found that, for out-of-plane compression, there were two failure modes, compression-failure and shear-failure mode. In cryogenic field, fiber tows were neat and tidy with few pull-out fibers. For in-plane compression, there was only compression-failure mode.

When braided composite is under impact compression, there is temperature rise caused by adiabatic heating. The progress of adiabatic heating and damage evolution induced by high strain rate compression could not be recorded simultaneously by experimental apparatus. The numerical method may be an effective way for finding the damage mechanisms. In this paper, a microstructure model was established based on 3-D braided architecture to numerically characterize the fully coupled thermo-mechanical behavior of 3-D braided composite at 26 °C and −100 °C under 1700 s^{-1}. From the numerical simulation, the damage evolution and adiabatic heat generation during the impact compression are revealed. Because the braided composite materials have been gradually applied to aircraft design, the fully coupled thermo-mechanical characterization is important to the application. It is envisaged that present study will provide insights to utilize the 3-D braided composites in aircraft design and manufacturing.

* Corresponding author. Tel.: +86 21 67792661; fax: +86 21 67792627.
E-mail address: gubh@dhu.edu.cn (B. Gu).

http://dx.doi.org/10.1016/j.ast.2016.03.027

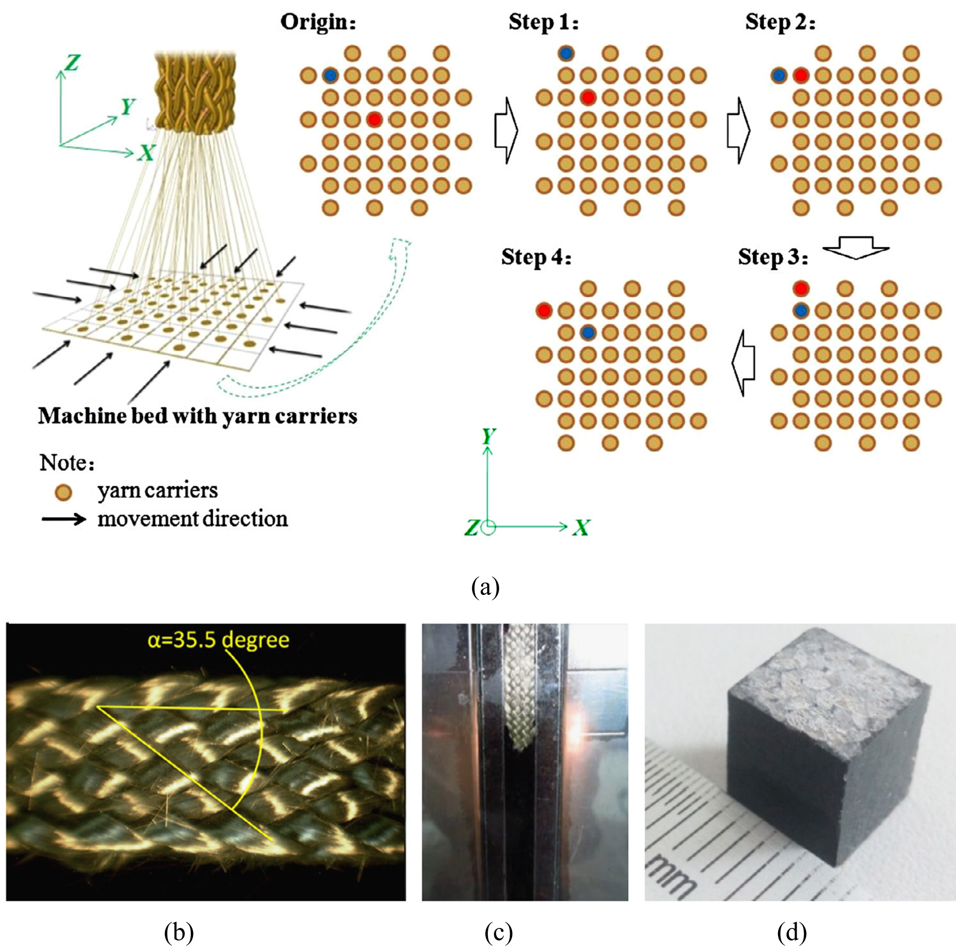

Fig. 1. (a) Schematic diagram of one cycle of the 4-step rectangular braiding process, (b) photographs of the 3-D braided preform, (c) photographs of the vacuum-assisted resin transfer molding process and (d) photographs of the composite sample.

Table 1
Specifications of basalt filament tows.

Fiber diameter (μm)	Fiber density (g/cm^3)	Tows linear density (Tex)
7	2.65	600 × 2

2. Modeling and numerical analysis

2.1. Geometrical modeling

2.1.1. Fabrication

The 4-step rectangular braiding in Fig. 1(a) was realized through the permutation of yarn carriers on a machine bed by row and column track movements in the X and Y direction, respectively, and the preform is fabricated in the Z direction. The 3D braided preform as shown in Fig. 1(b) was manufactured by the 4-step rectangular braiding process with the fiber tows' array of 6 × 6. The basalt filament tows were manufactured by Hengdian Group Shanghai Russia & Gold Basalt Fiber Co., Ltd. The specifications of basalt filament tows are illustrated in Table 1. The epoxy resin (consist of 54.5% bisphenol A and 45.5% modified anhydride, manufactured by Changshu Jiafa Co., Ltd) was injected into the basalt continuous filament braided preform by vacuum-assisted resin transfer molding process as illustrated in Fig. 1(c). The cure procedure included curing at 90 °C for 1 h, 110 °C for 3 h, 130 °C for 4 h followed by slow cooling to 23 °C over 12 h. The fiber volume of the composite was about 46%. The sample is shown in Fig. 1(d).

2.1.2. Finite element modeling

A three-dimensional microstructure model is established based on the 3-D braided reinforcement architecture. The braided reinforcement model is constructed by assembling internal unit-cells, surface unit-cells and corner unit-cells. The basic concept of unit cells of the 4-step rectangular braiding can be seen in Ref. [4]. Fig. 2(a) shows the architectures of internal, surface and corner unit-cells. First, internal unit-cell was repeatedly arranged on the XY plane to form a unit-cell assembly. Then the assembly of internal unit-cells was piled up along the Z direction. Finally the surface and corner unit-cells were used to cover the surfaces and corners of the unit-cell assembly. Finally the 3-D braided reinforcement geometrical model was built. The braided reinforcement, shown in Fig. 2(b), was meshed with 8-node brick elements. The resin matrix, in Fig. 2(c), was meshed with 4-node tetrahedron elements. All these thermally coupled elements have the freedom of displacement and temperature. The impact compression tests were conducted on a split Hopkinson pressure bar (SHPB) apparatus. The Hopkinson bars were meshed with 8-node linear brick elements. Fig. 3 shows the 3-D braided composite model during the out-of-plane and in-plane compressive loading.

2.2. Material modeling

Fiber tows contains tens of thousands of filaments with resin impregnated among them. Fig. 2(d) shows a typical orientation definition in fiber tows from transverse-isotropic material properties. Fiber tows are treated as transverse-isotropic unidirectional