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Finite element modeling of multiple transverse impact damage behaviors of 3-D braided composite beams at microstructure level

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ABSTRACT

Multiple transverse impact damage behaviors of 3-D braided composite beams with various braiding angles were investigated from finite element analyses (FEA) and tests in different impact energies. The impact behaviors were tested with a modified split Hopkinson pressure bar (SHPB) to obtain impact load-displacement curves during several stress wave periods. The impact deformations were photographed with a high-speed camera. Based on observations of the microstructure of the 3-D braided composites, a microstructure model was established for finite element calculation. In this model, the cross-section of braided yarns is regarded as hexagonal. We found that the impact peak load decreased gradually as the impact cycle continues due to the impact deformations and damages. The samples with greater braided angle have higher resistance of transverse impact fracture. The impact stress wave propagates along braided yarn path direction which leads to higher stress level at impact location in incident surface and the opposite location in backward surface. The braided composite with smaller braided angle has higher in-plane and transverse impact stiffness, while higher braided angle has higher transverse impact fracture resistance and impact stiffness.

1. Introduction

Three-dimensional (3-D) braided composite is a composite material which the preform is braided with fiber tows according to a certain spatial structure, and then impregnated into resin to form a rigid material [1,2]. It provides good structure integrity and high freedom of materials' design for near-net shape parts manufacturing.

As one of 3-D textile composite, the most prominent advantage of 3-D braided composites over 2-D laminates is the higher delamination resistance and impact damage tolerance [3]. It has become an important structural material in the field of aeronautics and astronautics, biomedicine, sports, transportation, ballistic protection and so on [3–6]. In the application of the above fields, the 3-D braided composites will inevitably be affected by accidental multiple impact loading and be at risk of experiencing structural damages and failure [7]. To guarantee the safety and reliability in service of braided composite, it is important to quantify the impact response and accumulated plastic deformation under multiple impact damage. The impact damage has been investigated from testing and numerical simulation. In testing, for example, Flanagan et al. [8] observed the damage morphology of 4-step 3-dimensional braided UHMWPE (ultra high molecular weight polyethylene) composites after ballistic perforation. Jenq et al. [9, 10] applied the quasi-static behaviors to ballistic penetration analysis of the braided composites. Turner et al. [11,12]studied the dynamic response and the damage mechanisms of three-dimensional (3D) woven carbon composites undergoing soft impact and ballistic impact. Shaker et al. [13] studied the failure mechanisms of 3-D braided Kevlar-fabric reinforced epoxy composites under low and high velocity impacts. Zhang et al. [14] presented phenomenological description of impact damage morphologies under different impact energies. Pan et al. [15] and Zhang et al. [16] tested impact compressive behaviors under high and low temperature environments. In numerical simulations, most of them are based on the unique unit-cell model of 3-D braided composite, namely corner, surface and inner unit cell [17]. Zhang et al. [18] defined the unit cell model of the 3-D braided composite and wrote a user defined material subroutine (VUMAT) and incorporated it into commercial finite element code ABAQUS/Explicit to calculate the transverse impact. Zhang et al. [19] established a finite element model based on three unit-cells to assess the penetration process of 3D braided composites under high-velocity impact. A 3D rate-dependent constitutive model is employed to determine the constituent behavior in the three unit-cells. Zhou et al. [20–22] studied the transverse impact performance, deformation and damage of 3-D circular braided composite tubes with experimental and numerical approaches. The influence of tube size, braided angle on the tube crashworthiness was analyzed from numerical simulation and experimental observations.

So far, the impact behaviors of 3-D braided composite have not been investigated from the deformation-record with high-speed cam-

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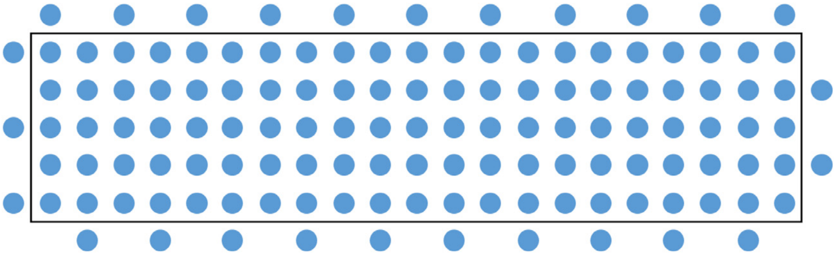
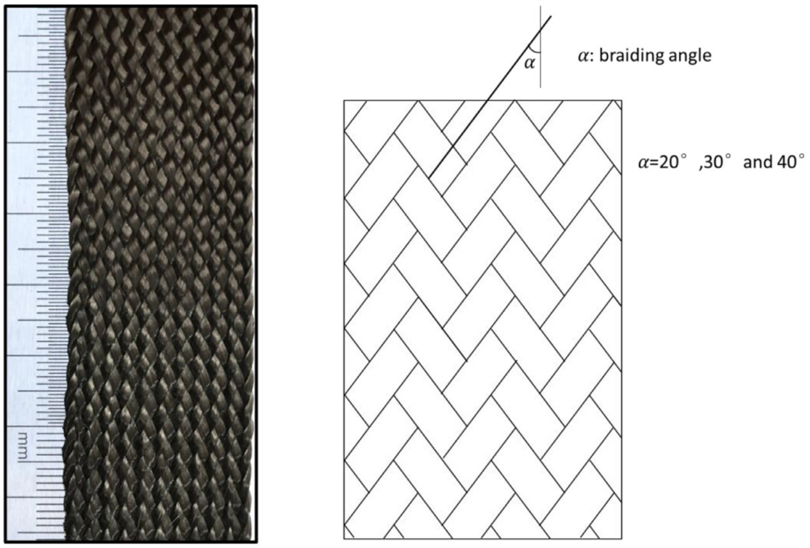
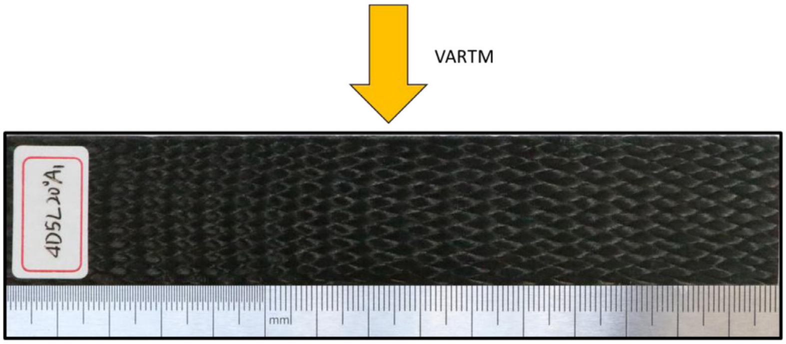


Fig. 1. Yarn array for 3-D rectangular braiding.



(a) 3-D braided preform



(b) 3-D braided composite

Fig. 2. Photograph of 3-D braided preform and composite.

era and to reveal the damage mechanisms at microstructure level in each time step. Here we will report the transverse impact damage of 3-D braided composite beam from high-speed photograph and FEA at microstructure level. A split Hopkinson pressure bar (SHPB) was employed to test the transverse impact behaviors with three impact gas pressures (corresponding to three impact energies). The impact deformation was recorded by high-speed camera. A finite element model was established at microstructure level to reveal the impact damage mechanisms. The impact load-displacement curves in several impact stress waves, deformation and damage histories were obtained in testing and compared with those in FEA. The influences of impact energy and braiding angles on impact damage will be analyzed for optimization of higher impact resistant braided composite design.

2. Experimental

2.1. Materials

The braided preforms were manufactured by four-step 1×1 braiding process with carbon fiber T700-12 K tows from Toray Inc. Japan. The braided yarn arrays were 21×5, as shown in Fig. 1. Three different braiding angles (20°, 30° and 40°) were chosen for braiding. The surface braiding angles is used to represent braiding angles, which is convenient for measurement and characterization. Fig. 2(a) shows the photograph of braided preform and braiding angle. The composite samples were prepared by epoxy resin (JA-02-type from Jiafa Chemical Inc., China) with the vacuum-assisted resin transfer molding (VARTM) technique. Fig. 2(b) shows the photograph of 3-D braided composite. The