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Damage accumulation in braided textiles-reinforced composites under repeated impacts: Experimental and numerical studies

Chen Wang[a,b,c], Zhong Chen[b,*], Vadim V. Silberschmidt[c], Anish Roy[c]

[a] *Joining Technology Group, Singapore Institute of Manufacturing Technology, 2 Fusionopolis Way, 138634, Singapore*
[b] *School of Materials Science and Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798, Singapore*
[c] *School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, Ashby Road, Loughborough LE113TU, United Kingdom*

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ABSTRACT

Composites reinforced with braided textiles exhibit high structural stability and excellent damage tolerance, making them very attractive for defence, aerospace, automotive and energy industries. Considering the real-life service environment, it is crucial to study a dynamic response of a composite structure and its energy-dissipation ability, especially under repeated low-velocity impacts. So, a series of drop-weight tests were carried out followed by X-ray computed micro-tomography to characterize damage morphology of braided composite specimens. Meanwhile, a multi-scale computational approach was explored and implemented as a user-defined-material subroutine (VUMAT) for ABAQUS/Explicit to capture main damage modes of a braided textile composite, while its delamination was modelled by employing cohesive-zone elements. Load- and energy-time curves were obtained both experimentally and numerically. The predicted levels of peak forces and absorbed energy were found to agree with the experimental data. An extent of delamination and damage accumulation in the braided composite was predicted numerically and analysed; it was found that material responses to repeated impacts had two types depending on the level of normalised impact energy. The presented modelling capability could contribute to design of braided composite structures for various applications.

1. Introduction

Composites reinforced with braided textiles are widely used in sports protective equipment, automotive components and aerospace structures thanks to their high structural stability and excellent damage tolerance [1]. For product design and optimisation purposes, dynamic behaviour of braided composite structures and their energy-dissipation ability should be well understood. As a consequence, studies of braided composites under low-velocity impact loads became important. In recent decades, numerous respective investigations have been carried out, remains the topic still challenging [1–4]. The main reason is the fact that failure associated with undulations and interlacing of the braided structure is difficult to deal with both in experimental measurements and finite-element modelling. Besides, typical damage modes caused by low-velocity impacts are barely visible in braided composites [4]. These features result in complex interactions between many stress and strain components.

In real life, structural materials are subjected to repeated impacts more often than single impact, during manufacturing, routine maintenance and daily service activities [5]. Although single impact generates only minor damage, these flaws can easily accumulate because of repeated impacts [6–8]. Thus, it is important to study such accumulating effects of repeated impacts on composite structures [9]. Comparing with many studies on the single-impact response, there are a few works concerning repeated impacts and damage accumulation [5,10,11]. Hosur et al. [5] studied the effect of stitching on a composite subjected to a certain number of repeated impacts with various impact energies. Belingardi et al. [12] developed an analytical model to describe a life time of composite materials subjected to repeated impact loadings. Atas et al. [9] presented an experimental investigation on a response to repeated impacts of woven E-glass/ epoxy composites with various thicknesses. Such studies about the behaviour of textile-reinforced composites after repeated impacts mainly focused on experiments. Additionally, there is a strong need to develop a FE approach capable of predicting dynamic behaviour of braided composites, considering different damage mechanisms, since experiments can be time-consuming and expensive. Although a few studies employed numerical simulations to establish the analytical model for glass/epoxy and fibre-metal laminates (FMLs), the shear-stress influence of the neighbouring layers on the interface delamination was not considered [2,3,10,13]. To

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* Corresponding author.
E-mail address: ASZChen@ntu.edu.sg (Z. Chen).

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the authors' knowledge, no FE model has been developed for braided composites to study their response to repeated impacts so far [14].

This work aims at investigating a response of a braided composite to multiple low-velocity impacts both experimentally and through FE simulations. A multi-scale computational approach was explored and implemented as a user-defined-material subroutine (VUMAT) for ABAQUS/Explicit to capture the main damage modes of braided textile composite. The results obtained with the developed computational model were compared to original experimental data for drop-weight tests. The resulting damage accumulation in braided composites is discussed. The presented modelling capability could contribute to design of braided composite structures for various applications.

2. Experimental procedure

A braided preform of the studied composite contained carbon-fibre tows (AKSAca A-42-12 k); a matrix material was Bakelite® EPR-L20 epoxy resin mixed with EPH-960 hardener at a weight ratio of 100:35, and the mixture was then degassed for approximately 30 min. The epoxy resin was injected into the preform employing a vacuum-assisted resin-infusion (VARI) method before curing for 24 h at room temperature followed by 15 h at 60 °C. The braiding angle in the laminates was 25° and a fibre volume fraction was about 55%. The plates were cut into pieces with dimensions of 55 mm × 55 mm × 1.6 mm; each plate consisted of two layers of the braided textile.

The drop-weight test programme was carried out with a 9250HV Instron Dynatup test system, as shown in Fig. 1. A spike-shape impactor was chosen considering real-life conditions of sports impact collisions between football shoes and shin-guards. The impactor had a flat bottom with a radius of approximately 5 mm (Fig. 1(b)) and a weight of 6.164 kg. The testing machine was equipped with an anti-rebound system to prevent multiple impacts on the tested specimen. The specimens were supported on a pair of pneumatically clamped rings with a 40 mm internal diameter. The low-velocity impact tests were carried out according to ASTM Standard D 7136. Before testing with repeated impacts, the perforation threshold of the braided composite plates (E_p) was evaluated, which was around 12 J in average. Then, repeated low-velocity impact tests were carried out with different impact energies (2 J, 3 J, 4 J and 6 J); this was achieved by varying the initial height of the impactor with a constant mass. For each specimen, the impacts were repeated at least 20 times and stopped if perforation occurred. Five specimens were tested for accuracy at each impact energy level.

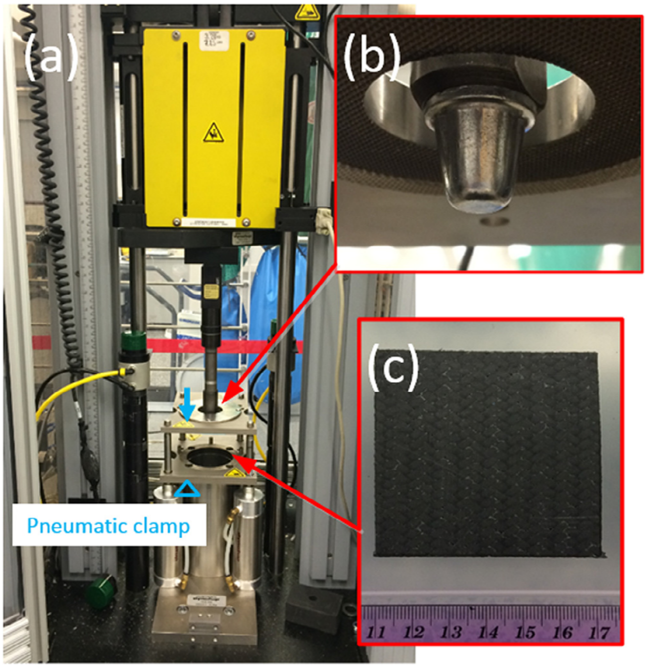

Fig. 1. (a) Drop-weight impact test setup with (b) spike-shape impactor and (c) plate braided composite specimen.

All the specimens were inspected post-test with X-ray micro-computed tomography (Micro-CT) measurements using a Metris 160H-XT XCT system to investigate the extent of the internal damage and delamination. Each scan was conducted at 60 kV and 150 μA using a tungsten target, with 2650 radiography projections taken over the 360° rotation for each specimen at an exposure of 500 ms.

3. Experimental results and discussion

3.1. Behaviour of braided composites under repeated impacts

The experimentally obtained load and internal energy responses of a braided specimen up to 20 repeated impacts with the impact energy of 2 J are shown in Fig. 2. For each impact, a roughly similar response was observed, and the impact duration time was identical. Under the first impact, oscillations of the load-time curve suggest the initiation of progressive failures in the material. After that, impact force has a relatively smooth curve with an increasing peak-load value. The energy-dissipation processes were also stable as shown in Fig. 2(b). The absorbed energies vary in a narrow range, indicating a slow damage-accumulation rate. Hence, braided composites performed robustly under repeated impacts with such a low impact-energy level.

In contrast, load- and energy-time curves of the braided composites under repeated 6 J impacts until final perforation exhibited another type of response: the peak load increased slightly after the first impact, then dropped down afterwards (Fig. 3). The sharp reduction of the impact force at the third strike is attributed to the occurrence of the fibre damage in yarns. The specimen dissipated more energy during successive impacts, leading to shrinkage of rebound energy. Once perforation occurs, there is no kinetic energy for rebound of the impactor. Hence, all of the impact energy is absorbed because of composite damage. It was also noticed that the engagement time between the composite and the impactor, governed by the friction forces and deflection, was longer with an increasing number of impacts.

In order to further investigate the effects of impact energy on braided composites under repeated impacts, the peak-force evolution was studied (Fig. 4). It can be observed that this peak increased during a few initial impacts as a result of a compaction process. The impactor contacted with a relatively softer matrix at the first few impacts and with the stiffer fibre-reinforced phase subsequently. The compaction process provides a stiffer surface with higher local fibre concentration for subsequent impacts, resulting in a higher peak load [15]. After the compaction, the peak force maintained a plateau for the impact energy of 2 and 3 J, indicating that at least 20 impacts were insufficient for fibre breakage and perforation. For impact energy higher than 3 J, a sharp reduction of peak force can be seen with an increasing number of impacts. Owing to propagation of damage and the stiffness loss, the maximum number of allowable impacts dropped down.

In addition, trends for impact-bending stiffness and maximum deflection during repeated impacts are presented in Fig. 5. The former was defined by the slope of the ascending section of the load-displacement curves; it represents the stiffness of composites under impact-induced bending in the beginning of the impact process. The maximum deflection means the maximum displacement of the impactor during each impact, reflecting the deformation of the composite specimen in the drop-weight test. For the impact energies of 2 and 3 J, it is obvious (Fig. 5) that the tested braided-composite plates have good impact resistances without a significant loss of bending stiffness. The maximum defection in these cases increased slightly with a similar rate. However, under impacts with energy larger than 3 J, the bending stiffness decreased dramatically, and the maximum deflection increased as a result of the bending-stiffness loss. The results also indicate that damage