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Braided textile composites for sports protection: Energy absorption and delamination in impact modelling

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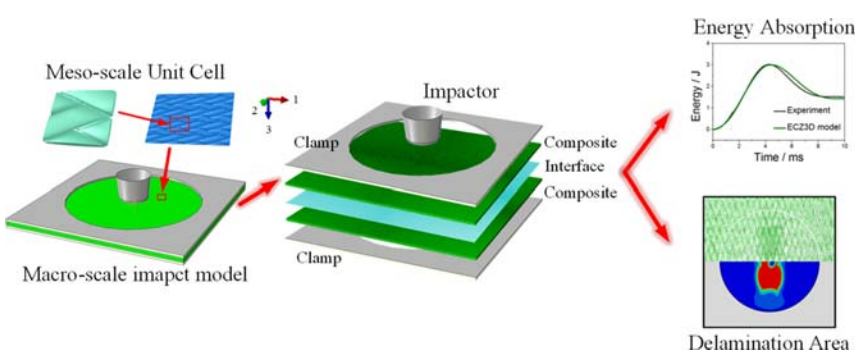
HIGHLIGHTS

- Dynamic responses of braided composites to low-velocity impacts and interface damage are investigated.
- A multi-scale modelling scheme is developed and verified with experiments for a shin-guard structure.
- Load and energy evolution in impacts is assessed using surface- and element-based cohesive zone models.
- The finite-element model with 3d elements provides good prediction for delamination and energy dissipation.
- Inter-yarn debonding is the main energy-absorption mechanism of braided composites under low-velocity impact.

GRAPHICAL ABSTRACT



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ABSTRACT

Composites reinforced with braided textiles exhibit high structural stability and excellent damage tolerance, making them ideal materials for use in sports-protection equipment. In sports impact scenarios, braided composites need to maintain their structure integrity and dissipate impact energy to protect a human body. Thus, it is crucial to study the dynamic response of a composite structure and its energy-dissipation mechanisms. Here, a multi-scale computational approach was explored to capture main damage modes of a braided textile composite; simulations were supported by experimental verification. A drop-weight test was performed with a spike-shape impactor to imitate real-life sports impact collision scenarios, followed by X-ray computed micro-tomography to characterize damage morphology of the specimen. The experimental results were compared with analytical models. The extent of delamination was quantified by applying surface- and element-based cohesive zone models. A ply-level model with three-dimensional continuum and shell elements was employed to explore the effect of through-thickness failure modes on energy absorption of the composite. The propagation mechanism of matrix cracks is also discussed. In addition, with the developed model, impact-attenuation performance of a shin-guard structure was simulated. The presented modelling capability can improve design of braided composite structures for sports and other protective and structural applications.

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1. Introduction

Composites reinforced with braided textiles exhibit high structural stability and excellent damage tolerance thanks mostly to yarn interlacing. With their high stiffness-to-weight and strength-to-weight ratios, braided composites are attractive materials for aerospace and automotive components as well as sports protective equipment [1–2]. Sports activities always have a potential risk of injury from impacts and collisions. In order to reduce this risk, protective equipment is designed, usually with a rigid outer shell and a soft liner (e.g. helmets and shin guards). Braided textiles composites were considered for the outer shell to improve its protective performance under low-velocity impacts. To enhance material design for such applications, a study of braided composites under impact loads becomes crucial [2]. Specifically for the components in sports-protection applications, energy-absorption capability is of a greater importance in contrast to structural integrity as in other structural applications.

Although extensive experimental and analytical studies demonstrated the materials response, damage morphologies and residual strength of composites subjected to a variety of low-velocity impact conditions [3–7], limited studies have been aimed at elucidating energy-absorption mechanisms of braided composites. In addition, barely visible internal damage (BVID) caused by low-velocity impact condition is difficult to detect experimentally and may often be overlooked with disastrous consequences. Therefore, there is a strong need to develop robust finite-element (FE) models capable of predicting dynamic behaviour of braided composites, considering multiple damage mechanisms [2–8]. Once successfully developed, the models can then be used to study and design structures under various impact conditions in sports scenarios that are either difficult or time-consuming to reproduce by experimental studies.

Recently, several numerical studies were focused on prediction of an impact response and, in particular, delamination induced in composites during impacts. For this, a virtual crack closure technique (VCCT) and cohesive zone models (CZM) were used widely to model processes at the composite interface. However, the VCCT is known to be sensitive to time increments in simulations and requires an assumption of a pre-existing crack (which may not be physically relevant). In contrast, the CZM combines strength-based criteria used to predict damage initiation with fracture energy criteria to simulate damage propagation, yielding acceptable results with fewer limitations [9]. Generally, the CZM uses surface- and element-based approaches. In the former, the interface is regarded as interaction between two adjoining surfaces, and thickness of the interface is neglected. Long et al. [10] and Qiu et al. [11] successfully developed a cohesive interaction scheme for prediction of initiation and propagation of delamination during impact. Zhang et al. [12] reduced the computation time by using a quasi-static load with a surface-based cohesive contact model available in the ABAQUS FE software package. In the element-based method, COH3D8 cohesive elements (available in ABAQUS) were inserted at the interfaces between composite layers. Using this approach, Feng et al. [13] investigated the influence of simulated intra-laminar damage modes on prediction of interface delamination. Kim et al. [14] studied the effect of delamination damage on performance of a whole structure. Although both approaches are acceptable, there is a lack of systematic studies to compare their advantages and shortcomings.

Modelling schemes based on continuum damage mechanics (CDM) models were adopted in the past few years to represent intra-laminar damage (such as matrix cracking and fibre fracture) developing in laminates under impact loading [15]. Planar CDM degradation models controlled by energy-dissipation constants were implemented in the ABAQUS/Explicit and DYNA3D FE codes for predicting the impact damage resistance of woven composite laminates [13,16]. The approach is popular because of its relative simplicity and acceptable results; however, some studies claimed that the normal stress in the through-thickness direction was neglected, therefore 3D stress and strain states with the use of a user-defined subroutine were adopted [17]. Continuum 3D stress elements were applied in these studies instead of shell elements to model composite plies. In summary, a large number of factors affect the impact behaviour of composites, making its numerical modelling a challenge [9–17]. As a result, a universal numerical approach, accounting for the impact load, energy and damage evolution during impact, is currently lacking.

This work aims at investigating a response of braided composite to low-velocity impacts both experimentally and through FE simulation. Capabilities for evaluation and prediction of energy absorption were developed to estimate better protection performance of the material. Macro-scale models of braided textile reinforced composites are presented as a part of multi-scale approach. It is used to study composite fracture and delamination under impact using ABAQUS/Explicit. Specifically, both surface- and element-based cohesive-zone models were analysed. The effect of out-of-plane stress component on the global response of the studied composite during impact was investigated by adopting plane and 3D CDM formulations. The damaged samples were characterized with X-ray micro-topography scanning. The experimental data were compared to results from analytical models and FE simulations, and the main energy dissipation mechanisms of the braided composite were discussed. Finally, as a case study for numerical evaluation of a sports product, the developed FE model was applied to predict the impact-attenuation performance of a shin-guard structure made of a braided-composite shell.

2. Experimental work

A braided preform of the studied composite contained carbon fibre tows (AKSAca A-42-12k); 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%. In sports applications, thickness of an outer shell in protective equipment is usually below 2 mm to reduce the weight. Hence, in the current work, the plates were prepared with dimensions of 55 mm × 55 mm × 1.6 mm. Each plate consists of two layers of the braided textile.

The drop-weight test programme was carried out with a 9250 HV 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 has 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 low-velocity impact tests were carried out according to ASTM Standard D 7136, with different impact energies (3 J, 6 J and 9 J); this was achieved by varying the initial height of the impactor with a constant mass. The specimens were supported on a pneumatically clamped ring with a 40 mm internal diameter. The ratio of a diameter of an area of the clamped sample exposed to the impact to the diameter of impactor's bottom was 4. Magnitudes of time, energy, force, deflection, and velocity were recorded automatically by the system.

All the specimens were inspected post-test with X-ray micro-computed tomography (Micro-CT) measurements using a Metris 160 H-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.

A shin-guard structure consists of a composite shell and an elastic-foam liner. In this study, a flat-shaped specimen was prepared, as illustrated in Fig. 2. The shell was made of the studied ±25° bi-axial braided composite. The backing layer (PORON® XRD™ Extreme Impact Protection) was a type of commercial foam with the thickness of 2 mm. As shown in Fig. 2, the supporting material was made of silicone rubber