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Material behaviour

Progressive damage in satin weave carbon/epoxy composites under quasi-static punch-shear loading

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ABSTRACT

Damage evolution in composites during a high velocity impact is difficult to observe. In this work, quasi-static punch-shear (QS-PS) tests were conducted in an effort to determine damage that could develop during a penetrating impact event. Eight satin weave carbon/epoxy composite samples were fabricated and tested under different load levels. Load-displacement (P-δ) curves were obtained and type and extent of damage were identified in two/three dimensions using optical microscopy and X-ray computed tomography. Corresponding displacements at which the damage occurred were marked on the P-δ plots. A finite element analysis (FEA) was performed using the ABAQUS/Explicit commercial package with a progressive damage model to simulate experimental observations. It is found that the load pattern of the plate changes from local shearing to overall bending, which corresponds to the inflection stage of the P-δ curve. The final failure is caused by major delamination and fibre breakage due to shear and tensile stresses developed during the QS-PS tests.

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1. Introduction

Polymer composite materials are used extensively in structural applications [1]. Mechanical response of laminated constructions is important because they are vulnerable to impact loading. Impact loads can be classified into three categories: low velocity impact (0–25 m/s), high velocity impact (500–1300 m/s) and hyper velocity impact (1300–3000 m/s) [2]. Due to the attribution of the short loading time during a high/hyper velocity impact, it is difficult to practically observe the damage evolution during penetration. It was proposed in the literature that the damage mechanisms during a high velocity impact are similar to those developed in a quasi-static punch-shear test [3,4]. Therefore, the punch-shear test was adopted by several researchers to characterise the material behaviour and identify types of damage that occurred at different load/displacement levels [4].

Damage evolution during a penetrating impact consists of a large number of competing mechanisms, such as matrix cracking, fibre/matrix debonding, surface microbuckling, delamination and extensive fibre breakage [5]. In many studies, these mechanisms have been investigated using static and impact penetration tests. It has been shown that penetration behaviour is sensitive to various factors in different configurations, one of which is the nose shape of the projectile penetrating into the composite target [6,7]. For blunt-ended penetrators, internal delamination is often generated as a consequence of the relatively low inter-laminar shear strength, and is unique to laminated composites [5]. As one of the major damage modes, delamination usually causes two drops in the load-displacement (P-δ) curve (Fig. 1-(a)). In contrast, rounded-tip penetrators show different behaviour, in which the punch P-δ curve has only one abrupt loading reduction

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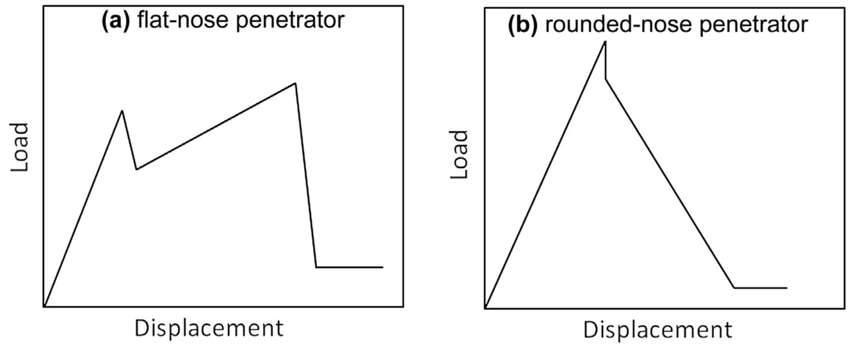

Fig. 1. Schematic plot of P-δ behaviour of composite plate punched by (a) flat-nose penetrator, (b) rounded-nose penetrator.

caused by major delamination damage [8,9] (Fig. 1-(b)). In the case of cylinder-conical projectiles, delamination does not seem to dissipate a large amount of energy [10].

Many analytical models have been developed using failure criteria and damage evolution laws based on early experimental results to simulate the damage evolution in composites [11,12]. In early work of Sun and Potti [3], they combined quasi-static P-δ curves with a Mindlin plate model to develop a “structural constitutive model” and succeeded in simulating damage propagation during static and dynamic penetration. Some classical models have been embedded in commercial software packages, such as the Chang-Chang model, a two-dimensional (2D) composite failure criterion initially adopted within LS-DYNA software. Although it can identify in-plane fibre and matrix damage modes, it cannot predict the failure in three-dimensional (3D) problems [13]. Based on 3D stress field, Yen developed a composite lamina model to capture the progressive damage evolution of a composite laminate [14]. It employs Hashin's theory [15] as the failure criterion and reduces all the stress components to zero when a failure threshold is reached. However, it does not represent the real behaviour of failure as composites fail in a progressive manner. For this reason, a continuum damage mechanics model for unidirectional composite layers based on plane-stress state was reported by Matzenmiller et al. [16]. Other progressive damage models used in penetration problems can be found in the literature [17–21], and comprehensive surveys on damage models of impact are given in [22] and [23]. However, the studies of penetration were exclusively focused on unidirectional and plain-weave composite laminates. Few studies have examined other configurations such as satin-weave composite laminates, which are studied in the present work.

This study aims to better visualise and understand the sequence of damage from initiation to growth that could occur in a penetrating impact by performing quasi-static punch shear (QS-PS) tests. The P-δ curves of satin weave carbon/epoxy composites were obtained and detailed observations of damage are presented using optical microscopy and X-ray computed tomography (X-CT). From this, an insight of damage evolution during a quasi-static penetrating process of such composite laminates is developed. Additionally, a finite element (FE) analysis was performed to reproduce the P-δ curve and help to identify the different damage modes in composite laminates. This study will be useful for simulating the progressive damage during high velocity penetration, but the influence of high strain rate effect is not in the scope of the present investigation.

2. Experiment

2.1. Materials

As a family of woven fabric patterns, satin weaves are more pliable, readily conform to complex curved surfaces and provide better drape characteristics than the plain weave pattern. In the five-harness satin weave, one warp tow passes over four fill tows and then under one fill tow, as shown in Fig. 2 [24].

The specimens used in this study are five-harness satin weave carbon fibre composites manufactured with a vacuum assisted resin transfer moulding (VARTM) process. All the specimens were provided by Jiangsu HengShen Fibre Materials Co Ltd. [25] in China, and the material properties

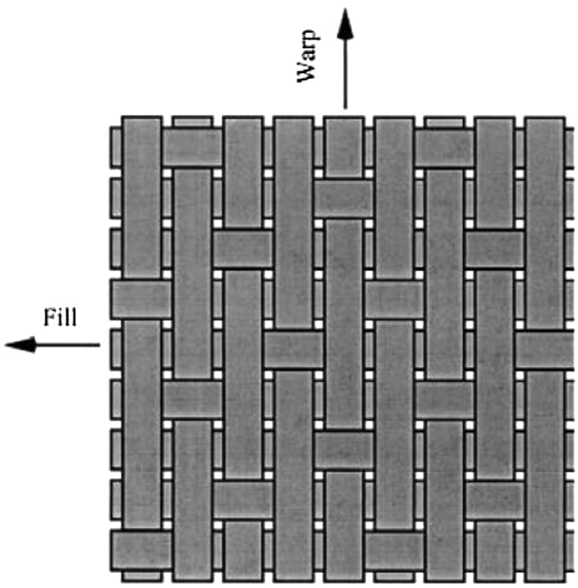

Fig. 2. Schematic of the five-harness satin weave fabric [24].

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