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The effect of target thickness on the ballistic performance of ultra high molecular weight polyethylene composite

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ABSTRACT

The ballistic performance of thick ultra-high molecular weight polyethylene (UHMW-PE) composite was experimentally determined for panel thicknesses ranging from 9 mm to 100 mm against 12.7 mm and 20 mm calibre fragment simulating projectiles (FSPs). Thin panels (~<10 mm thick) were observed to undergo large deflection and bulging, failing predominantly in fibre tension. With increased thickness the panels demonstrated a two-stage penetration process: shear plugging during the initial penetration followed by the formation of a transition plane and bulging of a separated rear panel. The transition plane between the two penetration stages was found to vary with impact velocity and target thickness. These variables are inter-related in ballistic limit testing as thicker targets are tested at higher velocities. An analytical model was developed to describe the two-stages of perforation, based on energy and momentum conservation. The shear plugging stage is characterised in terms of work required to produce a shear plug in the target material, while the bulging and membrane tension phase is based on momentum and classical yarn theory. The model was found to provide very good agreement with the experimental results for thick targets that displayed the two-stage penetration process. For thin targets, which did not show the initial shear plugging phase, analytical models for membranes were demonstrated as suitable.

1. Introduction

Polymer-based fibre-reinforced composites such as ultra-high molecular weight polyethylene (UHMW-PE) composite have been shown to be extremely effective against small calibre ballistic threats, particularly in weight-critical applications (e.g. personal protection vests and helmets) [1] or as contact spall liners [2]. It is considered that these materials, when applied in thicker sections, may be suitable as a primary armour component for protection against higher lethality fragmentation threats. It has also been found that the protection efficiency of some composites increases with thickness [3], which is driven by different penetration mechanisms occurring for thicker sections.

Although the ballistic performance of thin UHMW-PE composite is well known [4,5], there have only been limited published experimental results for thick targets. Heisserer and Van der Werff [6] and Heisserer et al. [7] investigated the ballistic limit and penetration of panels up to 50 mm and 25 mm thick respectively, though did not focus on the penetration mechanisms. Iremonger [8] and Greenhalgh et al. [9] found that thicker laminates show penetration under two distinct stages: an initial penetration stage characterised by shear failure of the fibres, and a second stage where partial penetration by the impactor causes a sub-laminate to bulge or break away (breakout) and undergo deflection and bending. The second stage is similar to the failure mode seen for thin laminates [10] or fabrics [11], with fibre failure in tension the dominant mechanism close to the ballistic limit.

Following on from these findings, there is still limited understanding of the damage and penetration mechanisms of thick UHMW-PE composite. The transition between the initial shearing stage and the bulging stage is not well understood, and the thickness of the sub-laminate formed in the bulging stage has not been

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Nomenclature

Symbols

A	area
AD	areal density
C	transition constant
c	wave speed
E	elastic modulus
E_x	energy
k	shear plugging thickness ratio
M	mass per unit length
m	mass
r	radius
T	tension force
t	thickness
V	velocity
v	volume fraction
β	radius multiplier
ε	strain
ρ	density
σ	normal stress
τ	shear stress

Subscripts

B	bulging
f	fibre
i	impact
max	failure
p	projectile
S	shear plugging
T	transition
t	target
50	50th percentile

characterised. Greenhalgh et al. [9] showed that thicker laminates exhibited a range of damage mechanisms, and demonstrated the occurrence of delamination, ply splitting, and fibre-matrix debonding. However, the fibre failure morphology was not characterised in this work, which is critical as the fibres are primarily responsible for the load-carrying and energy absorbance of the material. The ballistic performance of UHMW-PE composite for targets thicker than 50 mm has not been reported, and a clear definition has not been made of the transition between thin laminates showing only bulging, and thick laminates with two-stage penetration.

Analytical models of ballistic performance are critical to predicting performance in armour applications, and also provide significant insight into the governing penetration mechanisms. However, there are no models in literature that have been specifically developed for thick UHMW-PE composite, and no models for other composite materials that have been validated for use with thick UHMW-PE composite. Analytical models have been developed for composites under ballistic impact [10,12,13], but these models are not suitable for thick UHMW-PE composite as they are based on a single perforation stage. Gellert et al. [3] developed a multi-stage analytical model for thick GFRP based on energy laws to describe penetration by indentation, tensile failure, delamination and bulging. However, this model does not account for shear failure and also relies on several empirical constants, and as such cannot be applied to thick UHMW-PE composite.

In this paper, an experimental investigation is conducted into the deformation and failure mechanisms of thick UHMW-PE composites impacted by fragment simulating projectiles (FSPs). Ballistic limit tests have been performed on panels up to 100 mm thick, the results of which are used to identify the penetration mechanisms and study the morphology of the fracture surface through the laminate thickness. An analytical model for the ballistic limit is then developed based on energy and momentum laws, which also takes into account the specific behaviour of UHMW-PE composite observed in experimental testing. Predictions of the ballistic limit are compared with results from the experimental testing to demonstrate the capacity of the analytical model to predict ballistic performance across the range of target thicknesses investigated.

2. Experimental method

High strength gel spun UHMW-PE fibre is manufactured by, amongst others, DSM and Honeywell under the trade name Dyneema® and Spectra®, respectively. In this study Dyneema® HB26 is tested. The composite consists of approximately 80 percent by weight Dyneema® SK76 fibres within a polyurethane matrix. HB26 has uni-directional plies in a cross-ply layup that is manufactured by hot pressing [0/90/0/90] layers together. Micrographs of the cross-section show a circular fibre with a diameter of approximately 17 μm and a single ply thickness of approximately 60 μm [14].

The HB26 laminates tested in this program were consolidated by the manufacturer under a pressure and temperature of 14 MPa and 125 °C respectively. Panels up to a thickness of 50 mm were manufactured in this manner and tested as delivered from the manufacturer. For thicker sections (up to 150 mm thick), not all could be directly sourced and, as such, were consolidated from thinner (25 mm and 50 mm thick) panels in a secondary hot press process at 0.9 MPa and 125 °C. Results show that panels combined in this secondary process exhibit ballistic performance within the experimental scatter of panels manufactured at the full thickness.

Ballistic limit tests were performed for a range of thicknesses with MIL-DTL-46593B spec 12.7 mm and 20 mm calibre FSPs. A 50th percentile probability of perforation was used to define the ballistic limit, V_{50}. Calculation of the V_{50} was determined from an even distribution of partial penetration (PP) and complete penetration (CP) results, as per MIL-STD-662F. For targets 25 mm thick or less, initial ballistic limit tests were performed with the panel bolted between two 8 mm thick steel plates with four 100 mm diameter apertures. To ensure confinement did not influence the test results, verification tests were performed on full panels clamped to a steel frame. Results show targets constrained by aperture plates exhibit ballistic performance equivalent to a single shot on a full panel, consistent with results from other researchers [4]. For thicker targets, tests were performed on full panels due to excessive drawing of material at the target edge using the aperture configuration. All panels had in-plane dimensions of 300 mm × 300 mm, except for the 75 mm and 100 mm thick targets that measured 400 mm × 400 mm. A grid pattern of 20 mm × 20 mm squares was marked onto the front and back face of the targets. The grid on the front face was used to determine the degree of in-plane deformation on the front face while the back face grid was used to track the development of the back face bulge. A summary of the ballistic limit test results is given in Table 1.

3. Experimental results

The ballistic limit test results are plotted in Fig. 1 in terms of a non-dimensional areal density variable proposed by Cunniff [1],