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Mechanisms of the penetration of ultra-high molecular weight polyethylene composite beams

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ABSTRACT

A number of mechanisms have been proposed for the penetration of laminates comprising ultra-high molecular weight polyethylene (UHMWPE) fibres in a polymeric matrix. Two-dimensional ballistic experiments are conducted in order to directly observe the transient deformation and failure processes occurring immediately under the projectile via high-speed photography. Two sets of experiments were conducted on $[0°/90°]_n$ laminate beams. First, back-supported and free-standing beams were impacted by cuboidal projectiles of varying mass and fixed geometry. The observations indicate that in both cases, failure occurs in a progressive manner, with plies first failing immediately under the impact zone. The dynamic failure mode is qualitatively similar to that in a quasi-static indentation tests, and attributed to tensile ply failure by the generation of indirect tension within the plies. Direct membrane stretching is ruled out as failure that occurred with negligible beam deflection. In the second set of experiments, the projectile mass was kept constant and its width varied. No dependence of the projectile width was observed in either quasi-static indentation or dynamic penetration tests. This strongly suggests that failure is not governed by a shear process at the edge of the projectile. The observations presented here therefore suggest that tensile ply failure by indirect tension rather than membrane stretching or shear failure at the edges of the projectile is the dominant penetration mechanism in UHMWPE laminates.

1. Introduction

Ultra-high molecular weight polyethylene (UHMWPE) fibre is one of the highest specific strength materials available today [1,2]. These materials are used to make ropes, sails, tear and cut resistant fabrics, as well as in ballistic impact protection systems. For ballistic applications, 10–20 μm diameter fibres are combined with thermoplastic polymer matrices to form thin (~50 μm thick) unidirectional plies containing ~85% by volume fibres in a polymer matrix. Examples include Dyneema® (the commercial name for UHMWPE composites manufactured by DSM[1]) and Spectra made by Honeywell.[2] These unidirectional plies are typically combined to form a [0°/90°] cross-ply laminate that is now extensively used in ballistic protection applications.

A range of mechanisms has been proposed for the penetration/failure of fibre composite beams and plates impacted by a nominally rigid projectile. These include (Fig. 1): (i) tensile stretching failure in a string-like mode as first modelled by Phoenix and Porwal [3] and used to rationalise the Cunniff [4] scaling relationship; (ii) shear-off resulting in the formation of a plug [5]; and (iii) tensile fibre failure by the generation of indirect tension due to the compressive loading under the projectile [6,7]. A Hertzian cone-crack type fracture mechanism under the projectile as observed by Karthikeyan et al. [2] in the context of fibre composites with high strength matrices such as conventional CFRP composites (and many ceramic materials) has to-date not been reported for Dyneema® or the very similar Spectra composites. A number of investigations [8–11] have argued that the ratio of the thickness of laminate to the width of the projectile dictates the operative mechanism in a given setting.

A number of studies have been conducted to measure the static [12–14] and dynamic response [2,15–17] of UHMWPE fibres and composites. For example, Russell et al. [12] have observed that UHMWPE composites have tensile strengths of a few GPa but a shear strength of only a few MPa. Moreover, they found that the tensile strength of UHMWPE fibres displays nearly no strain rate dependence for strain rates up to $10^3\ s^{-1}$. Similarly, continuum models too have been proposed [18,19] to enable the modelling of penetration resistance of UHMWPE composites. While some penetration calculations have had some success in making quantitative predictions of the ballistic response [10], they have been unable to reproduce the progressive failure processes reported by Karthikeyan et al. [2].

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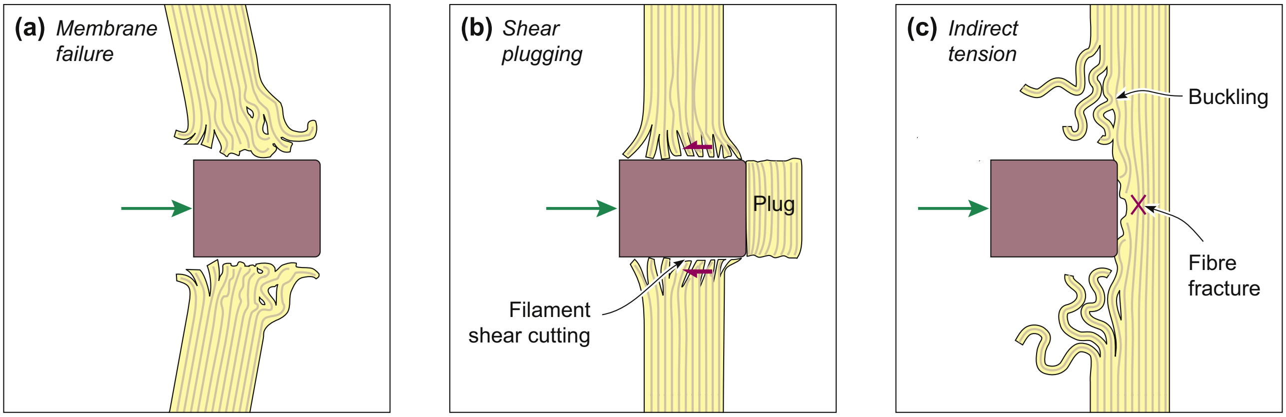

Fig. 1. Sketches of three penetration mechanisms for Dyneema® fibre composite beams. (a) Failure by tensile stretching in a string-like mode; (b) shear-off at the edges of the projectile and the consequent formation of a shear plug; and (c) progressive tensile ply failure by indirect tension developed due to the compressive stresses under the projectile.

A range of experimental studies to investigate the penetration mechanisms of UHMWPE fibre laminates has also been recently conducted [16,17,20–22]. These investigations have primarily focused on the ballistic resistance of plates. While high-speed photography enables the visualization of the transient deformation of these plates, the geometry of the experiment prohibits direct imaging of the dynamic deformation and failure processes at the critical locations, i.e. immediately under the projectile. Thus, these studies have relied on post-test characterization to infer the dynamic failure mechanisms. This leaves a number of uncertainties as the different failure modes (Fig. 1) cannot be definitely distinguished by post-test evaluations.

The aim of this study is to provide direct transient experimental observations and measurements to establish the failure and penetration mechanisms in composites comprising ultra-high molecular weight polyethylene fibres. The outline of the study is as follows. First we describe the experimental protocol to conduct "two-dimensional" ballistic experiments on beams so as to directly observe the region immediately under the impact site. Next we discuss the experimental observations to quantify the effect of (a) the boundary conditions of the beams; (b) the mass of the projectile; and (c) the projectile geometry. These observations are used to infer the penetration mechanisms for impact velocities up to 650 ms^{-1}.

2. Experimental protocol

The UHMWPE laminate used in this study was a commercial grade denoted HB26 by the manufacturer DSM Dyneema®. The laminate comprises plies orientated in an alternating [0°/90°] stacking sequence, with a ply thickness of 60 μm. Each ply is made up of 83% by volume of SK76 fibres in a polyetherdiol-aliphatic diisocyanate polyurethane (PADP) matrix. A detailed description of the process used to manufacture the composite is given in References 12 and 23. Briefly, the steps are as follows:

(1) The UHMWPE fibres are produced by gel spinning followed by hot drawing. Dissolved UHMWPE stock material is drawn through a fine spinneret to produce filaments which are quenched to form a gel-fibre. These fibres are drawn to form a highly aligned fibre with a diameter of approximately 17 μm.
(2) The fibres are coated in a resin and laid up into [0°/90°/0°/90°] sheets. The sheets are dried to remove the matrix solvent and stacked to produce a laminate of the required areal density.
(3) The laminate is hot pressed and the matrix part melts to bond the plies together, resulting in a plate with a density of 970 kg m^{-3} (these details are proprietary to DSM).

HB26 laminate material was supplied as 300 mm × 300 mm × 12.4 mm thick sheets by DSM Dyneema®. These were then cut into strips of length $L = 300$ mm and breadth $b = 12.4$ mm (and thickness t_b equal to the sheet thickness) with a medium-fine bladed band-saw. Due to the low shear strength and consequent ease with which the material delaminates, cutting required the laminates to first be sandwiched between two stiff plates (typically plywood). This confinement prevented delamination and resulted in a high quality finish with little discernible damage to the specimen edges. The 300 mm beam length was selected to allow fibre fracture to occur before the propagating stress waves reached the ends of the beam.

2.1. Experimental setup

A key aim of this investigation was to visualise the penetration process and especially the failure processes immediately under the projectile during an impact event. To achieve this aim, we designed two-dimensional (2D) experiments in which projectiles of rectangular cross-section impacted a beam as sketched in Fig. 2a. The breadth b of the projectile and beam was equal so that the experiment could be considered 2D, and the deformation and failure processes under the projectile visualised by imaging of the side edge of the beam is shown in Fig. 2b.

The projectiles were launched using a previously described gas gun apparatus [2]. However, most gas gun setups have cylindrical barrels and launch cylindrical projectiles. Cubical projectiles as required in this study could be launched using a sabot in a cylindrical barrel but here we instead chose to use an aluminium barrel with a square cross-section as sketched in Fig. 2a in order to reduce the yaw, roll and (importantly) spin of the projectile about its longitudinal axis. The planarity of the impact of the cuboidal projectile was confirmed by impact against a direct impact Hopkinson bar during calibration of the setup. The beams were tested using two boundary support configurations:

(1) In the "back-supported" configuration (Fig. 2b), the beam was adhered to a nominally rigid steel backing plate of thickness 45 mm using double-sided adhesive tape.
(2) In the "free-standing" configuration (Fig. 2b), the beam had a free span of 250 mm, and a 25 mm length at each end of