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Mechanisms of penetration in polyethylene reinforced cross-ply laminates

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ABSTRACT

The mechanisms of progressive penetration for two ultrahigh molecular weight polyethylene (UHMWPE) reinforced laminates have been investigated. One used an UHMWPE fiber reinforcement while the other utilized molecularly aligned tape. Both materials had similar out of plane compressive strengths, but the fiber system had a 40% higher in plane tensile strength than the tape. Laminated, 6 mm thick plates with a [0°/90°] ply architecture were impacted by a 12.7 mm diameter sphere under conditions that either allowed out of plane plate deflection or eliminated this deflection by rear support of the target. The depth of penetration and the ballistic limit in the rear-supported tests were identical for the two materials, and proceeded by progressive ply failure. However, tests in the edge clamped condition resulted in a substantially higher penetration resistance, especially for the higher tensile strength fiber-reinforced material. Edge clamped testing of a bilayer target, where the front third was composed of the tape material and the remainder comprised fiber reinforced laminate, had the same ballistic limit as a target composed of only the higher ply tensile strength fiber reinforced material. Penetration in both test support conditions was discovered to occur by tensile ply rupture under the projectile, consistent with a recently proposed mechanism for converting out of plane compression to in plane ply tension. Lateral displacement of plies was also observed near the sides of impact craters in both materials, indicating the existence of a second mechanism impeding penetration of the spherical shaped projectile.

1. Introduction

It is well known that composite laminates comprising high tensile strength polymeric reinforcements and compliant polymer matrices possess very high ballistic penetration resistances when configured in a [0°/90°] cross-ply architecture [1,2]. However, the mechanisms by which an impacting projectile momentum and kinetic energy are dissipated during penetration are much less well understood, and are the focus of the study reported here. The response to transverse (out of plane) impact of a thin laminate has been analyzed by analogy with that of a single fiber [3–5]. The central impact of a single, end clamped fiber generates strain pulses that propagate away from the impact site. The fastest of these elastic disturbances travels along the fibers at the fiber longitudinal wave speed,

$$c_L = \sqrt{(\lambda + 2\mu)/\rho} \quad (1)$$

where λ and μ are Lamé constants and ρ the density of the fiber [6]. A shear wave with a lower velocity $c_H = \sqrt{\mu/\rho}$ travels behind the longitudinal disturbance, enabling the fiber to undergo transverse deflection in the direction of projectile motion. The analogous wave speeds in a composite laminate are governed by the stiffness constants of the laminate, and are therefore orientation dependent [7]. For a [0°/90°] cross-ply lay-up, they are highest in the fiber directions, giving rise to a 'pyramid shaped' transverse deflection envelope during impact, Fig. 1a, whose base width expands with time.

Using dimensional analysis, Cunniff [1] showed that the ballistic limit of a fiber scales with the product of its longitudinal wave speed and the strain energy per unit mass needed to fail a fiber in tension. This combination of material properties gives rise to a Cuniff velocity:

$$\Omega = \left[\left(E_f/\rho\right)^{1/2} \sigma_f \varepsilon_f/(2\rho)\right]^{1/3} \quad (2)$$

where E_f, σ_f and ε_f are Young's modulus, tensile strength and failure strain of a linear elastic fiber and ρ its density. A comprehensive

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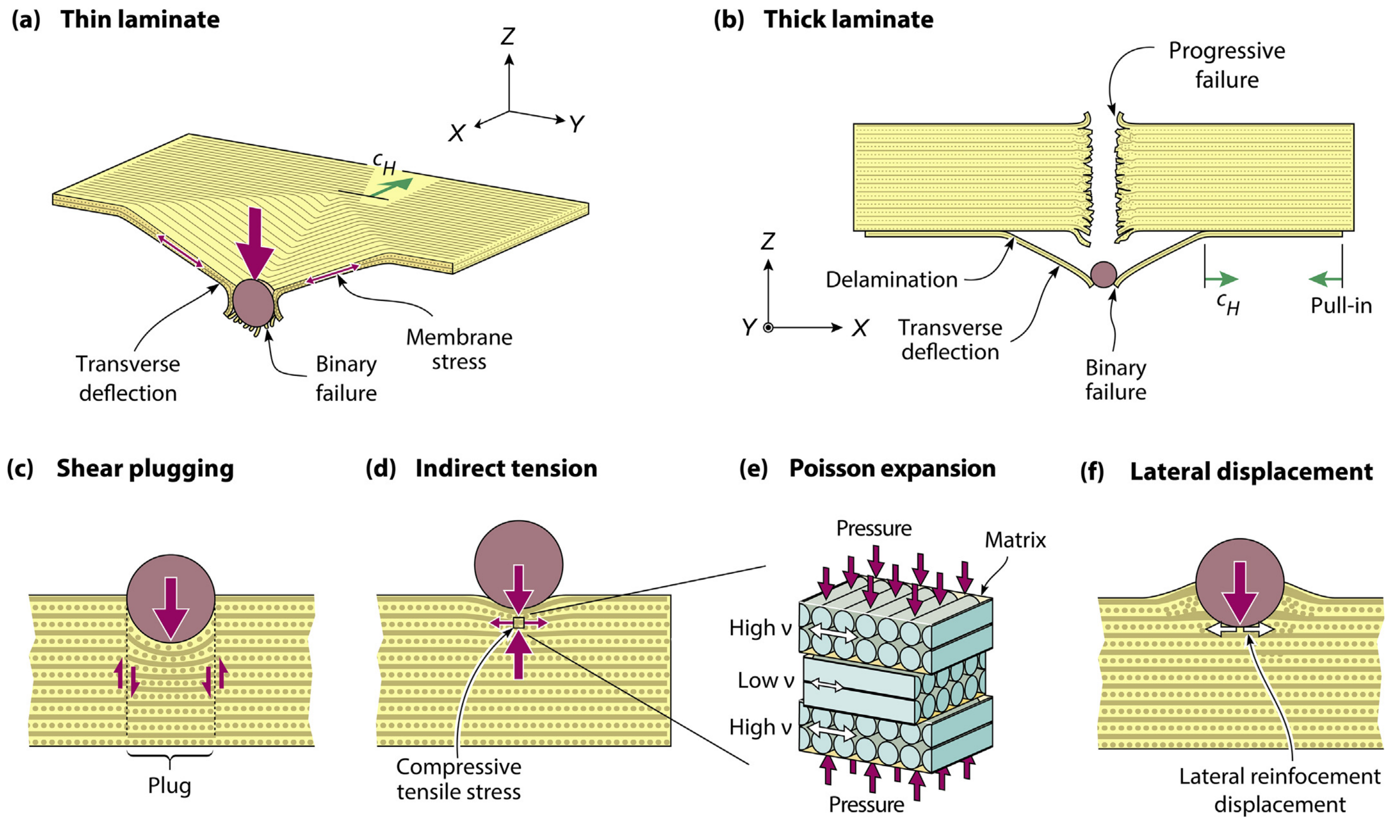

Fig. 1. Schematic illustrations of the response of (a) thin and (b) thick [0°/90°] laminates following impact by a spherical non-deforming projectile. Progressive failure of a thick laminate occurs by (c) shear plugging or (d) indirect tensile failure of the fibers due to anisotropic Poisson expansion of adjacent plies in a compressed [0°/90°] laminate (e) or (f) lateral displacement of the reinforcement.

compilation of the predicted Cunniff velocities of most high performance fibers has been given in Ref. 8 and indicates that ultra-high molecular weight polyethylene (UHMWPE) fibers should have a very high ballistic limit. However, this approach provides little insight into the mechanisms of penetration of [0°/90°] laminated composites constructed from such fibers.

Phoenix and Porwall [4] analyzed the deflection of an impacted laminate in the thin membrane limit where the transverse deflection of the laminate was governed by (tensile) membrane stresses supported by the fibers within the laminate. In this limit, the fiber stress is independent of depth, and laminate perforation occurs when the membrane stress attains the ply tensile strength. All else being equal, laminates with higher ply tensile strengths will have a greater resistance to perforation. While the ballistic limit predictions of the Phoenix and Porwall membrane stretching model are consistent with the dimensional analysis of Cunniff [1], failure was treated as a binary process; the laminate was either undamaged or fully penetrated by an impacting projectile. No partial penetration is permitted by such an analysis. However, numerous experiments have shown that UHWMPE fiber reinforced laminates fail progressively, with a depth of penetration that increases with impact velocity [8–13].

A study by Heisserer [11] using HB26[1] grade Dyneema® showed the depth of penetration by a hard spherical projectile increased linearly with projectile kinetic energy. Recent studies by Karthikeyan and Russell [13] using a spherical projectile and by Nguyen et al. [14] using fragment simulating projectiles (FSP) confirmed the existence of progressive penetration before the laminate ballistic limit was attained. All these studies indicate the penetration of these materials occurs in two stages schematically illustrated in Fig. 1b. The first "progressive" stage of penetration occurs early during the impact process. It is accompanied by minimal transverse deflection of the failed plies. The second corresponds to the out of plane deflection of the unpenetrated remainder of the laminate by a membrane stretching mechanism which results in fiber pull-in in the 0° and 90° fiber directions (converting a square sided panel into a pin cushion shape). Karthikeyan and Russell [13] estimated the second stage dissipated ~6.5 times more kinetic energy per perforated ply than that of the progressive penetration stage. Efforts to impede the progressive mode of penetration, forcing failure by the second membrane-stretching mode are therefore likely to result in substantial improvements to the ballistic resistance of these composite materials.

There are many mechanisms by which materials can be progressively penetrated by a projectile. For example, penetration can occur by shear plugging, and experimental evidence for this has been widely reported for carbon (CRFP) and glass (GRRP) fiber reinforced polymer composites constructed with impact resistant polymeric matrices [15–20]. This mechanism can be activated when the shear stress (normal to the fiber directions) created by the projectile reaches the dynamic shear strength of the laminate. A plug of material of roughly the diameter of contact surface is then formed beneath the projectile, Fig. 1c. However, the literature currently offers no observational evidence for the formation of such a shear plug in UHWMPE fiber reinforced composites. These materials have a very high fracture resistance under transverse shear loading because the fibers are very flexible (do not fracture upon bending) and their tensile strength is very high. Furthermore, He and Hutchinson [21] and more recently Noselli et al. [22] have

[1] A [0°/90°] cross-ply laminate consisting of 83 vol% UHMWPE SK76 fibers in a polyurethane matrix.