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Conical nosed projectile perforation of polyethylene reinforced cross-ply laminates: Effect of fiber lateral displacement

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ABSTRACT

Fiber lateral displacement refers to fibers being pushed aside transversely rather than being strained to tensile failure; a phenomenon that lowers the ballistic resistance of fabric composites. In this study, the effect of lateral displacement was examined for cross-ply laminates. Ballistic impact tests were performed on ultra-high molecular weight polyethylene (UHMWPE) cross-ply laminates of different thicknesses with a 90° or 60° conical-nosed projectile. Two types of laminates, HB26 and HB50 that contain the same fibers but different matrices, were tested. The number of fibers undergoing lateral displacement in each ply of perforated laminates was quantitatively determined and found to generally decrease from the impact surface to the rear surface of laminates. Following perforation by a projectile with 90° nose angle, fewer fibers lying in the projectile path failed in the weaker matrix HB50 laminate than in the stronger matrix HB26 laminate. On the other hand, the HB50 laminate exhibited a larger ballistic limit velocity than the HB26 laminate. For a projectile with 60° nose angle, more fibers failed during perforation of HB26 laminates but the ballistic limit was smaller than that of the 90° projectile. These contrary results demonstrate that for fibrous cross-ply laminates, the kinetic energy dissipated during projectile penetration is not proportional to the number of failed fibers and the ballistic resistance cannot be evaluated solely by the magnitude of lateral displacement. Localized direct tension along with membrane stretching, makes important contributions to fiber failure. The longer nose of the 60° projectile resulted in more extensive fiber breakage through this localized mechanism and thereby resulted in a smaller ballistic resistance than the 90° projectile.

1. Introduction

Fiber reinforced polymer matrix composites, such as ultra-high molecular weight polyethylene (UHMWPE) cross-ply laminates, have been shown to be extremely effective against small caliber ballistic threats. These composites are especially useful in weight-critical applications [1]. However, penetration mechanisms and ballistic performance of UHMWPE cross-ply laminates are sensitive to the projectile nose geometry [2].

Extensive experimental studies using either a spherical projectile or a fragment simulating projectile (FSP) have been conducted to determine deformation and failure mechanisms of UHMWPE cross-ply laminates under ballistic loading [3–5]. In general, a partially perforated laminate exhibits two distinct regions, a proximal region and a distal region, with features as shown in Fig. 1 [3,4]. The proximal region is perforated with a localized hole and broken fibers, and has no significant permanent deflection. In contrast, the distal region suffers large deflection; i.e. bulging. Delamination results in a relatively large volume of the material from the distal region dissipating energy through global mechanisms such as propagating hinges, membrane stretching and pull-in – these mechanisms result in the distal region being more efficient for energy absorption than the proximal region [3]. Recently, Karthikeyan et al. [3] and O'Masta et al. [6,7] have shown that fiber failure in the proximal region is caused by indirect tension [8]. This is related to out-of-plane compression and anisotropic Poisson expansion of plies directly beneath the projectile – it can result in fiber fracture without deflection of plies. Meanwhile in the distal region, fiber failure is caused by combined effects of indirect tension and membrane stretching due to increasing deflection of the plies as illustrated in Fig. 1 [9].

Although the deformation and failure mechanisms of UHMWPE cross-ply laminates impacted by a spherical projectile or a FSP have been extensively studied, there are limited published experimental results using a sharp-nosed projectile. Penetration and perforation of a fibrous laminate by a sharp-nosed projectile result in a different dominant penetration mechanism where the fibers are pushed aside

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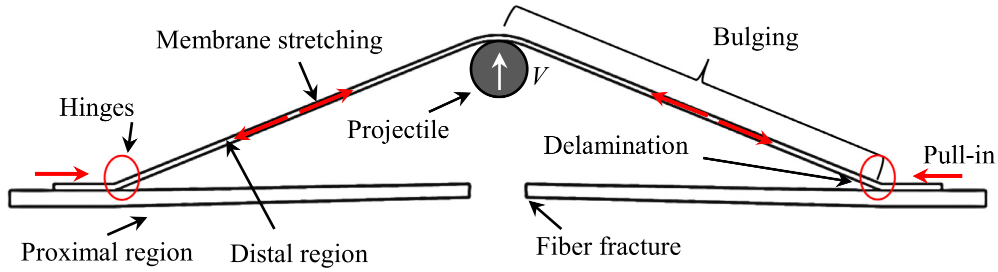

Fig. 1. Schematic illustration of deformation and failure mechanisms of a UHMWPE cross-ply laminate impacted by a spherical projectile.

transversely rather than being strained to tensile failure [10,11]. Tan et al. [10] performed ballistic impact tests on UHMWPE cross-ply laminates using projectiles with various nose shapes. They found that conical and ogival projectiles perforated the specimens mainly by pushing aside the fibers rather than breaking them as occurred for laminates impacted by hemispherical and flat-ended projectiles. However, the laminates used in the tests had only two plies, so they were much thinner than practical laminates used as armors. The effect of pushing aside of fibers has been frequently reported for dry fabrics and fabric composites. Its effect is to lower the ballistic performance of the fabric [12–16].

The relation between the ballistic performance and the number of displaced or failed fibers is not well understood for cross-ply laminates. Lee et al. [15] performed ballistic impact tests on UHMWPE fabric laminates with different matrix properties using a FSP. They found the laminate with stiffer matrix outperformed the laminate with weaker matrix since the energy absorption capacity of the composites depended on the number of yarns broken. A stiffer matrix prevented yarn movement to a greater degree, resulting in the projectile breaking more yarns. Karthikeyan et al. [17] used a spherical projectile for ballistic impact tests on UHMWPE cross-ply laminates with different inter-laminar shear strengths (due to different matrix properties). They found that the ballistic limit increased with decreasing shear strength; however, the effect of lateral displacement was not taken into consideration. Similar tests were conducted by O'Masta et al. [7] and fiber lateral displacement was observed. They indicated that for some projectile nose geometries, use of laminates with small inter-laminar shear strength might result in low ballistic resistance because of failure dominated by lateral displacement. For cross-ply laminates impacted by a sharp-nosed projectile, decreasing inter-laminar shear strength will likely result in more displaced fibers and fewer broken fibers.

In the present investigation, the ballistic limits of two types of Dyneema® UHMWPE cross-ply laminates (HB26 and HB50) were determined for conical-nosed projectiles with either 60° or 90° cone angle. The laminates were manufactured with either polyurethane (HB26) or rubber-modified Kraton (HB50) polymeric matrix. The results of HB26 laminates with different thicknesses were used to determine the effects of laminate thickness and projectile geometry on the ballistic performance. The results of HB26 and HB50 laminates with same areal density examined the effect of matrix properties on penetration and perforation. Elaborate postmortem inspection of the failure and deformation characteristics was performed. In particular, fiber failure width was measured in each ply of survived and perforated laminates to quantitatively determine the number of failed or displaced fibers as a function of ply depth, laminate thickness, matrix properties and projectile geometry. Comparisons of the failure width and global deformation characteristics were made between the laminates to investigate the effect of lateral displacement on the ballistic performance.

2. Materials and methods

2.1. Materials and their properties

Dyneema® UHMWPE HB26 laminates with thicknesses of 2 mm, 4 mm, 6 mm and 8 mm and HB50 laminates with a thickness of 6 mm, were tested in this study. HB26 and HB50 have ~83% of their mass composed of Dyneema® SK76 fibers and have similar ply thicknesses and same density [18]. The SK76 fibers exhibit elastic-brittle response with a high tensile failure stress of ~2 GPa and low fracture strain of ~2% at strain rates larger than 0.1 s^{-1} under axial tensile loading [19]. The HB26 laminate uses a polyurethane matrix (PADP) while HB50 uses a weaker and more compliant rubber-modified Kraton matrix (SISTC) – this results in different inter-laminar shear strengths of the laminates [6]. Ply thicknesses and inter-laminar shear strengths of HB26 and HB50 laminates are listed in Table 1.

According to the standard methodology provided by DSM (Netherlands) [6], both of HB26 and HB50 pre-pregs were stacked in the sequence of $[0°/90°]_n$ where n is the number of pairs of plies. The laminates were hot-pressed at 127 °C under a pressure of 20.6 MPa to obtain laminated plates of a certain thickness. The lay-ups and areal densities of the laminates used in the present study are listed in Table 2.

2.2. Ballistic test protocol

The experimental set-up is depicted in Fig. 2(a). A mild steel projectile with a diameter of 12 mm and mass of 17.6 g was accelerated by a 12 mm caliber gas gun to impact at a normal angle of obliquity at the center of the laminated plate target. Projectiles with two different nose angles, 60° and 90°, were used in this study. The impact velocity V_0 of the projectile was measured using a laser screen between the gun barrel and the target. A high-speed camera (Phantom V70, Vision Research, Inc, USA) with inter-frame time of 27 μs (or 47.6 μs), an exposure time of 3.44 μs and a resolution of 512 × 336 pixels was used. The camera was placed at the side of the target to measure the residual velocity V_r of the projectile and peak mid-span deflection H_p of the laminate.

Plates with two different in-plane sizes were used in this study. The small laminated plate had an in-plane size of 130 mm × 130 mm. This was sandwiched between a front steel ring and a back steel plate with apertures of 100 mm diameter (Fig. 2(b)). Twelve M6 steel bolts (slightly torqued to 0.14–0.15 Nm) were uniformly distributed on the circle of 115 mm in diameter to fix the laminate. This bolt boundary was similar to that used in the spherical projectile impact tests reported by Karthikeyan et al. [3]; the clamp restricted but did not totally prevent the laminate being pulled inward from the boundary (pull-in) during the impact. To investigate the boundary effect, a larger plate

Table 1
Ply thicknesses and inter-laminar shear strengths of laminates.

	Ply thickness, t_p (μm)	Inter-laminar shear strength (MPa)	Ref.
HB26	65	2	[8]
HB50	60	0.5	[8]