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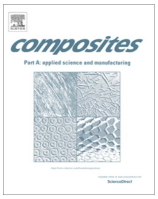

Indentation of polyethylene laminates by a flat-bottomed cylindrical punch

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ABSTRACT

Cross-ply polymer laminates reinforced by ultra-high molecular weight polyethylene (UHWMPE) fibers and tapes have been subjected to quasi-static indentation by a flat-bottomed, circular cross section punch and their penetration resistance and failure mechanisms investigated. Three fiber- and two tape-reinforced grades progressively failed during indentation via a series of unstable failure events accompanied by substantial load drops. This resulted in a 'saw-tooth' load versus indentation depth profile as the load increased with indentation depth after each failure event. The penetration behavior scaled with the ratio of the thickness of the remaining laminate to the diameter of the punch, and the indentation pressure scaled with the through thickness compressive strength. Failure occurred by ply rupture. The results are consistent with penetration governed by an indirect tension failure mechanism, and with experimental reports that tape-reinforced materials have a similar ballistic resistance to the higher tensile strength fiber-reinforced grades in rear-supported test conditions.

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1. Introduction

High performance fiber reinforced polymer matrix composites exhibit high impact resistance. The most promising consist of a [0°/90°] lamination of unidirectional plies each comprised of a high specific stiffness and tensile strength reinforcement dispersed within a low volume fraction, compliant polymer matrix [1]. Fibers of interest include those based upon carbon, S2 glass, Kevlar and ultra-high molecular weight (UHMWPE) which have high values of the Cuniff index [2,3]. Recent studies of the impact of thick, edge clamped UHMWPE laminates revealed the existence of two stages of projectile penetration [4,5]. Penetration was initially progressive, with the depth of penetration increasing linearly with impact velocity [4,6–8]. Little evidence of macroscopic out of plane plate deflection was found during this stage, and the mechanism of penetration was similar to that for a rear supported plate (with suppressed out of plane deflection) [3,8,9]. As progressive penetration was eventually arrested, a second mechanism of response became activated. This involved membrane stretching with significant out-of-plane deflection and a binary survival probability. This stage absorbed many times more impact energy per unit penetration distance than the initial, progressive penetration stage [4,5].

While progressive penetration of glass- and carbon-fiber reinforced composites, at both quasi-static (Q.S.) and dynamic loading rates, is controlled by shear plug crack propagation ahead of the indenter tip [10–16], direct observational evidence of shear plugging in UHWMPE composites at either quasi-static or dynamic rates has not be found in the literature [3,6,8,9,11]. To provide insight into the progressive penetration mechanism, Atwood et al. [17] have investigated UHWMPE cross-ply laminates placed under transverse (through the thickness) uniform compression, and shown that they fail by tensile rupture of the fibers. The plies respond to compression by plastic Poisson expansion in the direction transverse to their reinforcement direction, while Poisson expansion in the fiber direction is small due to the very high stiffness of the fibers. This highly anisotropic Poisson expansion causes each 90° ply to load the 0° plies above and below in tension in the reinforcement direction, and vice versa, Fig. 1. The stress is transferred between plies via a shear lag mechanism, and a ply fails when the tensile strength of the ply is reached. This indirect tension model predicts the significant sample size dependence of the laminates (through thickness) compression strength, and the observed increases in uniform compressive strength of UMWPE fiber reinforced laminates with increases in inter-laminar shear strength, increases in fiber strength and decreases in ply thicknesses

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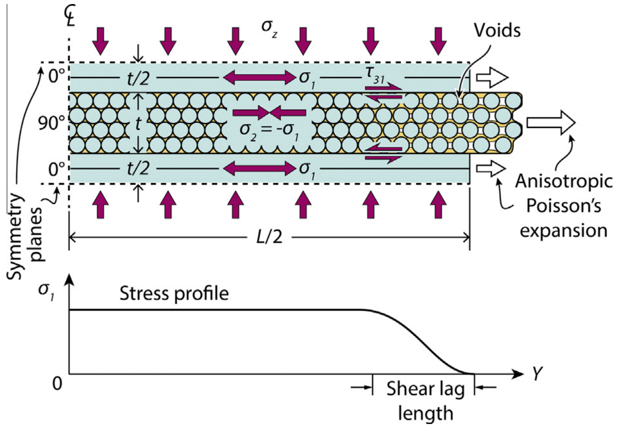

Fig. 1. Schematic illustration of a [0°/90°] cross-ply laminate loaded under uniform compression. A shear lag mechanism at the sample edge is activated by the large anisotropic plastic Poisson expansion, and converts the through thickness compressive stress into in-plane tension of the reinforcement. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

[17,18]. The model has also helped rationalize the significant variability in laminate compressive strength arising from variability in ply thickness and missing fibers within the laminates [18].

Recent experimental studies with UHMWPE laminates reinforced with solid-state tapes rather than fibers have shown that they possess a substantially higher compressive strength than that predicted by the fiber indirect tension model [8]. It has been argued that the out of plane compressive strength of these tapes is governed by elastic inter-laminar shear behavior, rather than the plastic shear behavior observed in the fiber based systems [18]. This progressive mode of penetration is investigated here for a variety of fiber and tape [0°/90°] laminates since its suppression is expected to significantly improve the impact resistance of a plate. A flat bottomed, cylindrical punch is used to quasi-statically penetrate rear supported, [0°/90°] composite laminates. The effects of punch diameter and laminate thickness on the penetration behavior are investigated, and non-dimensional parameters introduced to reduce the number of independent variables. Postmortem characterization of damage zones is used to identify the penetration mechanism in both systems.

2. Materials and properties

2.1. Materials

The study has investigated the Q.S. penetration of four fiber-reinforced and two solid state tape-reinforced cross-ply (0°/90°) UHMWPE laminates, Table 1. The study focused upon the response of Dyneema® fiber-reinforced grades HB26 and HB50 and the Tensylon® tape-reinforced grade HSBD30A since the supply of Dyneema® HB212 was limited and assembly of a [0°/90°] tape based laminate, referred to here as BT10m, from woven Dyneema® BT10 (using the method developed in Ref. [6]) was time intensive. HB26 and HB50 have ~83% of their mass reinforced by Dyneema® SK76 fibers and have similar ply thicknesses. HB50 used a weaker, but more compliant rubber-modified Kraton matrix (SISTC) while HB26 used a polyurethane matrix (PADP). The properties of these two materials have been extensively studied [19,20,6,21,18,22]. HB212 used the same matrix as HB50, but was reinforced with a stronger fiber and had thinner plies. The tape-reinforced grade HSBD30A contained an unknown resin, in low mass fraction, between plies. The fiber-reinforced grades were provided as $[0°/90°]_2$ pre-pregs, while HSBD30A was provided as a [0°/90°] pre-preg. Laminated $[0°/90°]_n$ plates were formed by hot-pressing stacks of pre-preg using the procedure reported in [18] using a pressure of 20.6 MPa. The pressing temperature for the fiber-reinforced grades was 127 °C, while BT10 m used 130 °C and HSB30A 105 °C (as recommended by the suppliers of the materials). Square samples were cut on a band saw while clamped between 6.35 mm thick Al plates.

2.2. Properties

Attwood et al. [17] showed that the compressive behavior of a polymer fiber reinforced laminate is controlled by the quasi-static tensile strength of a ply and the inter-laminar shear strength. These two parameters were therefore measured using laminate tension and inter-laminar shear tests using procedures described in [18]. The through-thickness compressive strength of each laminate grade was also measured using the procedure from [18]. Representative loading responses for each material type are shown in Fig. 2. Table 1 summarizes the average tensile and shear strengths from five tests. The unidirectional ply tensile strength was taken to be twice the measured $[0°/90°]_4$ laminate's tensile strength. Examination of Table 1 indicates that HB26 and HB50 have similar tensile strengths, σ_f, consistent with utilization of the same fiber, while HB26 had a shear strength, τ_0 that was five times that of HB50. The shear strength of HB50 and HB212 were similar but HB212 a tensile strength that was 1.5 times that of HB50. The two tape-reinforced materials had similar tensile strengths of 1.2 GPa (substantially lower than the fiber systems), and shear strengths approximately ten times that of HB50.

The through-thickness, uniform compression strength, σ_c, varies with in-plane sample length, L, because of the shear lag mechanism at the sample edges [17]. Square 1 mm thick samples used an in-plane length $L = 6$ to 15 mm, while 240 ply thick samples had $L = 20$ and 25 mm. The compressive strength (average of five tests) monotonically increased with increasing in-plane sample length, L, as the fraction of the loaded area within the shear lag region decreased, Fig. 3. At $L = 25$ mm, the strengths of all the material grades were within 0.4 GPa of each other. HB212 had the highest compressive strength, consistent with the material properties in Table 1 and the indirect tension model [23]. This data suggests that, if penetration resistance is governed by indirect tensioning of the plies, HB212 should have the greatest resistance.

3. Methodology

The samples prepared for the Q.S. penetration study were 100 mm (long) × 100 mm (wide) × H_0 mm (thick), with H_0 values of 3, 6, 12, 18 and 24 mm. Each sample was supported on an 18 mm thick, hardened A2 steel plate, Fig. 4. A picture frame, containing a 70 mm × 70 mm cutout was centrally located over the sample, and lightly clamped to prevent movement of the laminate during the test. A hardened A2 steel, flat-bottomed, right-circular cylindrical (RCC) punch then loaded the center of the sample. The loading end of the punch measured either 6.35 mm or 12.7 mm in diameter, d_p, with the uniform portion of the cross-section extending 25.4 mm in length. The perimeter of the flat punch bottom had a radius of 1.5 mm to minimize stress concentration. An Instron (Pleasanton, CA, USA) model 4208 mechanical testing machine equipped with a 300 kN load cell pressed the punch into a sample at a constant rate of displacement. No lubrication was applied to the punch. A global coordinate system was chosen with the X-axis aligned with the outermost ply (selected to be the 0° ply), the Z-axis was parallel to the loading direction, and the origin was located where the center-line of the punch intersected the initial punch-sample interface, Fig. 4. The Q.S. indentation

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