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Challenges associated with shear characterization of a cross-ply thermoplastic lamina using picture frame tests

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ABSTRACT

The current research investigates characterization of soft composite materials used in the manufacture of combat helmets. The material system considered is a cross-ply unidirectional (UD) sheet comprised of ultrahigh molecular weight polyethylene (UHMWPE) fibers consolidated with a polyurethane (PUR) based matrix. This paper presents efforts toward characterization of the material's shear behavior using the picture frame (a.k.a. trellis frame, shear frame, rhombus) test method and systematically investigates parameters influencing measurement of shear stiffness including sample arm geometry, forming temperature, strain rate, and mechanical conditioning. A specific emphasis is placed on the importance of arm geometry in the shear characterization. Overestimation of the force curve is found to result from interference of supporting arm material outside the central region of the test specimen. Removal of the excess arm material results in more accurate measurements of shear stiffness, which are subsequently available for input into FE models that simulate forming processes.

1. Introduction

The forming of unidirectional cross-ply thermoplastic laminates offers a time-efficient and cost-effective solution to the manufacture of small arms protective helmets. Thermoplastic polymer matrix composites (PMCs) occupy roughly 30% of the PMC market and possess favorable qualities that promote their increased use [1,2]. From a processing perspective, such attractive features include short cycle times and virtually infinite shelf life. Because there is no need to crosslink the polymer chains, processing cycle times are limited only by the time required to heat and cool the material [3,4]. Also, thermoplastic matrices are generally chemically inert and do not produce hazardous vapor byproducts; therefore, they promote a safe workplace for machine operators and have low impact on environment, health and safety [5]. The most favorable characteristic for military applications is the ductility of thermoplastics, which correlates with improved energy-absorption capacity during impact as well as enhanced fracture toughness relative to thermoset PMCs [3,4].

The material considered here (i.e., Dyneema® HB80) is comprised of a thermoplastic polymer matrix and a thermoplastic fiber reinforcement. Similar to the stamping of sheet metal, when polymer-fiber reinforcements are heated to a pliable temperature, the filaments have the ability to stretch while conforming to the tool geometry, as in creep forming [6]. However, extensibility of the fiber should be regulated in an effort to control part thickness and volume fraction [7]. Therefore, shearing of the lamina is required to mold geometries with double curvature [8]. Although the UD layers comprising the cross-ply are merely adhered by a molten matrix at the elevated forming temperature, Harrison et al. demonstrated that trellis shear is still the dominant deformation mechanism and inter-ply slip is essentially negligible [9]. As intra-ply shear is the governing mode of deformation for Dyneema® HB80 during forming, it is critical to properly characterize the lamina shear behavior.

The picture frame test rig, originally developed for woven textiles, imposes a pin-joint restriction on the shear specimen [10,11]. While some researchers have applied this same test method to unidirectional prepregs, either as single-ply [8,12] or double-ply (with 90° offset) [13,14], others have investigated experimental configurations that do not assume pin-joint behavior (e.g., off-axis tensile tests [15,16] and torsional bar tests [17]). The case can be made that, for unidirectional laminates, there exists no limit to the extent which a single ply can be sheared; therefore, the pin-joint assumption is not valid [8]. However, when UD sheets are assembled in a cross-ply manner and consolidated, the behavior has been shown to closely resemble that of a pin-joint network

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[18]. In the few publications available on the behavior of pre-consolidated cross-ply sheets, shear characterization is generally conducted using the methods developed for woven textiles: picture frame [8,9] and bias extension [18,19] tests. Analyses by Harrison et al. [20] suggest that, for viscous woven textiles, the picture frame test more closely replicates the deformation mechanisms experienced during composite forming processes than does the bias extension test. As such, the picture frame test method was selected for use in this research.

It is generally accepted within the textile characterization community that continuous-fiber reinforcements can be most accurately modeled by use of shear measurements corresponding to the lowest force curve for a given experimental condition [9,21–23]. This empirical observation has been explained as a consequence of the physical mechanisms of tow tensioning and alignment during the characterization test [21,22]. An additional mechanism to explain overestimation of the shear force curve is the added stiffness contribution created by interference of material outside the test area. Because equations relating the force/displacement measured from a universal testing machine to the stress/strain in the textile assume all loading is used to deform a central region, interference by material outside this area must either be accounted for in the calculations or eliminated [10]. For woven fabrics, the solution is simply to remove unclamped fringe tows from the arms of test specimen [24]. For cross-plies, however, material interference in the arms is previously unstudied. In this paper, the effect of the sample arm geometry on the accurate characterization of shear behavior for a pre-consolidated thermoplastic cross-ply sheet is systematically investigated. With proper arm geometry, the lowest possible load–displacement curve can be measured, thereby yielding the most accurate characterization of shear stiffness and thus increasing the fidelity of modeling efforts. For completeness of characterization, the influence of temperature, strain rate, and mechanical conditioning (i.e., repetitive loading/unloading) are also considered.

2. Material

Dyneema® HB80, a thermoplastic pre-consolidated sheet, is considered in this research and was selected specifically for application in the manufacture of combat helmets. The aforementioned lamina is comprised of four unidirectional layers that are cross-plied in a $(0/90)_2$ initial fiber configuration. Constituent materials include ultrahigh molecular weight polyethylene (UHMWPE) fibers suspended in a thermoplastic polyurethane (PUR) based matrix. The total ply thickness is approximately 0.148 mm, having roughly 10 fibers through the thickness, and the average areal density is 145 g/m^2 [25,26]. The matrix content (estimated, using the Rule of Mixtures, from the areal density, nominal sheet thickness, and respective matrix and fiber densities) ranges between 15% and 20% by weight (17.9% and 23.6% by volume). The manufacturer suggests a short-duration temperature limit of 130 °C but gives a range from cryogenic to 70 °C for long-duration exposures [27].

3. Background

Because the material used in this research is wholly thermoplastic, at standard ambient conditions out-of-plane deformation mechanisms are readily accommodated (i.e., facile flexure) whereas in-plane deformation mechanisms are not easily facilitated. The cross-ply lamina is therefore unable to shear in the rhombus rig at room temperature. As such, all forming operations and related characterization must be performed while the PUR-based matrix is in a molten state. Thus, an environmental chamber was designed, built and mounted on an Instron® 4464 universal testing machine to perform picture frame experiments on Dyneema® HB80 at elevated temperature conditions.

3.1. Experimental set-up for high-temperature material characterization

One critical objective in high-rate thermoplastic composite manufacture is to minimize cycle times, which correlate to rapid heating rates. There are three possible methods of heat transfer that can be used to heat a lamina up to forming temperature: (1) conduction, (2) convection, and (3) radiation. Radiation was the heating method selected for the material testing program in the current research. For radiative heating, thermal exchange occurs by electromagnetic waves that travel through space from a source to a target, exciting vibration of atoms that result in internal heating. Because air absorbs little infrared energy, radiation is a fast and efficient means to heat polymers [28].

Conduction and convection are less amenable for this application. Since manufacturing is a dynamic process, and because polymers tend to behave like thermal insulators (i.e., have low thermal conductivity and diffusivity), the direct-contact method of conduction is not preferable. While convection is a more suitable option, heat transfer across a secondary medium is relatively slow and not conducive to high production rates. Therefore radiative heating is the most attractive option to achieve short cycle times.

A radiation oven was designed and built for heating the cross-ply while it is secured in the shear frame mounted on the universal testing machine. A panel array of flat-faced infrared ceramic elements was implemented in an environmental chamber (Fig. 1), consisting of six square uniform emitters (12 cm × 12 cm) fitted to the back wall of the oven. To facilitate even heating of the shear specimen, the array was mounted to be centrally located about the rhombus rig (Fig. 1a). The heating elements were wired in parallel to achieve an equivalent temperature for all heating elements and marginal spacing was left between the emitters to create an effectively continuous 50-cm × 27-cm ceramic plate. Reflective insulation was adhered to the oven walls and circular holes were cut in the top and bottom surfaces to accommodate gripping of the test fixture. A feedback control system with a thermocouple sensor was used to regulate the temperature of the ceramic elements. An additional thermocouple was added to monitor the temperature of the composite lamina. The resulting heating apparatus was mounted on the universal testing machine (Fig. 1b) and evaluated for its efficacy.

A sample specimen was secured in the rhombus rig within the environmental chamber (Fig. 2a) and heated to a temperature of approximately 90 °C. Using an infrared (IR) camera, thermal images were recorded to observe the temperature gradient across the sample. Measurements queried at discrete locations (as indicated in Fig. 2b) yielded an average temperature of 89.7 ± 2.5 °C over the area of interest (denoted by the dashed square box in Fig. 2a) where the test specimen is expected to be in a state of pure shear. With the environmental chamber providing a uniform thermal profile over the shear specimen, picture frame experiments were then ready for the investigation of shear stiffness measurement sensitivity to factors such as sample arm geometry, temperate, strain rate, and mechanical conditioning.

4. Effect of sample arm geometry

As previously mentioned for woven fabrics, researchers have found that removing unclamped fringe tows from the arms of the test specimen eliminates the additional force contributions necessary to shear the textile in that region of the fabric [10]. Here, this principle was adapted for cross-ply textiles by introducing cuts into the arms of the picture frame specimens. Therefore, the effect of sample arm geometry on shear characterization of this cross-ply sheet was investigated. Tests were initially performed on four dif-