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Biaxial shear/tension failure behavior of Spectra single fibers

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ABSTRACT

An experimental study is conducted to develop the biaxial failure surface of single Spectra 100d and Spectra 130d filaments in a torsion-tension environment. The cross-sectional profiles of single fibers are evaluated using scanning electron microscopy and X-ray computed tomography. In efforts to hold the polyethylene single fiber, a pin-gripping method is developed. Effects of pin diameter on failure stress for both Spectra types are characterized. Additionally, the effect of sample gauge length on fiber tensile strength is investigated. Quasi-static experiments are conducted using an MTS servo-hydraulic system to apply tensile loads on pre-twisted single fibers. A tension Kolsky bar is employed to study the biaxial shear/tensile behavior of single fibers at high strain-rates. A decreasing trend of tensile strength with increasing torsional strain is observed for both Spectra 100d and 130d. Furthermore, a torsional pendulum apparatus is used to determine the apparent torsional shear stresses in pre-twisted fibers at various levels of axial loading and a relationship between apparent shear stress and axial stress is developed. Finally, a biaxial shear/tension failure envelope of each fiber type is established.

1. Introduction

High performance fibers have been extensively utilized in modern soft body armor since the 1960s due to their low weight and superior strength. Thus, previous multi-scale research has been performed to understand the mechanisms of high-performance fabrics resisting ballistic threats, thereby yielding a basic understanding of the impact phenomena [1,2]. Indeed, impact into soft armor systems is extremely complex, being a function of numerous different parameters such as but not limited to the number of plies within the pack, weave structure, friction interaction due to fiber/yarn seizing, and of most importance, the mechanical properties of the fibers themselves [2]. In order to understand the impact process on a more basic level, free from such a complex environment, study of transverse impact into single yarns is often performed [3–7]. The transverse impact response of an elastic string was first investigated in the 1950s [8]. After further investigation, tensile properties of fiber were directly related to the velocity of the produced transverse wave, which is described by a set of equations, namely Smith's theory [3]. With the help of high speed cameras, transverse wave velocities of yarns under impact loading were recorded, agreeing quite well with predictions by the classical theory [4,5]. Yet the projectile velocities that cause instantaneous rupture of a yarn measured from experimental work have been shown to be lower than the estimated breaking speeds predicted by Smith's theory, as shown in Table 1 [6,7]. As it is quite possible that complex loads of tension, shear, and compression act on the fiber during transverse impact, it has been suggested that multi-axial loading causes the performance of the yarn to be lower than the prediction by the Smith theory [9].

Among reported textile armor system transverse impact studies, it is important to note that the performance of Ultra High Molecular-Weight Polyethylene (UHMWPE) system was below expectation [10]. It has been proposed that this phenomenon can be attributed to the added transverse stresses and extra constraint that are induced by the additional plies [10–12]. It is also known that at and above the ballistic limit of a fabric, local failure appears around the impact point [11–14]. Furthermore, immediately above the ballistic limit of a fabric, there exists a sharp drop in energy absorption capabilities due to such local fabric failure, wherein only minimal time is available for energy to be dissipated away from the impact site [10]. Thus, any mode of reduction in the fiber failure criterion will inherently reduce the effective halting capability of the armor system. Additionally, based on a tremendous amount of armor system transverse impact experiments [13,15–17], Cunniff performed non-dimensional analysis on the transverse impact process of textiles, thereby generating the following non-dimensional parameters:

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Table 1
Breaking speed for different types of yarn (from [6]).

Yarn	Breaking speed from experiments (m/s)	Breaking speed from classical theory (m/s)
KM2 S5705	621–634	934
Dynemma SK-65	517–583	1100
PBO	523–610	1105

$$\Phi\left(\frac{V_{50}}{(U^*)^{1/3}}, \frac{A_p A_d}{m_p}\right) = 0 \tag{1}$$

where

$$U^* = \frac{\sigma\varepsilon}{2\rho}\sqrt{\frac{E}{\rho}} \tag{2}$$

In the above equations, V_{50} is the fabric ballistic limit, σ is the failure axial tensile stress of fiber, ε is the failure strain of fiber, ρ is the density of fiber, E is the longitudinal modulus, A_p is the presented area of projectile, m_p is the mass of projectile, and A_d is the areal density of fabric armor. With the help of the Cunniff equation, the ballistic limit of a specific armor system may be predicted via knowing said parameters of the desired system, without performing actual impact tests. Most importantly, Eq. (2) demonstrates that the yarn specific toughness governs the resulting V_{50} performance of the fabric, thus a reduction in such a value will inherently alter the V_{50} response. Although the Cunniff parameter works extremely well for aramid fabrics, the ballistic resistance of several UHMWPE armor systems were found to reside below predictions from the Cunniff equation [2]. It is quite possible that shear properties of different fiber types is an influencing factor that is missed in the equation.

Therefore, understanding the mechanical properties of a single filament under multi-axial loading has a significant benefit of uncovering the failure mode of high performance fabrics and yarns under ballistic threat. However, very limited work has been performed in understanding fiber response when loaded in multi-axial conditions. Among previous biaxial loading studies, the ultimate tensile stress of Kevlar 49 fiber has been shown to decrease significantly after an applied torsional strain of 10% [18]. Meanwhile, it was reported that the apparent or measured shear modulus of high performance fibers increases with an increase in axial loading [19–21] and a linear function was identified to relate the measured shear modulus with tensile stress for Kevlar 49 [19]. Recently, the degradative effect of shear strain on the tensile properties of Dyneema SK76 [9] and Kevlar KM2 [22] was elucidated during dynamic tensile loading [9]. Clearly understanding of such multi-axial loading on single fibers is of importance in predicting the resulting failure strength during a complex loading environment.

In this study, efforts are made to investigate the failure criteria of high performance fibers under biaxial shear/tension at various strain-rates. The fibers discussed in the present paper include Spectra 130d and Spectra 100d. Spectra fiber is a kind of UHMWPE fiber manufactured by Honeywell.

2. Experimental

2.1. Imaging techniques for fiber cross-section

When determining both the axial and shear stress levels of the pre-twisted filaments, understanding the fiber cross-sectional geometry along the entire gauge length is imperative. Thus, in efforts to determine the cross-sectional profiles the filaments under investigation, scanning electron microscopy and X-ray tomography techniques are utilized. A dual beam FEI-SEM/FIB is implemented to detect the profiles of the Spectra fibers. Single filaments of fiber are carefully extracted from the bundle and then nine samples, three taken from each end and the middle of the fiber, are mounted on a conductive holder using carbon tape. A Hummer ® 6.2 Sputter System is used to coat a thin layer of AuPd on the fiber surface. Coated fibers are imaged with an SEM at 10 kV acceleration voltage. The diameters of the specimens are then analyzed and estimated. In order to unveil the cross-sectional shapes of the Spectra fibers directly, the focused ion beam is used to mill single filaments. A stepwise voltage/current milling process is utilized in order to ensure minimal damage to the fiber surface. Next, platinum deposition is used to coat the newly created surface to make it detectable by SEM.

X-ray tomography of fiber cross sections is performed in beam line 2 BM-B at the Advanced Photon Source of Argonne National Laboratory. Single filament and yarn are placed on a static load device, which is mounted on a rotating stage, and then carefully stretched straight and perpendicular to the X-ray beam, as shown in Fig. 1. Direct monitoring of the force detected by a load cell ensures that no axial tensile stress is present in the fiber. Consecutive X-ray images are then taken as the stage is rotated. These images are then re-constructed to reveal the cross-sectional shapes of the fibers in the yarn.

2.2. Tensile test sample preparation

Generally, for single filament sample preparation of tensile experiments, a single fiber is laid straight on a cardboard substrate possessing a cut hole [23]. Appropriate adhesive is then used to attach both sides of the fiber to the edges of the hole, as shown in Fig. 2(A). However, due to the extremely high slipperiness of the surface of UHMWPE fiber and its low shear strength, a pin-gripping method is utilized to hold the ends of the single filaments, similar to a capstan device. To prepare the required gauge length of the sample, one end of a single fiber is wrapped on a small rod (pin), and then the pin is attached to the cardboard substrate at the edge of the circular cutout. The other pin is then wrapped with some of the remaining fiber, and attached to the other side of the cutout, as shown in Fig. 2(B). The specimen is then mounted on the loading apparatus and both left and right sides of cardboard substrate are cut just before the axial tensile load is applied.

To investigate the effect of added shear strain to the tensile strength of a filament, a twisting apparatus was built for single fibers to achieve specific degrees of shear strains, as shown in

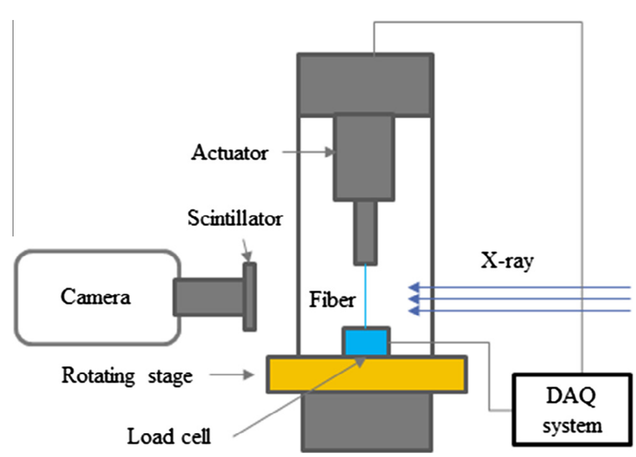

Fig. 1. Schematic of X-ray tomography apparatus. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)