A Device for Mechanically Folding Yarns and Woven Fabrics of Ballistic Fibers

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A device was designed and built that attaches to servohydraulic machines that typically perform material fatigue testing. The device was designed to systematically fold woven fabric and yarns of ballistic fibers to assess the impact of mechanical folding, such as may occur during use, on ballistic fiber properties. Initial tests indicate that the device repeatedly folds a piece of woven fabric at the same location. However, when the device is in the open position, a consistent 1 cm *movement of the fabric was observed. A slight modification of the device is required to eliminate this movement. After cycling a piece of woven poly(benzoxazole) (PBO) fabric for 5500 cycles, an 18% reduction in the ultimate tensile strength and strain to failure of the PBO fibers was observed. Research is continuing to determine a relevant and optimized testing protocol.* [DOI: 10.1115/1.2755131]

1 Introduction

It has been suggested that folding of the ballistic fibers that comprise soft body armor may also be a factor in the performance deterioration observed worn in soft body armor. In an attempt to quantify the impact of this mechanism, a device was designed and built to simulate the folding that may occur to the ballistic fibers while the vest is in use. This effort is part of a research program being conducted by the National Institute of Standards and Technology Office of Law Enforcement and Standards (NIST-OLES) under the auspices of the National Institute of Justice (NIJ). A key objective of this research program is to develop relevant and nondestructive test procedures that link personal body-armor performance to fundamental and measurable properties of the materials that are used in its construction. One long-term goal of the folding research on ballistic fibers is the development of a controlled procedure for simulating the folding that occurs in an actual vest during various stages of its proposed lifespan. This type of procedure would then allow ballistic fiber tests to be performed on body armor whose wear and deformation history are known. Such tests on controlled materials should help to establish the link between use and life expectancy of the body armor.

The device described in this report was designed to fold individual yarns and single and multiple layers of woven fabrics of ballistic fibers by using servohydraulic testing equipment that is often available in laboratories that perform fatigue testing of materials. Since the concept is new, a major design goal was to incorporate sufficient flexibility into the design to allow most of the deformation parameter space that occurs during actual use to be systematically probed, with the end result being an optimized and relevant deformation protocol. Furthermore, the use of off-the-shelf testing equipment, such as the servohydraulic testing equipment, should facilitate peer review and use by others.

2 Motivation: The Single-Fold Test

The research of Cunniff and Auerbach [1] has shown that, within the elastic limit, a correlation exists between the ballistic fiber properties and ballistic performance if the energy absorbed by the ballistic fibers is decoupled from the absorbed energy associated with the vest construction, i.e., the areal density. That is, the material properties of the fiber are decoupled from the vest construction parameters known to depend on a manufacturer's vest design. From their research, the correlation between ballistic performance and the mechanical properties of the active fiber is quantified by the $(U^*)^{1/3}$ parameter shown in Eq. (1). Therefore, $(U^*)^{1/3}$ is a theoretical parameter that estimates the maximum velocity of a bullet that the fibers of a vest can stop and is independent of vest construction. This equation has also been derived theoretically by Phoenix and Porwal [2,3].

$$[U^*]^{1/3} = \left[\frac{\sigma_f^u \varepsilon_f^u}{2\rho} \sqrt{\frac{E_{1f}}{\rho}} \right]^{1/3} \tag{1}$$

where σ_f^u is the fiber ultimate axial tensile strength (UTS), ε_f^u is the fiber ultimate tensile strain, ρ is the fiber density, and E_{1f} is the longitudinal linear elastic fiber modulus.

In a previous publication, it was shown that a *modified* single fiber test (m-SFT) [4], based on ASTM C1557-03 [5], could be used to obtain the fiber properties for Eq. (1). In another report [6], it was shown that changes in ballistic performance could be detected in a worn vest that was presumed to arise from ultraviolet (UV) exposure and hydrolytic action. Since it is probable that mechanically induced degradation may also induce subtle changes in ballistic fiber properties, 50 fibers were extracted from a single yarn of virgin poly(benzoxazole) (PBO) fibers and placed uniformly across two pieces of poster board (see Fig. 1). The two adjoined poster boards were then folded together, and 11.8 kg bricks were placed on the folded poster boards and left overnight to simulate a worst-case scenario. The visible damage induced by the single fold is shown in Fig. 2. To ascertain the effect of this damage on the mechanical properties of the fiber, 50 folded and 50 nonfolded virgin PBO fibers were tested randomly using the m-SFT.

Fiber diameters were measured on each specimen by using an optical micrometer (Excel Technologies Inc., Model VIA-100[2])

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[2]Certain commercial materials and equipment are identified in this paper to specify adequately the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply necessarily that the product is the best available for the purpose.

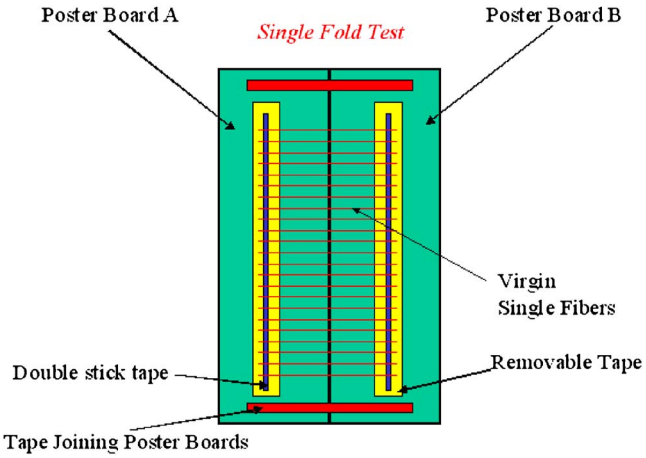

Fig. 1 Pictorial representation of single fibers stretched across two adjoining pieces of poster board

attached to a Nikon Optiphot-POL microscope equipped with a video camera (Optronix LX-450 RGB Remote Head microscope camera). The fiber image was viewed on a Sony PVM-1344Q color video monitor. All fiber samples had diameter measurements made at five equally spaced locations along the 6 cm gage length.

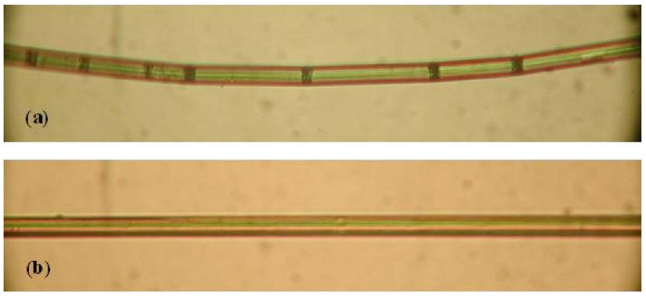

Fig. 2 (*a*) Damage induced by single fold of PBO fiber, (*b*) nonfolded virgin PBO fiber

The five individual diameter measurements were averaged to give an average diameter value for each fiber sample. The average fiber diameters from the folded specimens were found to be (12.6 ± 0.5) μm, and those of the nonfolded specimens were found to be (12.5 ± 0.5) μm. The folded and nonfolded populations of average fiber diameter values were indistinguishable at the 95% confidence level ($p=0.125$).

From the m-SFT, the strain-to-failure and ultimate tensile strength of the folded virgin PBO fiber was reduced by $\sim$10% relative to the nonfolded fibers ($p=0.011$ and 0.004, respectively). Histograms depicting the shift in the distributions are shown in Fig. 3. In contrast to previous results on worn vests, the modulus of the virgin fiber was also found to decrease about 15% from (164 ± 9) GPa to (156 ± 12) GPa. These results indicate that the property changes in folding should be quantifiable and that the m-SFT is sensitive enough to observe these changes.

2.1 Device Design and Operation. The design of the experimental device was motivated by the desire to use the controlled fatigue testing features inherent in most servohydraulic test machines. To minimize damage to the servohydraulic machine by the device, it was designed to fit on a 250 kN (55 kip) Model 810.25 MTS machine equipped with a 158.5 mm dia piston rod. To convert the precise linear motion of the servohydraulic machine to precise rotational motion, a bracket was fitted to the piston rod that containing a spur gear and rack as shown in Fig. 4. The 28 teeth spur gear was a 16 pitch −12.70 mm face width with the following specifications: (i) pitch diameter: 44.45 mm, (ii) hub diameter: 38.10 mm, (iii) outer diameter: 47.75 mm, and (iv) overall width (including face width): 25.40 mm. This spur gear required a bore size between 12.70 mm and 22.23 mm.

To effect the folding of the ballistic fiber material, a two-piece clamshell design is employed (see Fig. 5). To minimize mass, most of the device is constructed using aluminum, except where otherwise specified. The lower plate is connected to a platform that is attached to the servohydraulic machine through the column mounting brackets. Interchangeable folding rods were constructed out of 0.635 cm dia and 1.27 cm dia stainless steel and attached to this plate. The upper plate is attached to a 1.27 cm^2 stainless steel rod that is turned at each end to 1.27 cm dia to conform to the required bore size of the spur gear. The top plate is attached to the platform using two base-mount ball bearings that accommodate a

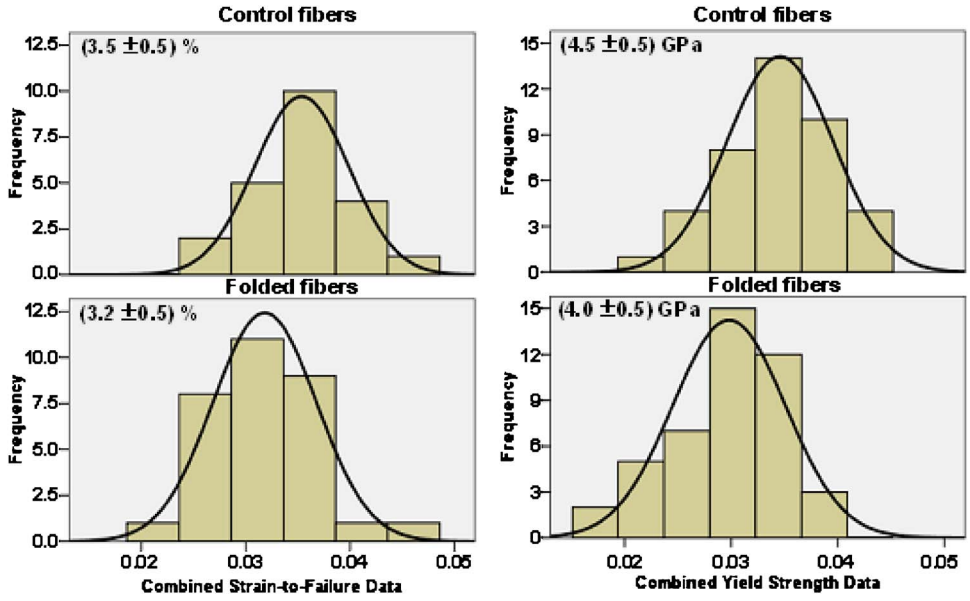

Fig. 3 Histograms showing the change in strain-to-failure and ultimate tensile strength of virgin PBO fibers caused by the single-fold test

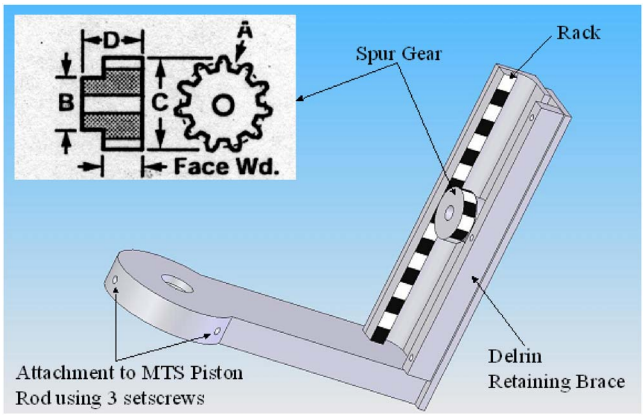

Fig. 4 Piston rod bracket for converting linear motion of MTS 810.25 servohydraulic machine into rotational motion. Inset shows schematics of spur gear with detail specifications given in the text. Delrin is polyoxymethylene.

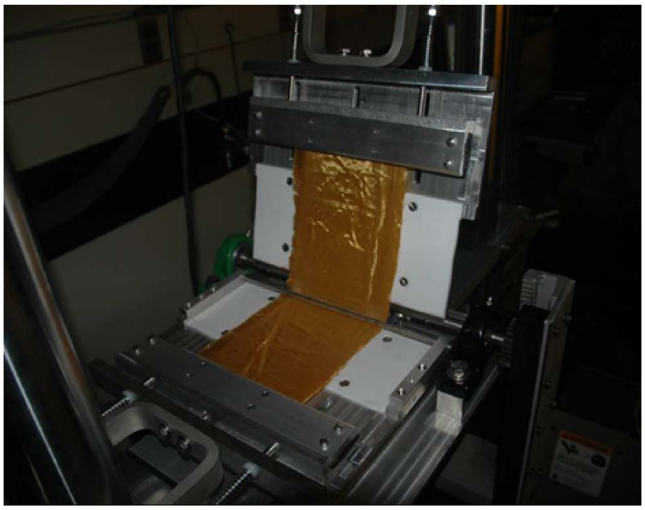

Fig. 6 Folding device with fabric clamped in the sliding brackets and around the folding rod

shaft diameter of 1.27 cm.

Each plate is equipped with teflon sheets to minimize friction between the ballistic material and the plate surface, and in order to hold the fabric or yarn in place, each plate is equipped with a sliding bracket. Each sliding bracket is held in place by two 0.635 cm dia stainless steel rods that attaches to constant force springs (rods not shown in Fig. 5). The constant force springs were rated for 40,000 cycles and are used to maintain constant tension on the woven fabric or yarn.

2.2 m-SFT. This test procedure was described in a previous publication [4] and is repeated here for the reader's convenience. Fifty individual fibers, each ~30–40 cm long, were obtained from a harvested yarn and mounted onto a paper tensile testing template. The template, printed on typical 21.6 cm by 27.9 cm printer paper that contains 1 cm major graduations and 1 mm minor graduations, held two or three rows of five fibers. Therefore, one fiber strand generated two or three test samples, each with a 6 cm gage length. Individual fibers were initially attached temporarily to the paper template outside the region of the fiber that would undergo diameter measurement and tensile testing with double-sided tape (3M Stationary Products Division, St. Paul, MN). Prior to epoxy gluing, small strips (approximately 1.2 cm $\times$ 0.2 cm) of silver reflective tape (United Calibration Corp.) were applied to the template at the top and bottom of the gage section of each fiber sample. The reflective tape allows elongation measurements to be made by the laser extensometer (United Calibration Corp. Model EXT 62 LOE) while the sample is undergoing tensile testing. The fibers were then permanently bonded to the template by epoxy adhesive (Hardman Water-Clear Epoxy, Double/Bubble Green Package No. 04004). The epoxy adhesive was allowed to cover up to 0.1 cm thickness of the reflective tape to avoid the slip between fiber, paper template, and reflective tape.

The five individual diameter measurements were averaged for each fiber sample. Between steps in the mounting, diameter measuring, and tensile testing processes, fiber samples were stored in the dark, in wooden map cabinets.

Although the compliance method in ASTM C1557-03 has been found to be satisfactory for quantifying the properties of new fibers, the use of noncontact extensometers to detect gage section elongation directly is often suggested if a more accurate measure of strain is required, since specimen fragility prevents the use of normal strain-sensing devices, such as strain gages or mechanical extensometers. Consistent with this recommendation, a United Calibration Corporation Model EXT-62-LOE laser extensometer was used.

An initial gage length of 5.1 cm or greater is required for optimum performance of the laser extensometer. Furthermore, because fiber strength is typically gage-length dependent, a specimen length reflective of the amount of material that may be deformed during ballistic action is probably necessary. Therefore, a gage length of 6.0 cm was chosen. The laser extensometer was calibrated using an Epsilon extensometer calibrator Model 3590C that has 10 cm of travel. The standard uncertainty in the strain at 6.1 cm associated with this measurement is 0.0001. The standard uncertainty in the load cell at 100 g is 0.001 g.

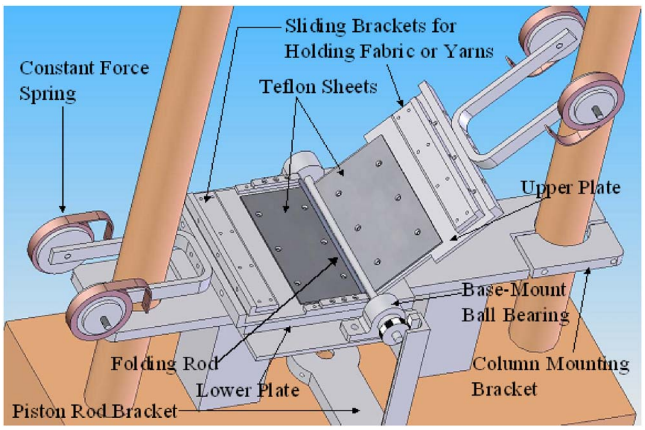

Fig. 5 Basic design of folding device attached to servohydraulic machine. Constant force springs attach to sliding brackets using 0.635 cm dia stainless steel rods (not shown). Note: Delrin brace on piston rod bracket removed to better show clamshell design.

3 Results and Discussions

To test the effectiveness of the device, a piece of woven fabric (12.7 cm $\times$ 38.1 cm) was attached to each sliding bracket and under the 0.635 cm folding rod (see Figs. 5 and 6). The device was rotated through 90 deg ($\pi/2$ rad) as shown in Fig. 7 and held at each end point for ~15 s. The movement of the linear actuator was controlled at 25.4 mm/s. Manual markings were made in permanent ink on the edge of the sample to monitor movement of the folded region as the specimen was repeatedly folded for approximately 5500 cycles. The folded region location remained constant throughout the test. However, in the open position

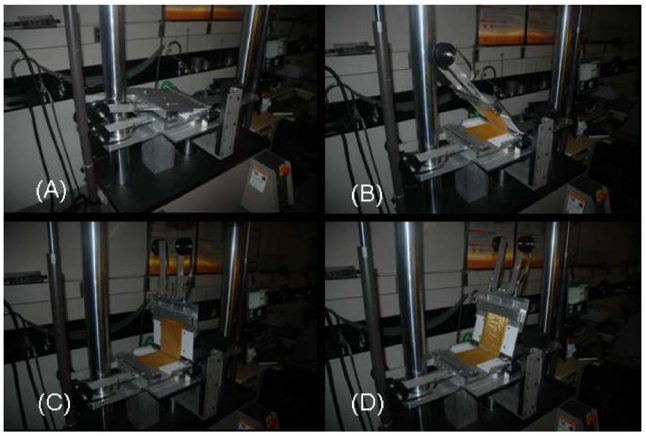

Fig. 7 Collage showing the fabric as it goes from a closed position (A) to the fully open position (D)

(90 deg), the fabric moved a consistent 1 cm distance away from the folded region. Analysis of the motion of the device indicates that immobilizing the sliding bracket on the lower plate and adjusting the travel distance on the sliding bracket of the upper plate can eliminate this movement.

Under the folding conditions with both brackets sliding, the strain-to-failure and ultimate tensile strength as measured by the m-SFT decreased by ~18% when subject to 5500 cycles (see Table 1). The modulus and fiber diameter were unchanged.

4 Conclusions

The device as designed can consistently fold woven fabrics and yarns in a manner useful for test measurements. After the cyclic folding of the woven fabric using this device, the tensile strain and strength of the fibers collected from the folded woven fabric showed an 18% reduction compared to the nonfolded fibers. Although slight modifications are needed to control the damage that may occur to the fibers due to frictional sliding on the folding rod, the folding device introduces a controlled damage region in the fiber that can be quantitatively assessed by the modified single fiber tensile test. More testing is planned to determine the optimum and relevant testing conditions required to simulate the impact of mechanical folding over a period of 5–10 years of use. Further tests are underway to quantify the mechanism of mechanical degradation.

Table 1 Effect of repeated folding (5500 cycles) on woven fabrics composted of poly(benzoxazole) fibers

Fiber properties	Control (NF_14)	Folded (FF_15)	ANOVA statistics for 95% confidence level	
			F	F_{crit}
Fiber diameter (μm)	13.14±0.67	13.24±0.27	0.276	4.210
Modulus (GPa)	145±11	144±10	0.122	4.210
Strain-to-failure	3.14±0.26	2.59±0.54	12.364	4.210
UTS (GPa)	3.54±0.23	290±0.49	19.884	4.210

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