AN APPARATUS FOR FOLDING YARNS AND WOVEN FABRICS OF BALLISTIC FIBERS

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ABSTRACT

Folding of ballistic fibers comprising soft body armor may be a factor in the performance deterioration that has been observed in used soft body armor. To quantify the impact of this mechanism, an apparatus was designed and built to simulate the folding that may occur to the ballistic fibers while the vest is in use. The device systematically folds woven fabric and yarns of ballistic fibers to assess the impact of folding on ballistic fiber properties. Initial test results indicate that the device does repeatedly fold a piece of woven fabric at the same location. After cycling a piece of woven poly(benzoxazole) (PBO) fabric for 5,500 cycles, a 14 % reduction in the ultimate tensile strength and strain to failure of the PBO fibers was observed. Research is continuing to optimize the testing procedure. It is anticipated that this device will be a useful tool in understanding how ballistic fibers degrade.

KEY WORDS: Aging/Service Life

1. INTRODUCTION

It has been suggested that folding of the ballistic fibers comprising soft body armor may be a factor in the performance deterioration observed in used soft body armor. In an attempt to quantify the impact of this mechanism, an apparatus 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 Standards (NIST-OLES) under the auspices of the National Institute of Justice (NIJ). One of the objectives of this research program is to develop relevant and non-destructive 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 apparatus described in this report was designed to fold individual yarns and single and multiple layers of woven fabrics of ballistic fibers by using servo-hydraulic 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 servo-hydraulic 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 ballistic impact on fiber properties is decoupled from the vest construction parameter of 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 $(U^*)^{1/3}$ of equation 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].

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

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 the above equation. 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 will 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 Figure 1). The two adjoined poster boards were then folded together. 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 Figure 2. To ascertain the impact of this damage on the mechanical properties of the fiber, 50 folded and 50 non-folded virgin PBO fibers were tested randomly using the *m*-SFT.

Fiber diameters were measured on each specimen using an optical micrometer (Excel Technologies Inc., Model VIA-100) [7] attached to a Nikon Optiphot-POL microscope equipped with a video camera (Optronix LX-450 RGB Remote Head microscope camera). The standard uncertainty in the measurement of fiber diameters is 0.4 µm. 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 gauge length. The five individual diameter measurements were averaged for each fiber sample. The average fiber diameters from the folded specimens was found to be (12.6 ± 0.5) µm and those of the non-folded specimens (12.5 ± 0.5) µm. The folded and non-folded 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 strengths of the folded virgin PBO fiber were reduced by approximately 10 % relative to the non-folded fibers ($p = 0.011$, 0.004 respectively). Histograms depicting the shifts in the distributions are shown in Figure 3. In contrast to previous results on worn vests, the modulus of the virgin fiber was also found to decrease by 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 Apparatus Design and Operation The design was motivated by the desire to use the controlled fatigue testing features inherent in most servo-hydraulic test machines. To minimize damage to the servo-hydraulic machine by the apparatus, the device was designed to fit on a 250 kN (55 kip) Model 810.25 MTS machine equipped with a 158.5 mm (6.25 in) diameter piston rod. To convert the precise linear motion of the servo-hydraulic machine to precise rotational motion, a bracket was fitted to the piston rod that contained a spur gear and rack as shown in Figure 4.

To effect the folding of the ballistic fiber material, a two-piece clamshell design is employed (see Figure 5). To minimize mass, most of the apparatus is constructed using aluminum, except where otherwise specified. The lower plate is connected to a platform that attached to the servo-hydraulic machine through the column mounting brackets. Interchangeable folding rods were constructed out of stainless steel and attached to this plate. The upper plate is attached to a stainless steel rod that is turned at each end 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 shaft.

Each plate is equipped with Teflon sheets to minimize friction between the ballistic material and the plate surface. 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 stainless steel rods that attach to constant force springs obtained from Associated Spring Raymond (rods not shown in Figure 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 approximately 30 cm to 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 (8.5 inch) by 27.9 cm (11 inch) 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 gauge 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 55119). Prior to epoxy gluing, small strips (approximately 1.2 cm × 0.2 cm) of silver reflective tape (United Calibration Corp.) were applied to the template at the top and bottom of the gauge 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 #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 non-contact extensometers to detect gauge 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 gauges or mechanical extensometers. Consistent with this recommendation, a United Calibration Corporation Model EXT-62-LOE laser extensometer was used.

An initial gauge length of 5.1 cm or greater is required for optimum performance of the laser extensometer. Furthermore, because fiber strength is typically gauge length dependent, a specimen length reflective of the amount of material that may be deformed during ballistic action is probably necessary. Therefore, a gauge 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.

3. RESULTS AND DISCUSSIONS

To test the effectiveness of the device, a piece of woven fabric was attached to each sliding bracket and under the folding rod (see Figures 5 and 6). The apparatus was rotated through a 90^o angle as shown in Figure 7 and held at each end point for approximately 15 s. Marks, using a permanent marker, were made on the edge of the sample to monitor for movement of the folded region as the specimen was repeatedly folded for approximately 5,500 cycles. The folded region location remained constant throughout the test. However, in the open position (90^o) ($\pi/2$ rad), the fabric moved 1 cm away from the folded region. Analysis of the motion of the apparatus 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 approximately 14 % when subjected to 5,500 cycles (see Table 1). The modulus and fiber diameter were unchanged, which suggests a 10 % reduction in the ballistic resistance of the fiber as calculated through equation 1.

4. CONCLUSIONS

The apparatus as designed can consistently fold woven fabrics and yarns. Slight modifications are needed to control the damage that can occur to the fibers due to frictional sliding on the folding rod. 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 to 10) years of use. Further tests are underway to quantify the mechanism of mechanical degradation.

5. ACKNOWLEDGEMENT

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7. Certain equipment, instruments or materials are identified in this paper in order to adequately specify the experimental details. Such identification does not imply recommendation by the National Institute of Standards and Technology nor does it imply the materials are necessarily the best available for the purpose.

Table 1.

Effect of Repeated Folding (5,500 cycles) on woven fabrics composed of poly(benzoxazole) fibers

Fiber Properties	Control (NF_47)	Folded (FF_50)	ANOVA Statistics for 95 % Confidence	
			F	F_{Crit}
Fiber Diameter, μm	13.06 ± 0.34	13.00 ± 0.26	0.295	3.941
Modulus, GPa	143 ± 98	146 ± 85	2.975	3.941
Strain-to-Failure, %	2.90 ± 0.25	2.50 ± 0.21	28.480	3.941
UTS,GPa	3.36 ± 0.14	2.90 ± 0.18	32.447	3.941

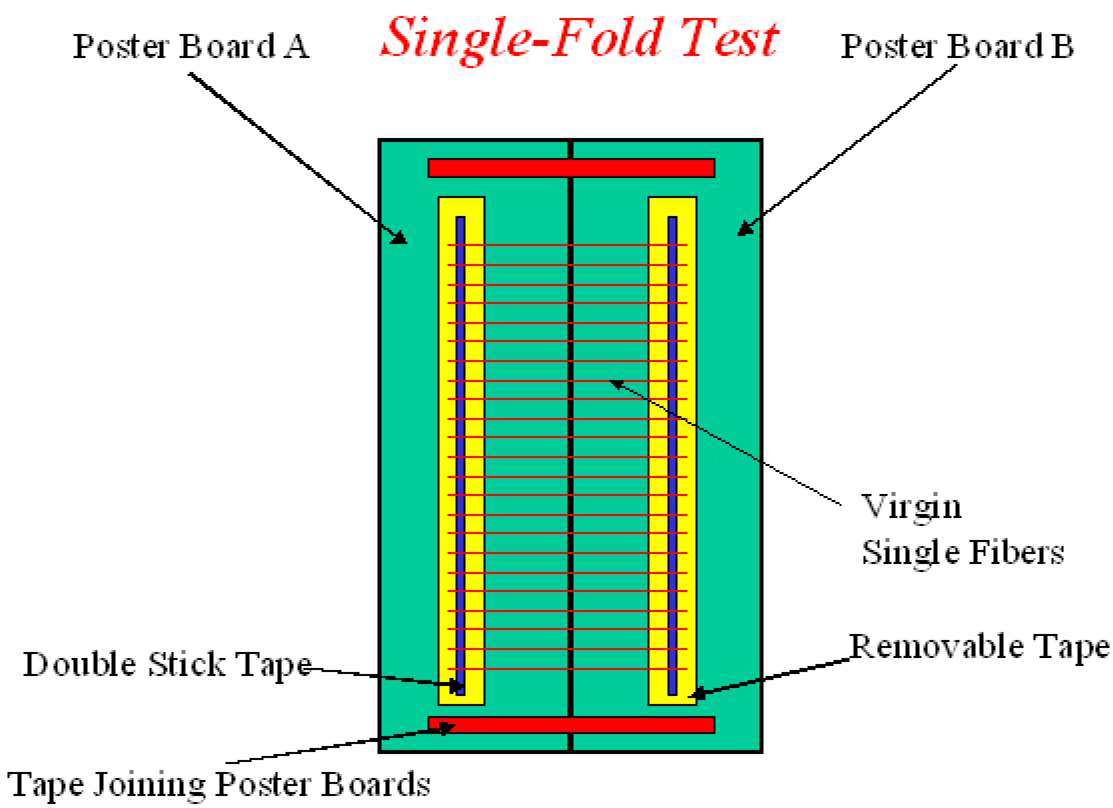

Figure 1. Pictorial representation of single fibers stretched across two adjoining pieces of poster board.

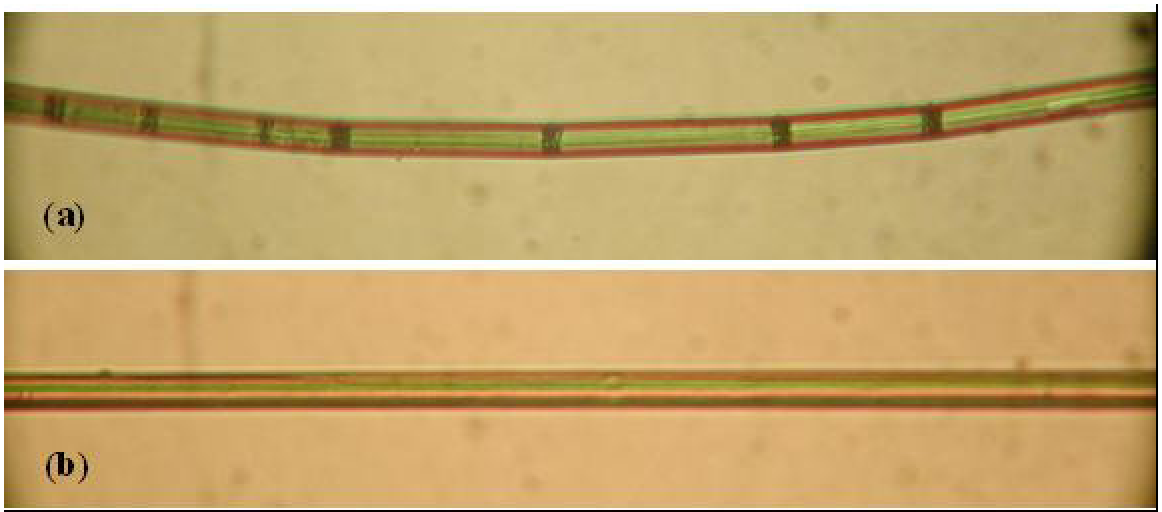

Figure 2. (a) Damage induced by single fold of PBO fiber. (b) non-folded virgin PBO fiber.

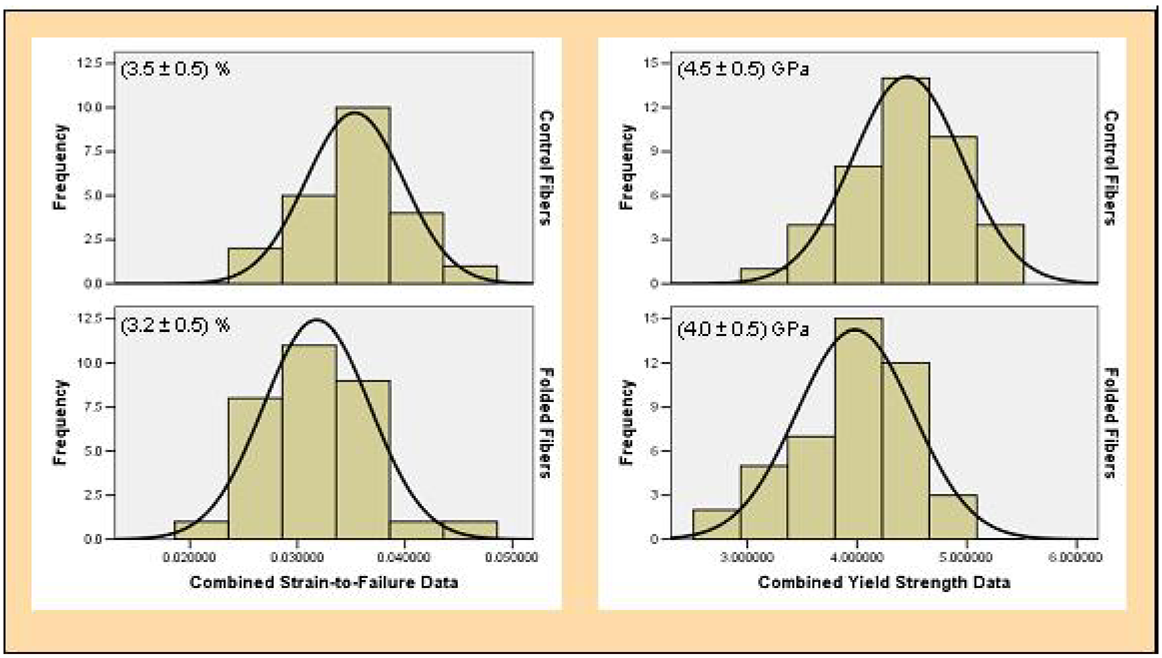

Figure 3. Histograms showing the change in Strain-to-Failure and Ultimate Tensile Strength of virgin PBO fibers caused by the single-fold test.

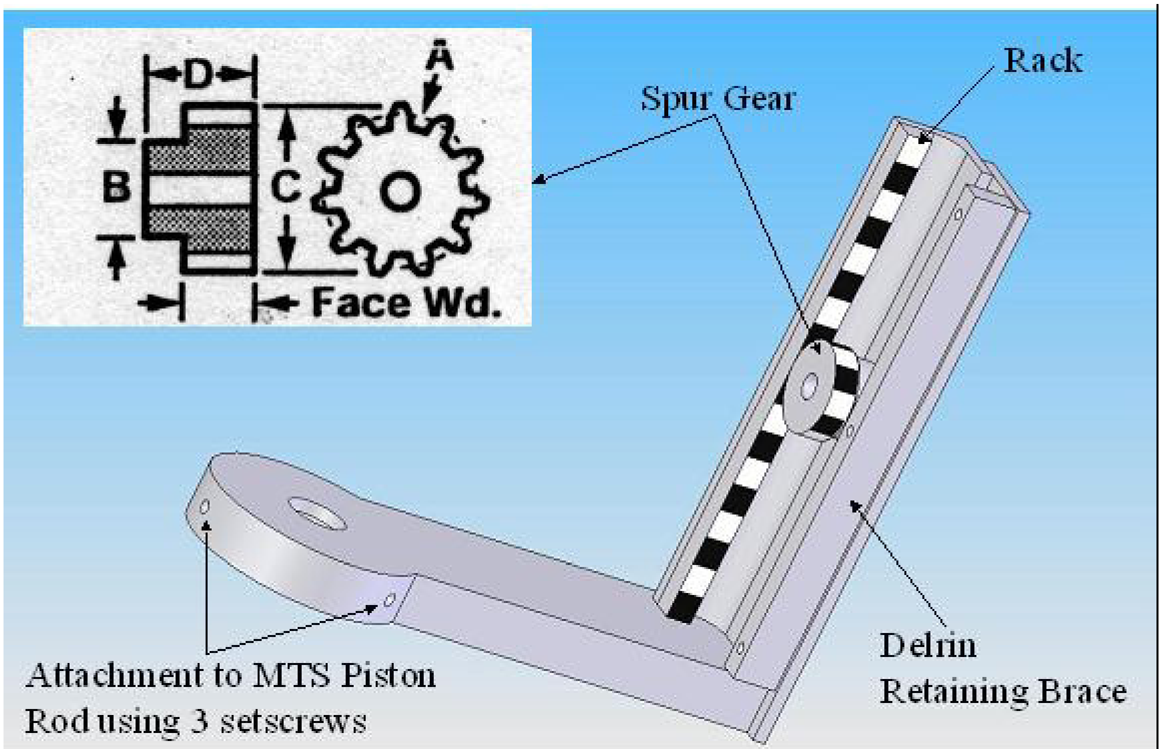

Figure 4. Piston rod bracket for converting linear motion of MTS 810.25 servo-hydraulic machine into rotational motion. Insert shows schematics of spur gear with detailed specifications given in the text.

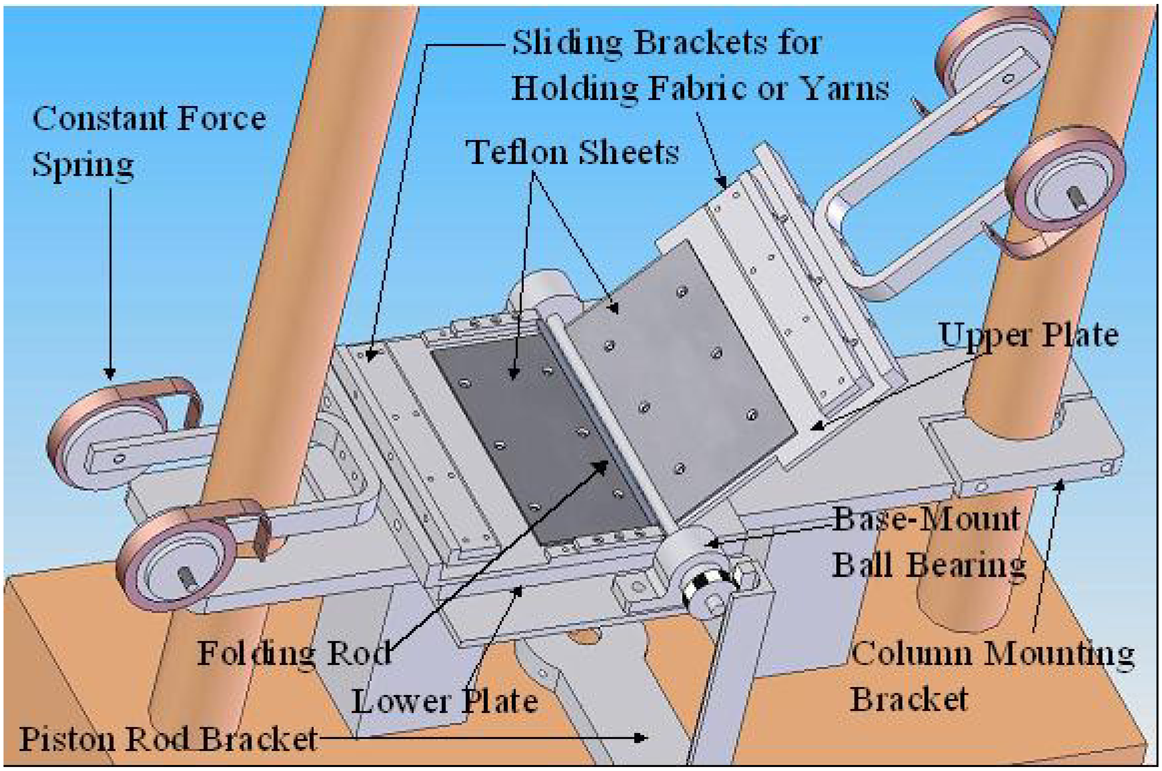

Figure 5. Basic design of the folding apparatus attached to servo-hydraulic machine. Constant force springs attach to sliding brackets using stainless steel rods (not shown). Note: Delrin brace on piston rod bracket removed to better show clamshell design.

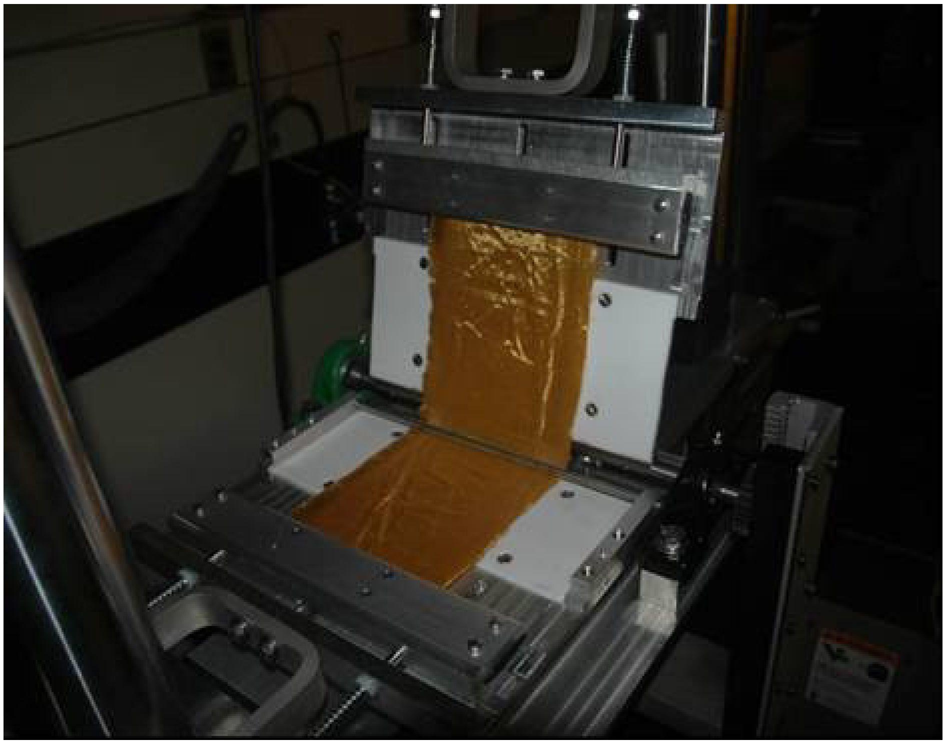

Figure 6: Folding apparatus with fabric clamped in the sliding brackets and around the folding rod.

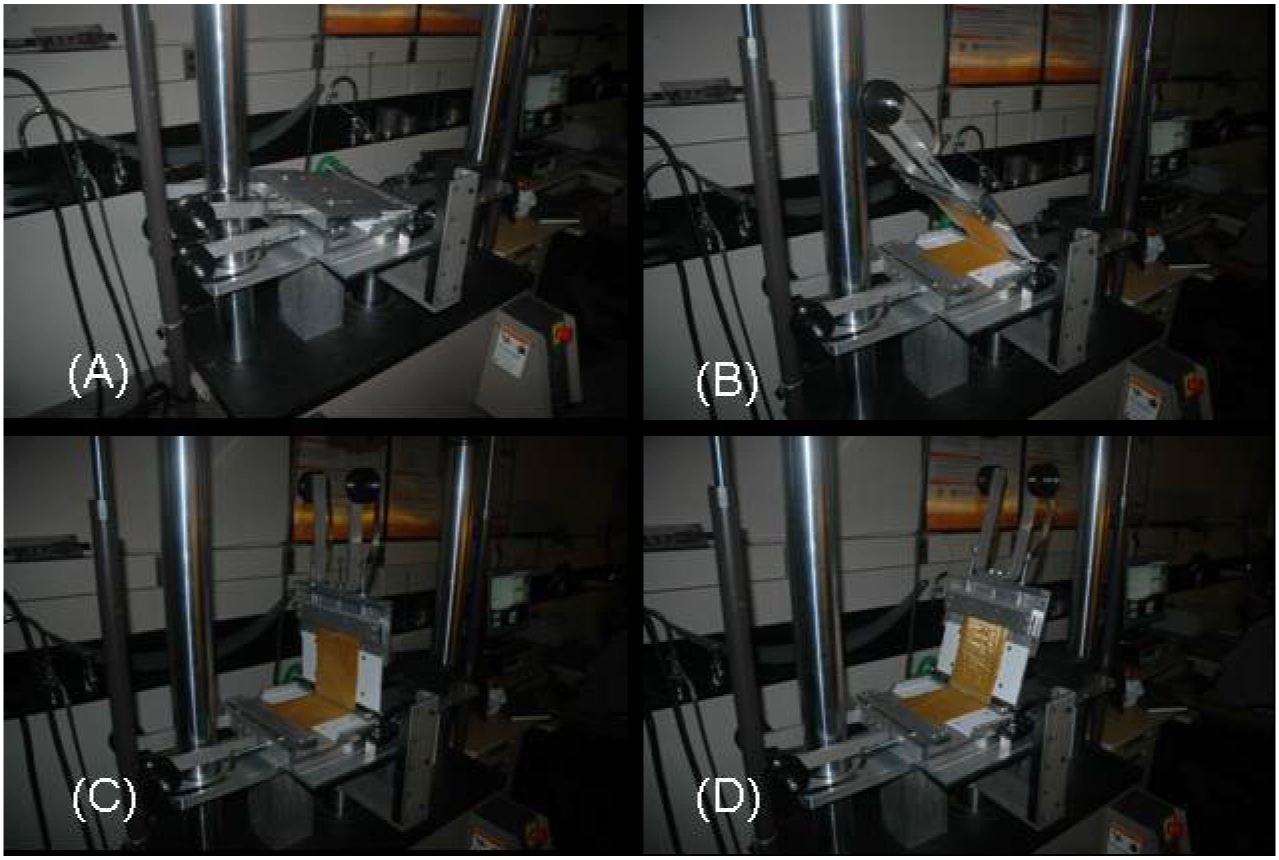

Figure 7: Images showing the fabric as it goes from a closed position (A) to the fully open position (D).