

# Aging Effects on the Dynamic Tensile Response of Zylon Fibers

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## ABSTRACT

As an important class of shock-mitigating materials, high-performance polymeric fabrics have been widely used in soft body armor and other attack resistance systems. Because these materials are used in personnel protection applications, there is an urgent need to develop a better scientific understanding of the mechanical response of these fabrics. The starting point for studying the soft body armor performance is to investigate the individual fibers used in making the fabrics. In particular, the effect of aging on the single fiber's mechanical response under dynamic loading needs to be understood. In this research, we have investigated the dynamic mechanical response of single fibers that have been aged by exposures to elevated temperature and high moisture levels prior to testing with a modified split Hopkinson tension bar. The dynamic failure strength of aged single fibers is reported.

## Introduction

High performance polymeric fibers, woven into fabric, are used in soft body armor. There are different types of fibers used for these purposes. The fibers studied in this report are the Zylon<sup>\*</sup> fibers, or poly(p-phenylene-2,6-benzobisoxazole) (PBO). The light weight, high strength, and high strain-to-failure of the Zylon material make these fibers attractive for fabrics used in vests and other protective devices worn by law enforcement officers. There is always a serious trade-off between flexibility/weight and attack protection. Even though a heavy vest may provide more protection in some instances, the added weight and lack of flexibility can limit motion in critical situations and thereby actually increase risk from attack. Therefore, it is important to make vests from strong, flexible, and light-weight fabrics. In developing products and setting standards for soft body armor, it is important to understand the effects of high rate loading such as those induced by a bullet impact. The effects of aging on the fabric/fibers are also of critical concern because often the body armor vests are exposed to elevated temperatures and high humidity during normal use. The purpose of the current work is to assess the effects of various aging conditions on the dynamic performance of the Zylon fibers.

Body armor vests that have been in service for several years have experienced aging, of course, but they have also experienced handling and flexing that contribute to degradation of performance. The effects of bending and mechanical damage have been investigated: for example, Forster, et al, report work focusing on the mechanical damage of PBO fibers [1]. The current work is directed at the aging due to environmental conditions independent of the mechanical damage.

The modeling of the performance of actual fabrics or complete vests is an extremely difficult problem. A photo of a vest fabric panel without the outer covering is shown in Figure 1, which illustrates some of the complexity that has to be handled in full models. An example of research into developing fabric models using the finite-element method is presented by Lim, et al [2]. The modeling of the fabric depends on parameters such as the friction between the fibers that are spun into yarns. Also, the friction between yarns and the weaving pattern must be considered in realistic modeling of body armor fabrics. These materials are neither isotropic nor homogenous, and strain rate effects are important. However, all modeling also depends on

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<sup>\*</sup> Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

the strength of single fibers and therefore the current work is a starting point that will eventually aid in the development of the more complex models of real vests in the future.

The strength of single fibers can be tested by pulling in a conventional tension testing machine. An example of this type of test is the method described in ASTM D3379-75 and discussed in the SEM Monograph: Experimental Mechanics of Fiber Reinforced Composite Materials [3]. The fiber is mounted in a tab which assists in loading the fiber into the jaws of the tension machine and then the tab is slit carefully prior to applying the tension load. In this testing method the load is typically applied to maintain a strain rate on the order of  $1 \times 10^{-3}$  per second. The tension test performed with the modified Hopkinson bar used in the current work allows a much higher strain rate, approximately 500 per second. The higher strain rate is considered because the vests must be designed to withstand high strain rate events like a bullet impact.

## Fiber Aging

The single fibers were extracted from commercial, non-deployed, body armor fabric manufactured for this study. The fabric was a ballistic panel constructed from 20 layers of woven PBO fabric stacked and diagonally stitched together, inserted in a water vapor-permeable fabric liner, and placed in a cotton fabric carrier. Twenty-four ballistic panels enclosed in liners and carriers were aged in a Cincinnati Sub-Zero Z32 environmental chamber at 50 °C and 60 % relative humidity (RH) for 84 days and then at 60 °C and 37 % RH for an additional 73 days. The increase in temperature to 60 °C and decrease in relative humidity to 37 % were intended to accelerate the kinetics of fiber degradation by increasing the temperature while maintaining the same absolute water content in the environment.

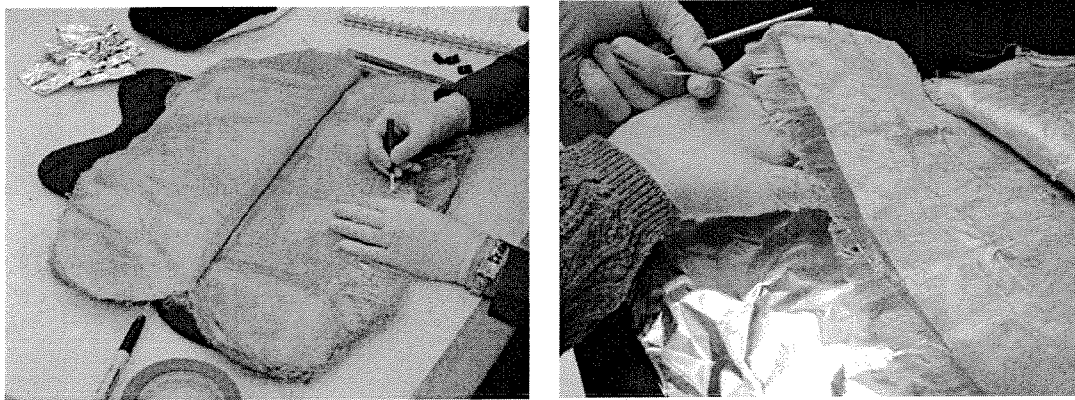


Figure 1. (a) Photo of ballistic fabric used in a soft body armor. The soft body armor fabric is woven from yarns made of many fibers. (b) Individual yarn being extracted from fabric, that is then separated in to single fibers.

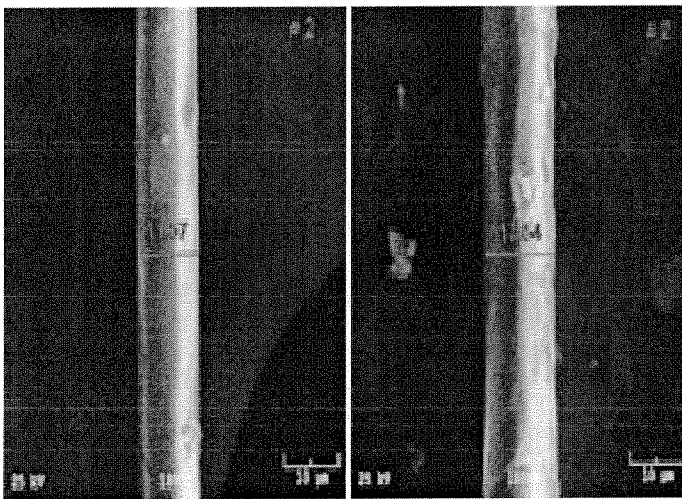


Figure 2. SEM measurements of fiber diameters. Two different locations on the same fiber are shown. Mean diameter was used for the stress calculations. Fiber diameters are shown in  $\mu\text{m}$ .

At each inspection time, 15 horizontally oriented yarns were extracted from four layers in two different ballistic panels, with two out of the four layers of each panel sampled every two weeks. The samples for dynamic testing in the work reported were taken from these samples and identified by the date of extraction. Dynamic testing was not done with samples from all fiber extractions, only those dates reported. Seams were cut from the bottom 5 cm to 6 cm of the ballistic panel to free the layers. As shown in Figure 1, individual yarns were loosened and extracted one-by-one from the lower half of the layer using a small hook, and taped down on cleaned aluminum foil-wrapped cardboard holders. Each yarn was labeled with panel number, layer number, yarn number, and extraction date. Nitrile gloves were worn throughout the entire procedure to prevent contamination of the yarns. Single fibers for dynamic testing using the split Hopkinson bar were extracted from these yarns. Additional information related to the handling of the fibers and the aging process is presented by Chin [4].

## Fiber Diameter Measurements

To calculate the stress produced by the loading of the fibers, it is necessary to measure the diameter of the fibers. In preliminary studies it was determined that the fibers tend to vary in diameter, even within one batch, so for this project a sample of each of the fibers tested was retained for measurement by imaging the sample in a scanning electron microscope (SEM). An example of this measurement approach is shown in Figure 2. The SEM images show the texture of the actual fibers and the indicator bars show a typical diameter measurement. Shown in Figure 2 are two different locations on the same fiber, which indicates there was considerable variation within each fiber. As much as 20 % variation in fiber diameter within one fiber was noted during these measurements.

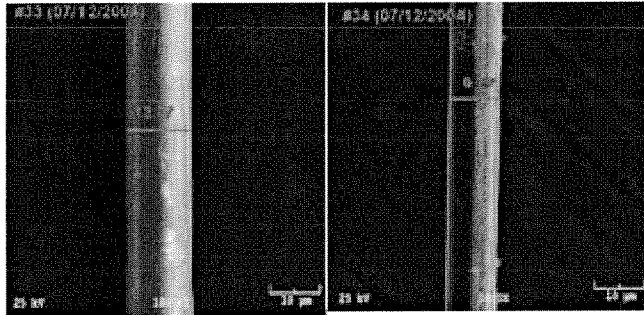


Figure 3. Diameter (shown in  $\mu\text{m}$ ) and surface quality vary between fibers in a batch with the same manufacturing date.

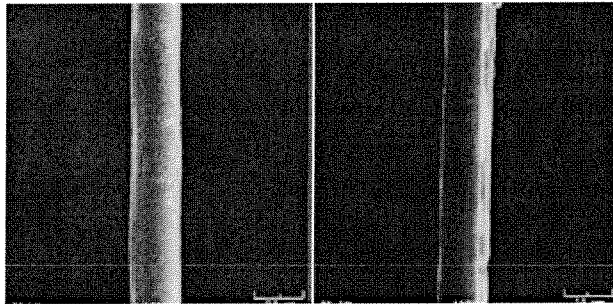


Figure 4. Fibers may vary in quality at different locations on the same fiber.

Figure 3 illustrates the variation of fibers from the same batch, i.e., extracted from the vest fabric on the same day. Figure 4 illustrates that there was obvious variation in the quality of the fibers even within the same fiber.

The resolution of the fiber diameter measurement using the SEM techniques is estimated as approximately  $0.02 \mu\text{m}$ . The variation in fiber diameters used in this study was as much as  $4 \mu\text{m}$ , or on the order of 35 %. The maximum diameter variation with a single fiber was approximately 20 %. For the stress calculation the readings of a single fiber were averaged, but using the maximum and minimum diameter of a single fiber could result in a variation of up to 40 % in the stress calculation.

## Split Hopkinson Bar Apparatus for Tension Testing Single Fibers

A common method for obtaining dynamic stress-strain curves for metals and other engineering materials is referred to as the split Hopkinson pressure bar (SHPB). The traditional SHPB, also called a Kolsky bar, consists of two long bars with the sample installed between the bars. A compression or tension pulse is started by impacting the end of the first bar and the strain wave is transmitted through the sample to the second bar. Strain gages on the first bar record the time history of the incident and

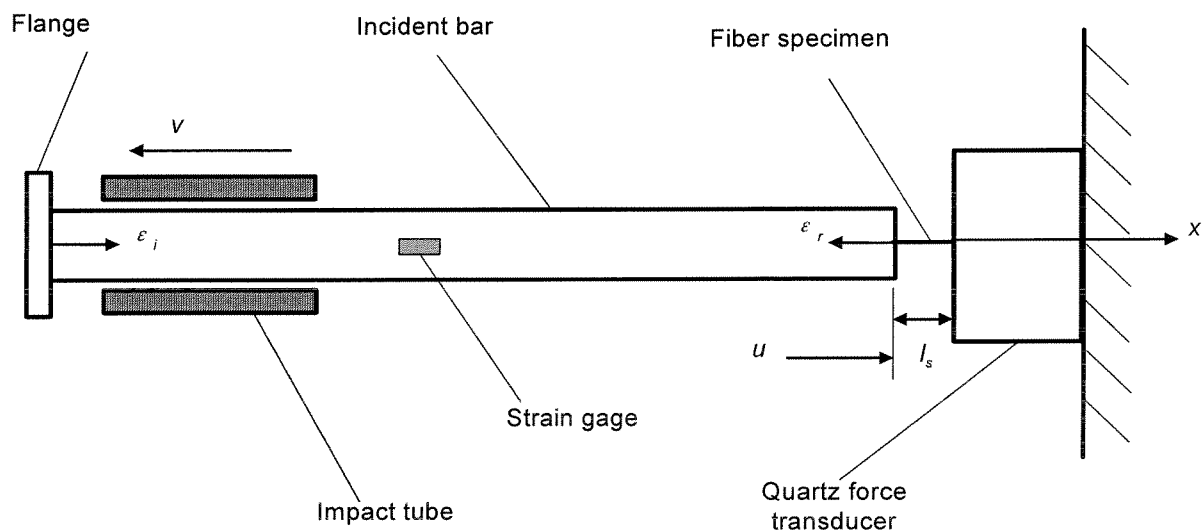


Figure 5. Modified Split Hopkinson Tension Bar for testing single fibers.

reflected pulses and the strain gages on the second bar record the transmitted pulse. The reflected pulse is proportional to the strain rate imposed on the sample and the transmitted pulse is proportional to the stress in the sample. The theory and operational procedures of the traditional SHPB are presented in many references, for example, see Gray [5].

A special small Hopkinson bar was built for this project that can produce a very small tension pulse for testing the single fibers. The set-up is shown schematically in Figure 5. This mini-Hopkinson bar is based on the traditional split Hopkinson bar, but uses a load cell to replace the transmitter bar. To start a test the impact tube is pulled back against a spring (not shown) and then released. The tube then slides smoothly along the incident bar and impacts the flange starting a tension strain wave down the bar to the right. The strain gage, mounted in the center of the bar, records the incident pulse through a common Wheatstone bridge and digital oscilloscope. The tension wave loads the fiber up to the failure load and then reflects back down the incident bar to the left as a compression pulse. The strain gage records the reflected as well as the incident pulse, and the bar is long enough so that the signals are separated. The force is measured with a quartz force transducer and recorded as a force time history on a second recording channel of the oscilloscope. A typical strain gage and force transducer record is shown in Figure 6.

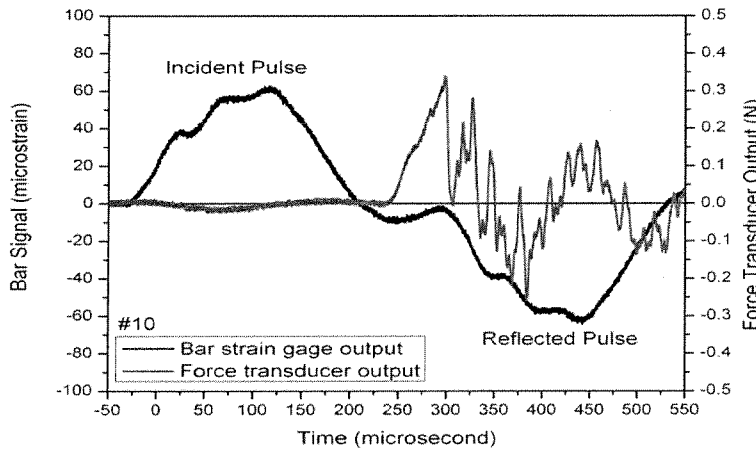


Figure 6. Typical output signals from the modified Hopkinson bar system.

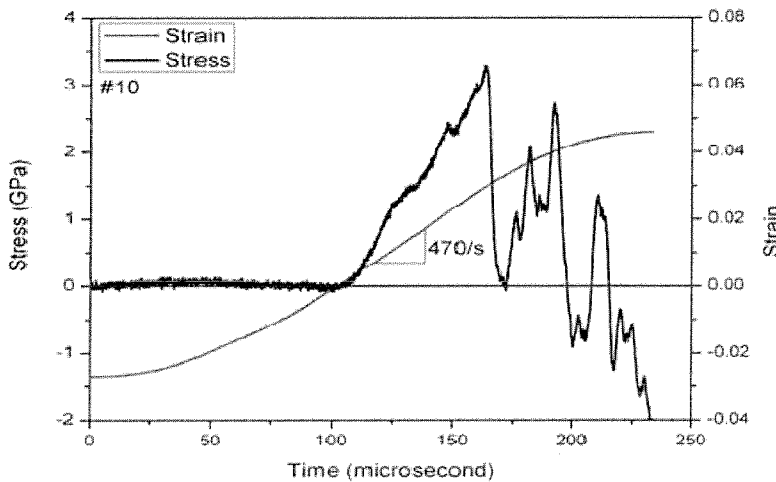


Figure 7. Typical stress and strain histories calculated from output signals. Negative strain is prior to tension pulse.

The procedure for testing the fibers in the mini tension Hopkinson bar was to glue a piece of the single fiber between the end of the incident bar and the force transducer. The adhesive used for this operation was ARAIDITE 2043.

The length of the fiber being tested was nominally 1.5 mm.

The strain in the fiber as a function of time,  $\varepsilon$ , is calculated from the formula:

$$\varepsilon = \int_0^t \frac{c_b}{l_s} (\varepsilon_i - \varepsilon_r) d\tau$$

Where  $c_b$  is the wave speed in the bar,  $l_s$  is the length of the fiber sample being tested,  $\varepsilon_i$  and  $\varepsilon_r$  are the incident and reflected strain gage readings indicating the strain in the bar.

The stress in the sample is calculated from:

$$\sigma = \frac{F_s}{A_s}$$

Where  $F_s$  is the force in the sample as a function of time recorded from the force transducer, and  $A_s$  is the cross sectional area of the fiber calculated using the measured diameter of a piece of the same fiber as being tested.

Typical stress and strain histories calculated using the formulas and the output signals are shown in Figure 7. The negative strain shown is related to the straightening of the fiber prior to the tension load. A resulting typical

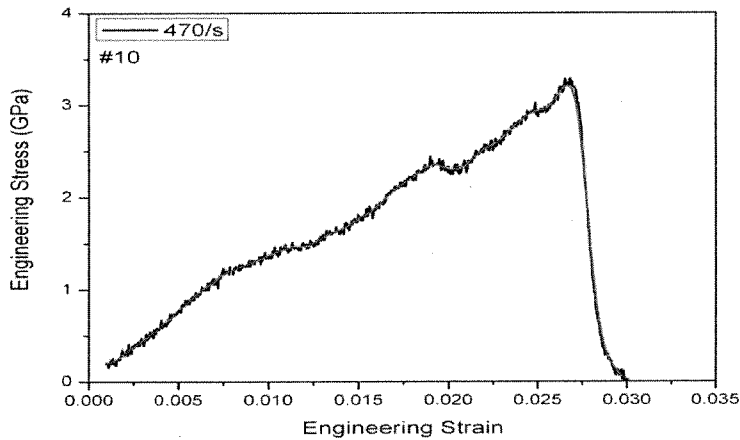


Figure 8. Typical stress-strain curve obtained from a single fiber experiment. The stress is calculated using the actual measured diameter. The peak stress is taken as the tensile strength.

stress-strain curve is shown in Figure 8. The peak stress, in this test shown as approximately 3.3 GPa, is reported as the tensile strength of the particular fiber being tested.

## Results and Discussion

The results of the series of dynamic tests on single fibers are presented in Figure 9. The fibers supplied that were not woven into the vest fabric, or virgin fibers (labeled reference), show a slightly higher tensile strength of approximately 4.4 GPa, averaged for the four tests. The fibers extracted from the vest before the start of the aging process (labeled 02/06/2004) show an average tensile strength of 3.2 GPa which might indicate the effect of the weaving process on the tensile strength of individual fibers. There is no obvious loss in tensile strength due to the aging. It appears that the fibers have as high a tensile strength after

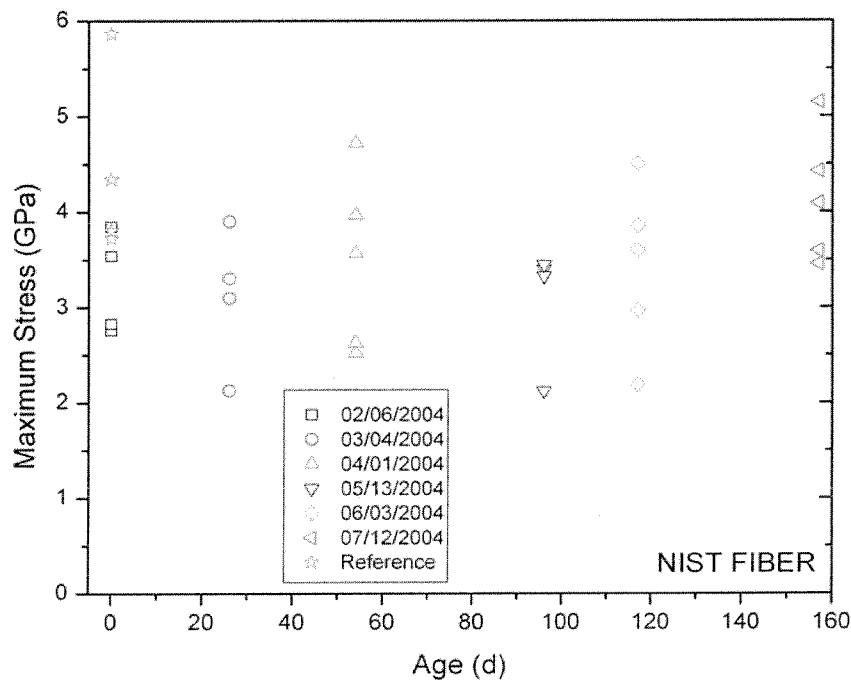


Figure 9. Summary of all tests of the aged single fibers. The date shown is when the fiber was removed from the vest in the aging environment. The "reference" data is from virgin fibers that had not been woven into fabric.

160 days as they did at the beginning of the aging process. However, other studies by Chin, et al [4] do show loss in tensile strength when testing with very low strain rate, or quasi-static loading, on aged fibers from this same experiment. The fact that the dynamic tests do not show loss in strength with aging may be due to other differences in the test methods; for example, the quasi-static tests were done with a much longer gage length. There may be differences in how the material responds under the high strain rate loading that contributes to the differences in dynamic strength versus the quasi-static loading. Also, the degree of variation in each test series for the dynamic tests is high; for example, the five individual tests for the 04/01/2004 fibers show a range from about 2.5 GPa to 3.8 GPa. Variations in diameter in a single fiber and fiber surface defects might account for this spread in test results.

## Conclusions

Single fiber testing is a vital step in understanding the overall performance of soft body armor. The dynamic loading of the fibers in this work was achieved using a modified Hopkinson bar that provides high strain rate loading for simulating the high rates associated with bullet impacts in fabrics. The dynamic testing of aged fibers extracted from a vest indicates there will be some loss in strength after a fiber is woven into a vest as compared to a virgin fiber, possibly from mechanical damage, although there is no trend noted for change in tensile strength with aging shown by our dynamic test data. The tensile strength measured in the dynamic tests of the aged fibers is between 2 GPa and 4 GPa. Future work will be directed at improving the understanding of the large variation in the dynamic breaking strength of the Zylon fibers and the differences between quasi-static and dynamic results. There is a need for advanced modeling techniques to quantify the effect of fiber strength variations in the actual armor performance.

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