STRAIN RATE EFFECT ON SINGLE PPTA FIBER TENSILE BEHAVIOR

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1 General Introduction

Soft body armor has effectively protected several thousand law enforcement officers against ballistic impact over years since the 1980s. The ballistic performance of soft body armor depends on multiple factors, such as the structure of the woven fabrics, speed and geometry of projectiles, and material properties [1]. High-strength and high-modulus polymer fibers such as PPTA (poly(p-phenylene terephthalamide) are widely used in soft body armor. When the fibers in the body armor are impacted, they experience a sharp stress increment, the magnitude of which is related to the impact velocity at the contact region of the projectile and fibers. Cunniff [1] modelled ballistic impact as the product of the specific fiber toughness multiplied by fiber sonic velocity to explain the material contribution to ballistic performance. In contrast to actual ballistic application of the high strength fibers, mechanical properties of fibers used in soft body armors are often obtained by test conditions at slower deformation rates (i.e. quasi-static) than at the high strain rate (HSR) deformation incurred during ballistic impact.

In order to study HSR deformation of materials, the split Hopkinson bar (or Kolsky bar) which has been widely used in compression and tensile loading for materials, is used [2]. A tension Kolsky bar has been utilized for testing aramid yarns at \( \approx 450 \text{ s}^{-1} \) by clamping a yarn specimen [3]. In addition, single fiber tests within a range of (1400 to 2500) \text{s}^{-1} were conducted by gluing a single fiber on the Kolsky bar [4]. Since testing under HSR loading condition requires a relatively short sample aspect ratio (< 200 [4]), gluing a fiber can be problematic due to possible adhesive wicking into the fiber gauge length [5]. Furthermore, tensile properties of a single fiber exhibit high variation and statistical analysis of fiber data is rarely reported when less than 30 fibers have been tested. 50 specimens is known to be acceptable [6]. Therefore, a gripping method to avoid adhesive wicking and increase test throughput is desirable. A comparison study of the glue and direct gripping methods performed under quasi-static loading conditions clearly showed that the direct grip method produces more reproducible results in particularly short fibers (aspect ratio <1000). Consequently, a direct gripping method was applied to the HSR test to minimize the disadvantages of the glue method and to better facilitate the statistical analysis of the fiber strengths [7].

In this study¹, single PPTA fibers with various gauge lengths were tested using the Kolsky bar to investigate strain rate effects on tensile strengths, moduli and failure strains. PMMA (polymethyl methacrylate) and rubber as gripping materials were used for clamping a fiber, and the effects of the gripping materials on the fiber tensile properties are investigated.

2 Experiments

2.1 Tensile tests under quasi-static and high strain rate loading conditions

Tensile tests on single PPTA fibers have been carried out under quasi-static and HSR loading conditions. Prior to the tests, diameters for individual single fibers were measured by an imaging system with a CCD camera and 60 x optical microscope. Each average diameter for a single fiber

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was obtained by measuring five diameter measurements across evenly distributed spaces.

For testing under a quasi-static loading condition, a screw driven tensile test machine shown in Fig. 1 is used. The procedure for the quasi-static tensile test was as follows: a single PPTA fiber was clamped between the blocks under a slight tension using a deadmass with clamp forces for the blocks controlled by a spring. The tensile tests were performed under a constant strain rate (0.00056 s⁻¹).

Fig. 1. Enlarged gripping area for the tensile test under quasi-static loading conditions. Note the top and bottom grips (PMMA) are both in open positions.

For the tensile test under HSR loading, a miniature Kolsky bar was used in conjunction with the direct gripping device (Fig. 2). Prior to the HSR test, a single PPTA fiber was temporarily adhered to a plastic template with slight tension (0.001 N). The specimen was placed on the clamp area and only the fiber section of the specimen was clamped by tightening screws under a constant torque. After setting up the specimen on the grips of the Kolsky bar, the impact of a tubular projectile on the flange area of the incident bar generated a loading pulse that deforms the fiber at high strain rate. Since the wave signal transferred through the fiber is extremely small, a quartz-piezoelectric load cell with a capacity of 22.24 N (5 lbf) was used to detect tensile load at a failure [4]. The estimated uncertainty of the load cell obtained from the manufacturer was ± 1%.

Fig. 2. Schematic (a) and photos (b) of the Kolsky bar set-up and gripping device for single fiber tensile test under high strain rate test

In order to measure tensile strains of the single fibers for the Kolsky bar test, a laser system was used to measure the displacement of the grip on the incident bar as shown in Fig. 2. Detailed information on the laser system is provided elsewhere [8]. A 100 mW laser with 658 nm wavelength was used as the source laser. A thin laser
line generated by a Powell lens\(^2\) illuminated the target that was attached to the gripping area of the Kolsky bar, and the laser intensity was measured by a photo detector. The laser intensity being detected at the photo detector increased as the displacement of the Kolsky bar increased. Calibration for the bar displacement and the laser intensity was performed by measuring the grip positions under a microscope and the voltage outputs of the photo detector.

All signal acquisitions from the dynamic load cell and the laser signal for the HSR test were recorded by a high speed data acquisition system with a resolution of one microsecond.

3. Statistical analyses

3.1 Nonparametric analyses

Data distributions are often graphically illustrated by a histogram. However, where there is insufficient data, a histogram can misrepresent the true distribution of the data. A histogram is a kernel density estimate computed at the mid-points of the bins, with fixed bin width and a boxcar function [9]. A kernel density plot can be regarded as a smoothed histogram as shown in Fig.3. Kernel density plots for fiber tensile properties are used here to illustrate and estimate data distributions.

![Fig.3. Schematics of histogram and kernel density plot](image)

The quantile-quantile plot shown in Fig.4 is a graphical technique that is used to determine whether two data sets come from a common distribution. The quantiles of the first data set are plotted against the corresponding quantiles of the second data and compared with a 45° reference line. Departure from this 45° reference line indicates a different underlying distribution [10].

![Fig.4. Schematic of quantile-quantile plot](image)

2.2.2 Parametric analyses

The analysis of experimentally generated strength data with the Weibull distribution is a common approach to modeling strength variability. Under the Weibull model, a fiber is regarded as an assembly of chain units, where each unit has length \(L_0\), and a characteristic failure stress \(\sigma_0\). If the failure probability of one unit is \(P(\sigma_0)\), then the survival probability of a chain at \(\sigma_0\) is \(1-P(\sigma_0)\). The failure probability of the entire chain at \(\sigma_0\), assuming each unit is independent of the others, would be \(1-[1-P(\sigma_0)]^N\), and the cumulative failure probability for large numbers of chain units ( \(N \rightarrow \infty\) ) becomes \(1-\exp(-N\cdot P(\sigma_0))\).

Since \(N\) is proportional to the length, \(L\), of the fiber, the Weibull cumulative distribution function is given by:

\[ F(x) = 1 - \exp\left( -\frac{L}{L_0} \left( \frac{x}{\gamma} \right)^\beta \right) \] (1)

\(^2\) 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 necessarily imply that the product is the best available for the purpose.
where \( x \) is the strength obtained by a test, and the constants \( \gamma \) and \( \beta \) are the scale and shape parameters respectively. In this parameterization, \( L \) is the gauge length at which the fibers are tested, and \( L_0 \) is the reference length (\( L_0 = 1 \) mm here).

Stoner et al. [6] conducted a statistical analysis which indicated that tensile test data below 40 mm can be influenced by end effects. Since the fiber must survive both end effects and the true flaw population at a given stress level prior to failure, the total probability of survival can then modeled by another extension of the Weibull distribution. A cumulative Weibull-like distribution for fiber tensile strengths including the influence of end effects can be expressed by:

\[
F(x) = 1 - \exp\left(-\frac{L}{L_0} \left(\frac{x}{\gamma_1}\right)^\beta_1 - \left(\frac{x}{\gamma_2}\right)^\beta_2 \right) \] (3)

While Weibull type distributions address fiber size effect on strength, the normal (Gaussian) distribution is often used to analyze material fracture involving no size effect [14], or failure strain when eliminating the effect of the fiber diameter in the statistical analysis of the material fracture [15]. Since a primary objective of this study is to determine the underlying distribution for the fiber strengths and failure strains measured by two different gripping methods, normal distribution fits are also tested here. The normal probability density function \( f(x) \) is

\[
f(x) = \frac{1}{\sigma \sqrt{2\pi}} \exp\left(-\frac{(x - \mu)^2}{2\sigma^2}\right) \] (4)

where \( \mu \) is the mean (location parameter), and \( \sigma \), the standard deviation (scale parameter).

3 Results and Discussions

3.1. Tensile behaviors for the PMMA and rubber grip tests at quasi-static loading

Typically as fiber length decreases, the influence of the gripping effects increases [16], so that the respective load-displacement curves for the 2 mm and 60 mm fibers are compared to investigate the gripping effects during the tensile tests. Fig.5 shows load-displacement curves for 2 mm and 60 mm single PPTA fibers obtained by the PMMA and rubber grips under a quasi-static loading condition. Load-displacement curves for both grip tests with 60 mm fibers are almost linear until fiber rupture. Comparing with the load-displacement curves of 60 mm, the slope of the load-displacement curves for the 2 mm tests did not show significantly different behaviors for both grip tests.
Fig. 5 Load-Displacement curves of the single fibers for the PMMA (a, b) and rubber grip (c, d) tests under quasi-static loading condition. Note: some load-displacement signals were automatically truncated.

3.2 The calibration curve for measuring displacements of the Kolsky bar at HSR loading

Fig. 6 shows the laser-set up for measuring the displacement of the Kolsky bar. Fig. 6 (a) briefly illustrates how the laser system measures the bar displacement. As the Kolsky bar moves in tension mode, the length of the laser line blocked by the target increases. The linear calibration curve between the laser output and displacement is shown in Fig. 6 (b). The coefficients of variation of the laser output on each position varied from 0.0006 to 0.0012, which are extremely small as indicated by the small error bars in the graph.

3.3 Tensile behaviors for the PMMA and rubber grip tests at HSR loading

Fig. 7 shows typical signals for strain wave history, bar displacement, and tensile behavior of a single fiber under a high strain rate test. The experiment shown in Fig. 7 was conducted with a gauge length of 2 mm at a strain rate of approximately 1000 s⁻¹, and the strain rate was obtained from the slope of the laser displacement-time curve and the fiber length. As shown in Fig. 7 (b), the output signal from the laser strain measurement system increases monotonically as the specimen is deformed.
3.4 Kernel density plots of the tensile strengths of single fibers

Fig. 8 shows kernel density plots for single fiber strengths for the PMMA grip test measured under the quasi-static loading condition. The kernel density plots for both grip tests display two peaks in strength distributions and the width of the kernel density plots for both grip tests is similar.

3.5 The quantile-quantile plot of the tensile strengths of single fibers

Fig. 9 shows a quantile-quantile plot for a 2 mm fiber tested using the PMMA and rubber grips under the quasi-static loading condition. The two strength quantiles are closely distributed along the 45° reference line. This lack of clear deviation from the comparison reference line indicates that two underlying strength distributions are similar to each other. This reconfirms the results of the kernel density plots.

3.6 Parametric statistical analysis of the tensile strengths of single fibers using the 2-parameter Weibull distribution

Typically, the 2-parameter Weibull distribution is used to analyze strength distributions for fibers, as mentioned above. To obtain the Weibull parameters and investigate the data distribution, the Weibull model is often fit in a double logarithm form which is often known to be a Weibull plot. Since other distributions are also used here, the probability plot is employed instead of the Weibull plot. Fig. 10 shows probability plots of the 2-parameter Weibull distribution for the strengths obtained by the PMMA and rubber grips with 2 mm fibers. The linearity of the probability plot demonstrates the goodness-of-fit for the data to the distribution. The probability plot correlation coefficient for the PMMA grip test was 0.981 and that of the rubber grip test was 0.978. Since the PCC values of the 2-parameter Weibull distribution were not higher than 0.99, a normal distribution was also fit to the data.
3.7 Parametric statistical analysis of the tensile strengths of single fibers using the normal distribution

Fig. 10 shows probability plots of the normal distribution for fiber strengths obtained by the PMMA and rubber grips with 2 mm fibers. The normal probability plot for the PMMA grip test exhibits a higher linearity than the Weibull distribution particularly in lower strength values, as confirmed by a higher PPCC, 0.993. The PPCC value of the normal distribution (0.987) for the rubber grip test is also higher than that of the Weibull distribution.

4 Conclusions

Single PPTA fiber tensile tests were carried out under quasi-static and high strain rate loading conditions using the PMMA and rubber grips. In the quasi-static tests, no significant difference for the load-displacement curves of the 2 mm and 60 mm fibers obtained by the PMMA and rubber grips was observed. Kernel density plot for the 2 mm fiber showed a slight bimodality in the strength distributions. In addition, fitting with normal distribution showed higher PPCC than the 2-parameter Weibull distribution.
References


