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by Brett Sanborn, Nicole Racine, and Tusit Weerasooriya

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14. ABSTRACT
Understanding the mechanical behavior of woven Kevlar fibers at high loading rates is needed to develop material models that mathematically represent the deformation and failure for computer codes that are being developed or used to simulate high–loading-rate events such as impact on fiber-based protective items. When fibers are woven into fabric, they may get damaged, thus reducing their strength. In order to understand the effect of weaving on the strength of Kevlar fabric, individual fibers from both the warp and weft directions must be studied. In this experimental study, the strengths of warp and weft fibers from plain-woven Kevlar KM2 fabric, as well as unwoven virgin fibers, are measured and compared to quantify any damage due to weaving. The fiber responses are evaluated at low, intermediate, and high strain rates, with 5-mm-gauge-length samples. Low- and intermediate-rate mechanical deformation experiments are conducted using the Bose ElectroForce test system, and the corresponding high-rate experiments are conducted using a split Hopkinson tension bar modified for fiber characterization. This report presents a comparison of strengths of woven fibers with that of unwoven fibers to determine the possible degradation of strength at different loading rates due to weaving.

15. SUBJECT TERMS
SHPB, Kevlar, weaving, single fiber

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1. Introduction

Kevlar* is an aramid fiber with highly oriented polymer chains produced from poly-paraphenylene (PPTA). Developed at DuPont† in 1965, Kevlar fibers are para-aramid, and are much stronger along the axial direction than in the transverse direction. Kevlar is a linear elastic, transversely isotropic, and homogeneous material (*1, 2*). As a high-performance fiber, Kevlar is widely used in flexible armors and other impact-resistant applications due to its high strength, light weight, and exceptional stability at high temperatures.

The high-rate properties of Kevlar have been studied previously by Cheng et al. (*3, 4*). They studied the material behavior in both longitudinal and transverse directions. For longitudinal experiments, Cheng et al. studied a wide strain-rate range that included high rates using a unique novel high rate experimental method, while transverse experiments were restricted only to low rates due to lack of transverse experimental techniques at high rates. They did not observe an increase in longitudinal strength at high strain rates. In a subsequent investigation, Lim et al. studied the effects of gage length, loading rates, and damage on the strength of PPTA fibers (*5*). Although Lim et al. analyzed the mechanical behavior of Kevlar, the type of weave was not specified.

The ability to determine mechanical properties of single fibers at different strain rates is important for high-fidelity simulation of fibrous bodies in composite laminates in vehicle armors because the strength of individual fibers in these systems at different loading rates influences the overall performance of the system. Individual fibers must retain their strength during the fabrication to fiber-based systems to fully disperse impact energy from projectiles in ballistic impact (*6*). When Kevlar fibers are woven into fabric, yarns running lengthwise in the warped direction are held in tension and crimped to accommodate for yarns running horizontally in the weft, or fill, direction that are weaving over and under the vertical yarns as shown in figure 1. During this weaving process, fibers may become damaged, reducing strength, thus reducing the full potential of the fabric-based armor systems. Therefore, quantifying the possible damage during the conversion of the virgin fiber to fabric will provide realistic values for the strength used in computer simulation of the impact on fiber based systems as well as develop methods to quantify this damage to fibers. This damage quantification will allow development of methods to reduce the damage to fibers during processing into fabrics. Studying the mechanical behavior of Kevlar fiber at various strain rates will ultimately lead to advancements in protective fibrous equipment.

* Kevlar is a registered trademark of E. I. DuPont de Nemours and Company, Wilmington, DE.
† DuPont is a registered trademark of E. I. DuPont de Nemours and Company, Wilmington, DE.

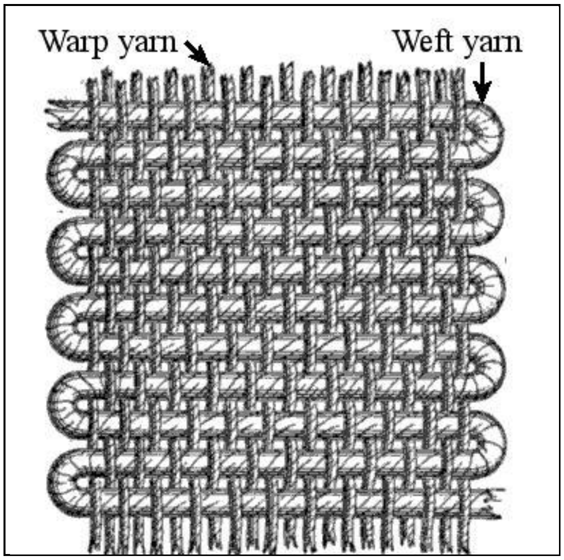

Figure 1. Warp and weft yarns directions in a woven fabric.

In this experimental study, the strengths of fibers from the warp and weft directions of Kevlar KM2 style 706, 600 denier fabric are measured and compared to the strength of unwoven fibers to quantify any damage due to plain weaving. The fiber responses are measured at a quasi-static rate of 0.001 s^{-1}, an intermediate rate of 1 s^{-1}, and a high rate of 1000 s^{-1}. Strength of the fiber varies with the gage length of the sample because with a longer gage lengths there is a greater possibility of the presence of critical defects associated with the failure within the gage length of the sample. In this study, a constant gage length of 5-mm samples was used. In a future study, the effect of gage length on the strength of fibers will be investigated. Comparison of strengths of woven fibers with that of unwoven fibers will enable us to quantify degradation of strength at different loading rates due to plain weaving.

2. Experimental Method

2.1 Materials

Single fibers from plain-woven, style 706 Kevlar 600d are chosen for the warp and weft samples. Plain-woven fabric consists of yarns interlaced alternatingly, with one over and one under every other yarn (*7*). For the unwoven fiber samples, Kevlar KM2 600d yarn is used since 600d is the raw material for style 706 woven fabric. The strengths of the warp, weft, and unwoven fibers are evaluated at three strain rates: a quasi-static rate of 0.001 s^{-1}, an intermediate rate of 1 s^{-1}, and a high rate of 1000 s^{-1}. Low- and intermediate-rate experiments are conducted using a Bose ElectroForce test system, and high-rate strength is measured using a split Hopkinson tension bar (SHTB) modified for fiber characterization.

For each experimental condition, ten fiber samples are used to obtain the strength of the fiber. 3M Scotch-Weld* Structural Plastic Adhesive DP-8005 (black) is used to glue a single fiber to a cardboard specimen holder. Different cardboard specimen holder formats are used for low, intermediate, and high rate evaluations, based on the loading configuration. The fiber is extracted carefully from the fabric and yarn so it will not further damage during the extraction, and glued to the cardboard. Slotted setscrews with lengths of 1/4–3/16 in are glued to both sides of the high-rate samples using cyanoacrylate adhesive. The setscrews are threaded into the SHTB and load cell. In both low/intermediate rate and high rate experiments, the sides of the cardboard specimen holder are cut to allow only the fiber to span between the load cell and the grip of the SHTB.

At all rates, the stress (σ) of the fiber is calculated using the equation:

$$\sigma = \frac{P}{A_0}, \tag{1}$$

where P is force measured by the load cell and A_0 is the initial cross-sectional area of the fiber. To calculate the cross sectional area of the specimen, the diameter of the fiber is required. Although Kevlar fibers are generally uniform, fiber diameter varies slightly along the length of the fiber, hence within the gage length of the specimen. Due to this variation, and for increased accuracy, a scanning electron microscope (SEM) is used to measure the average diameter of each fiber from a small sample trimmed from the end of each fiber used to make the samples.

2.2 Quasi-Static and Intermediate Rate Experiments

Strength of the warp, weft, and unwoven fiber samples are evaluated using the Bose ElectroForce test system at low and intermediate rates of loading. The strain (ε) and strain rate ($\dot{\varepsilon}$) of the fiber specimen are calculated using the following equations:

$$\varepsilon = -\frac{d}{l_s}, \tag{2}$$

and

$$\dot{\varepsilon} = -\frac{v}{l_s}, \tag{3}$$

where d is the change in length of the fiber, l_s is the length of the specimen, and v is the velocity of the experiment (*4, 5*). The specimens are pulled at 0.005 mm/s and 5 mm/s for low and intermediate rate experiments, respectively.

2.3 High-Rate Experiments

High-rate strengths of warp, weft, and unwoven fibers are obtained using a modified split Hopkinson tension bar (SHTB), also known as a Kolsky tension bar, shown in figure 2. The modified-fiber SHTB consists of an incident bar with a flange at one end, and a fast-acting quartz-piezoelectric load cell. This sensitive load cell replaces the usual transmission bar in a

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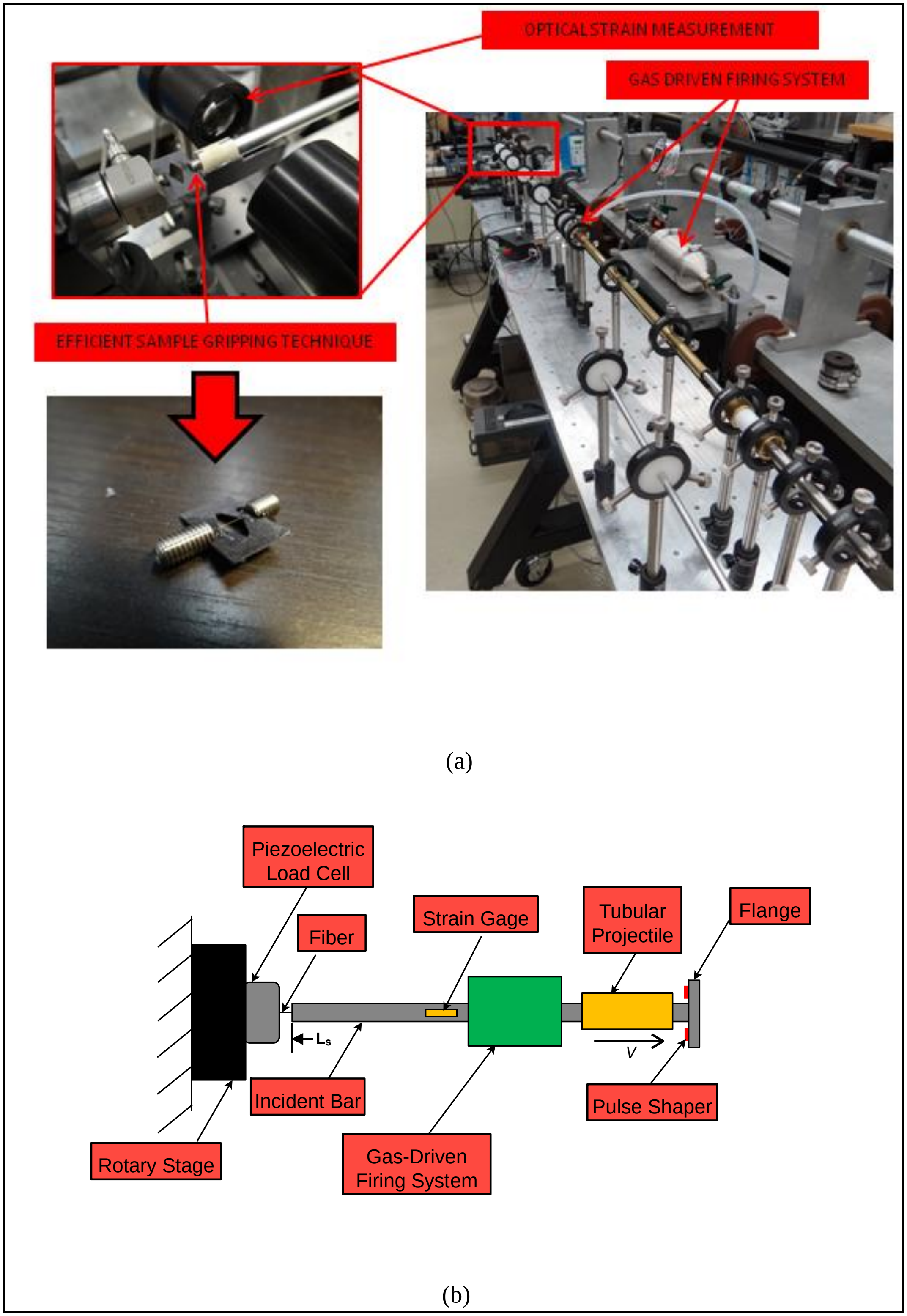

Figure 2. (a) Modified fiber tensile Hopkinson bar and the fiber specimen high-rate characterization of the fibers. (b) Schematic of the modified fiber tensile Hopkinson bar.

standard SHTB, to capture and record the weak transmitted signal when the fiber deforms and fails at high rate. The flange in the incident bar acts as the impact surface of the bar. The striker, a thin-walled tube, is accelerated by a compressed air gun and travels down the incident bar and impacts on the flange, generating a tensile pulse that travels to the other end of the incident bar and loads the fiber-specimen at high loading rate (*4*, *5*). Part of the stress pulse is transmitted into the specimen, while the other part is reflected back into the incident bar as a compression pulse.

A non-contact, high-rate laser technique was used to measure strain of the fiber for high-rate experiments. The laser technique consists of a linear laser, which generates a 25.4-mm-wide plate of laser light with uniform intensity across the plate and a high-speed laser-light detector connected to a high-speed oscilloscope. This linear laser extensometry enables the measurement of motion at the end of the incident bar by converting the motion into a voltage output proportional to the displacement. To calibrate the linear-laser-extensometer before the fiber experiments, a micrometer was used to cover the laser light reaching the detector by known distances. This correlated the voltage change on the oscilloscope to the distance of the obstruction of the linear laser plate. Extension measured this way can now be used in equations for strain and strain rate (equations 2 and 3) and can be applied to both slow and high-rate experiments.

3. Results and Discussion

Results of the measured strengths of fibers are given in figure 3. Based on the measured strengths, Kevlar KM2 fibers depend on the loading rate, and increases with the strain rate. At low-, intermediate-, and high-rate experiments on unwoven fibers, the average failure strengths are 3.59 ± 0.14 GPa, 4.27 ± 0.20 GPa, and 4.64 ± 0.36 GPa, respectively. The unwoven fibers are 29.22% stronger at the high rate than the low rate. Similar behavior is seen for warp and weft fibers despite possible damage to the fibers. The average failure strength of warp fibers at low, intermediate, and high rates are 2.66 ± 0.40 GPa, 2.98 ± 0.81 GPa, and 3.75 ± 0.22 GPa, respectively, which results in the warp fiber being 40.78% stronger at the high rate than the low rate. The weft fibers are 13.8% stronger at the high rate than the low rate with average stresses of 4.32 ± 0.57 GPa at the low rate, 3.64 ± 0.82 GPa at the intermediate rate, and 4.91 ± 0.67 GPa at the high rate.

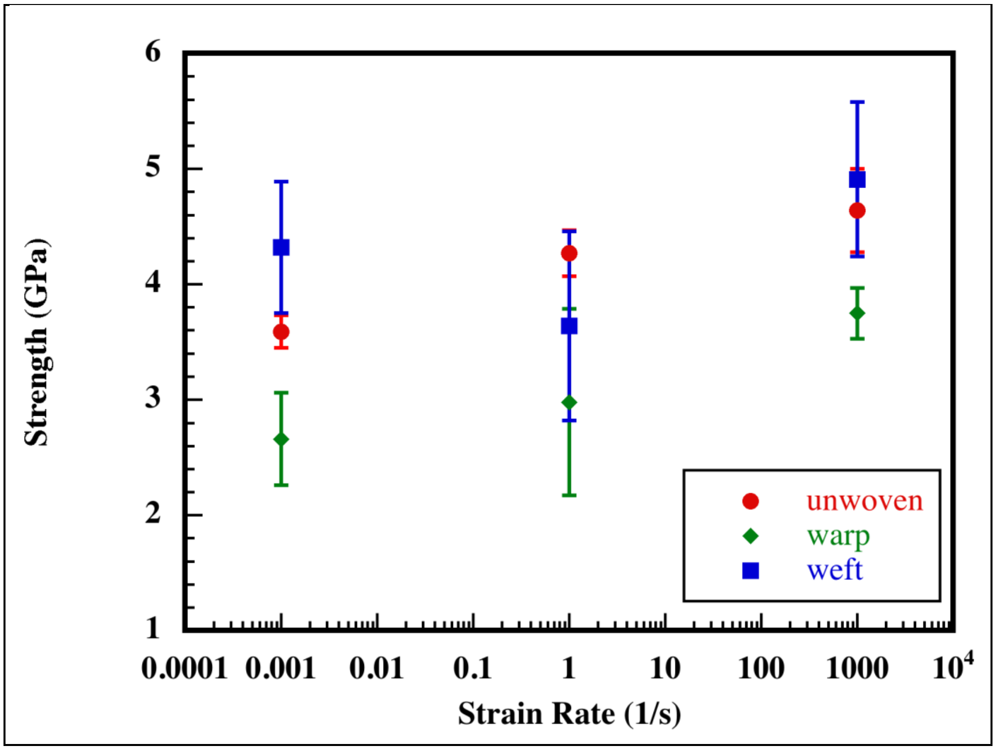

Figure 3. Average strengths of fibers as a function of strain rate. Each data point represents the average value from 10 experiments.

For all of the strain rates, warp fibers are 20%–30% weaker than unwoven fibers. Furthermore, measured strengths have a higher standard of deviations for the warp fibers compared to that of the unwoven fibers. From this, it is concluded that the warp fibers are damaged as a result of weaving. Conversely, the strength of weft fibers were 20% higher than unwoven at low rate, 15% lower at intermediate rate, and 6% higher at high rate. These variations in the strength of the weft fibers are within the bounds of the observed scatter in the measured strength of the unwoven fibers. Consequently, it can be concluded that the weaving process does not appreciably compromise the strength of the weft fibers.

In addition to the failure strength of Kevlar fibers, in this study failure strain was also measured, and is shown in figure 4. The failure strain of warp fibers is 21% lower than that of the unwoven fibers for all three investigated strain rates. Failure strain of weft fibers is similar in magnitude to the failure strain of unwoven fibers. However, because only one gage length was studied, a compliance correction based on the ASTM-C-1557-03 standard (*8*) could not be used (*9*). Since compliance correction was not used, the measured strains are higher than the actual strain. Thus, no direct conclusions are made about failure strain.

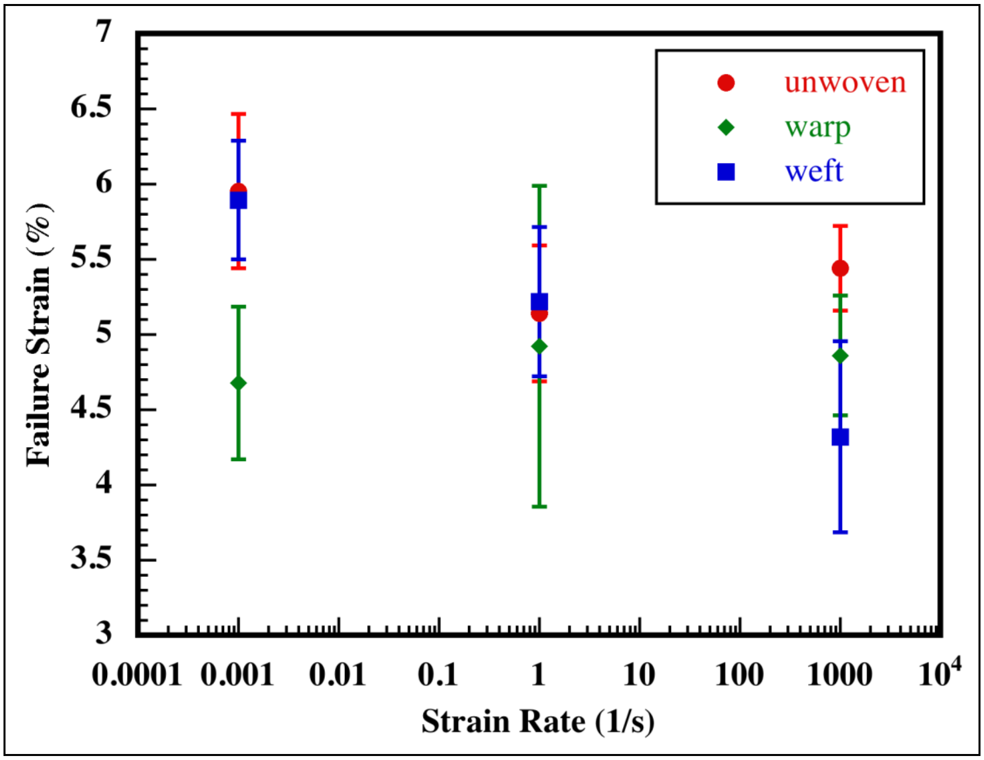

Figure 4. Average strains of fibers as a function of strain rate. Each data point represents the average value from 10 experiments.

4. Conclusions

The mechanical behavior of warp and weft fibers was compared to that of unwoven fibers at quasi-static, intermediate, and high strain rates at a constant gage length of 5 mm. Quasi-static and intermediate rate experiments were conducted using a Bose ElectroForce Test System, while high-rate performance was measured using a miniature tension Kolsky bar. Experimental results indicate that warp fibers have lower strength for all three strain rates when compared to unwoven fibers, indicating that warp fibers were more likely damaged during the weaving process. However, the weaving process does not appear to compromise the strength of weft fibers because the measured strength of the weft fibers showed no significant difference from the unwoven stress. Because only one gage length was studied, a compliance correction could not be applied and no direct conclusions from the observed variations in failure strain between woven and unwoven fibers are made.

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