Strain Rate Effect on the Failure Behavior of Kevlar 49 Fabric and Single Yarn

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Abstract: High strength woven fabrics are ideal materials for use in structural and aerospace systems where large deformations and high-energy absorption are required. Their high strength to weight ratio and ability to resist high-speed impacts enables them to be more efficient than metals in many applications, including ballistic armors, propulsion engine containment systems and fabric-reinforced composites. In order to facilitate the design and improvement of such applications, this study investigates the mechanical behavior of Kevlar 49 fabric and single yarn under quasi-static and dynamic tensile loadings. The experimental results show that the fabric exhibits non-linear in tension, and can deform up to 20% before complete failure under quasi-static loading. The fabric has identical Young's modulus in warp and fill directions, but has different crimp strain, tensile strength and ultimate strain. The sample size has little effect on the mechanical properties of the fabric. The dynamic tensile behaviors of the fabric and single yarn were investigated at strain rates from 25 to 170 s^{-1} by using a high rate servo-hydraulic testing machine. Results show that their dynamic material properties in terms of Young's modulus, tensile strength, maximum strain and toughness increase with increasing strain rate.

Keywords: Fabrics, Dynamic, Strain rate, Kevlar 49

1. Introduction

High strength woven fabrics are ideal materials for use in structural and aerospace systems where large deformations and high energy absorption are required. Their high strength to weight ratio and ability to resist high speed impacts enables them to be more efficient than metals. Materials loaded at high strain rates can exhibit mechanical characteristics that are different from those obtained under quasi-static loading. High strain rate applications are quite varied and include structural, military, aerospace, and sports disciplines. Aramid and other high strength fibers and fabrics have been studied extensively in a wide range of applications, creating a demand for numerical modeling of fibers, yarns, and fabrics. While quasi-static tensile strength data for the single fibers is available, results cannot be extrapolated and scaled up for yarns consisting of many fibers, woven, knitted, or bonded fabrics with a 2-D or 3-D microstructure. Furthermore, the strain rates observed in static experiments is not in the same order of magnitude as those observed in ballistic applications [1]. Five types of testing systems are commonly used in generating the rate dependent material data: the conventional screw drive load frame, servo-hydraulic system, high rate servo-hydraulic system, impact tester and Hopkinson bar system. However, the experimental techniques to generate stress-strain data at the medium strain rates in the range of 1~100 s^{-1} are not well established [2]. Two types of equipment have been used to generate data in this strain rate range: high rate servo-hydraulic testing machines [3-5] and drop-weight impact machines [6, 7].

The primary objective of our research is to investigate the effects of gage length and strain rate on the mechanical properties of Kevlar 49 fabric and single yarn, as a part of the project on explicit finite element modeling of multi-layer composite fabric for gas turbine engine containment systems [8-12]. In the next section we present the experimental procedure and results of fabric and single yarn specimens under quasi-static and dynamic tensile loadings and the results of Weibull statistical analysis. Images captured during loading process are used to study the deformation and failure mechanisms of the fabric and yarn.

2. Experimental Program

2.1. Specimen preparation

The plain-woven Kevlar® 49, a high performance fabric for ballistic protection application, made by EI du Pont de Nemours & Co., is used in this study. The fabric is manufactured using a plain-weave of 17×17 yarns (per linear inch) each consisting of hundreds of filaments. The bulk density (mass per unit of volume) and linear density (mass per unit of length) are 1.44 g/cm^3 and 1.656 × 10^{-3} g/cm, respectively. The cross-sectional area of each yarn was calculated as 1.15 × 10^{-3} cm^2 by dividing the linear density of the material by its bulk density [13]. This value is then taken as the total c/s area of individual fibers within the yarn.

To make a strip specimen for quasi-static tests, the fabric was first cut into an oversized rectangular strip, and then a number of yarns along the fabric length were removed from both sides, thereby producing a sample without yarn crossovers along the edges. This step is necessary to ensure that the edge defects are minimized and that the loaded yarns will not slip out of the cross yarns during the test. The final sample dimension had a length of 250 mm with two alternate widths of 30 mm and 60 mm. In each set, yarns are removed from both sides of the strip such that the samples are left with 17 and 34 longitudinal yarns, respectively. The initial gage length was 200 mm. The total cross-sectional area of a specimen was defined as the cross-sectional area per yarn multiplied by the number of yarns within the width. In order to investigate the effect of gage length on the mechanical properties of the fabric, additional specimen sizes of 25 × 280 mm and 25 × 355 mm were also tested in warp direction under the same loading rate.

Smaller specimens were used for dynamic tensile tests. The fabric was cut to the width using an electric scissor allowing eight yarns in the section of gage length. Thin aluminum sheets were glued using high-strength epoxy to the ends of the test specimen to reduce the stress concentration and improve load transfer in grips so as to prevent any slippage, as shown in Fig. 1. The single yarn specimen was constructed to contain one yarn in the central position by removing the rest of the yarns as shown in Fig. 2. Two different gage lengths of 25 mm and 50 mm were tested for both fabric and single yarn specimens.

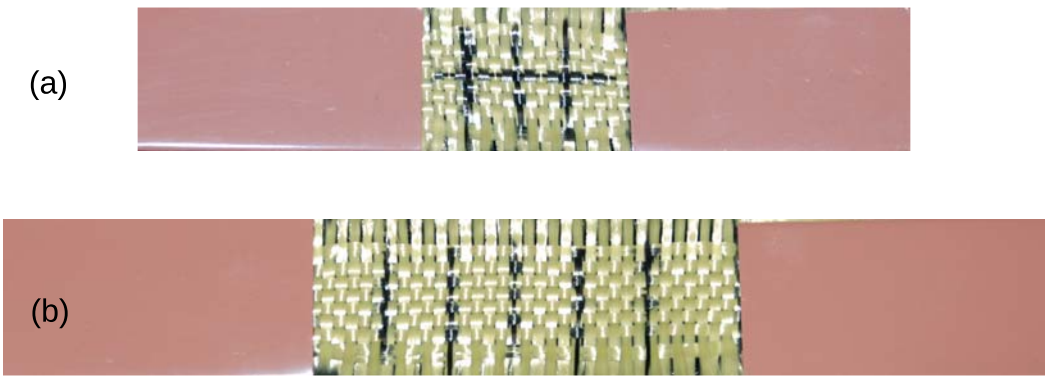

Figure 1. Fabric specimens with (a) 25mm and (b) 50mm gage length for dynamic tensile tests

(a)

(b)

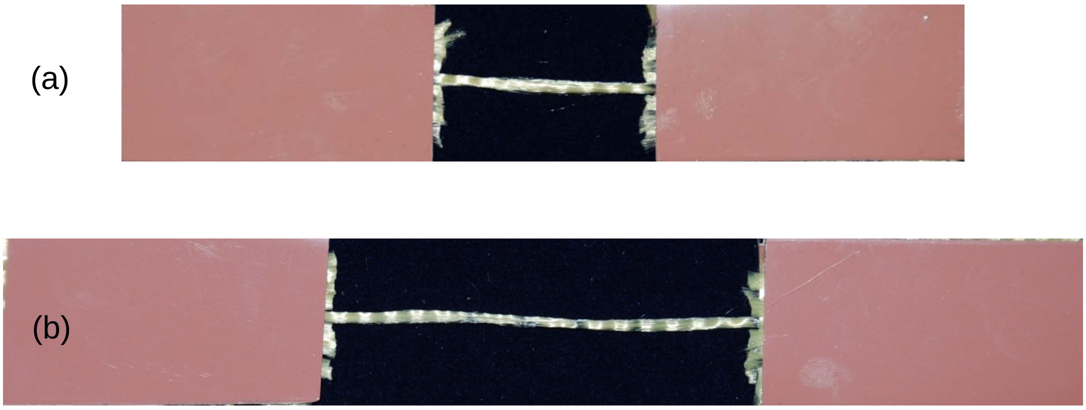

Figure 2. Single yarn specimens with (a) 25mm and (b) 50mm gage length for dynamic tensile tests

2.2. Quasi-static tensile testing

Quasi-static tensile tests of Kevlar fabric were performed on a 90 kN INSTRON machine operated under closed-loop displacement control with a displacement rate of 2.5 mm/min. Digital data acquisition was used to collect data at a sampling rate of 2 Hz. The test was continued until complete failure of the specimen. The overall specimen deformation was measured by stroke movement. The two plates were held together within the hydraulic grips to ensure uniform pressure application and prevent any fabric slippage (more details in Naik et al. [9]). Five replicates were tested for each specimen size in both warp and fill directions, and the deformation and failure behaviors of the specimens were recorded by a CCD monochrome camera.

In order to measure the mechanical properties of the yarn, single yarns were extracted from fabrics and only the warp yarns were tested. A low capacity load cell (275N) was used to record the force. A universal joint was connected to the testing frame to allow rotation of the grip and remove any potential bending moment. The universal joint also helped in the alignment of yarn during test. To avoid any slipping of test sample during testing, the yarn was wrapped around the upper and lower mandrels and aligned using a laser beam alignment level [14]. Ten replicate samples of six different gage lengths (50, 125, 200, 275, 350, 425 mm) were tested on an MTS test frame under displacement control at a strain rate of 4.2×10^{-4} s^{-1} (quasi-static).

2.3. Dynamic tensile testing

Dynamic tensile tests were conducted on an MTS high rate servo-hydraulic testing machine operated in open-loop control [3]. The speed of the stroke is controlled by the opening and closing of the servo-valve of hydraulic supply. By manually turning the servo-valve, the rate of flow of hydraulic fluid can be controlled, resulting in different stroke speeds. However there are some differences in the actual stroke speeds between individual tests although the opening of servo-valve is not changed, especially at higher stroke speeds. The actual stroke speeds of individual tests are determined by the slopes of real-time displacement-time curves obtained from the tests. A description of the high strain rate testing system, test setup and data processing procedure are provided in the references [3, 13]. The fabric samples of two different gage lengths (25mm and 50 mm) were tested at strain rates ranging from 25 to 170 s^{-1}. The Young's modulus, tensile strength, maximum strain, and toughness were investigated at these strain rates. Single yarn samples were tested at strain rates of 30, 50 and 100 s^{-1} for the 25 mm gage length, and at strain rates of 20 and 60 s^{-1} for the 50 mm gage length. It should be noted that the strain rates listed above are the average values and the actual strain rate of an individual test may be slightly different.

3. Results and Discussion

3.1. Quasi-static response

The typical stress versus strain relationship and the fabric deformation under uniaxial tension are shown in Fig. 3. There are four distinct regions in the stress-strain behavior of both warp and fill directions: crimp region, linear pre-peak region, linear post-peak region and non-linear post-peak region. In the undeformed, but undulated state (strain ε=0), the warp and fill yarns are orthogonal to each other and free of any stretch. In the crimp region, the stress increase is relative low due to the straightening of the undulated yarns in loading direction with limited yarn stretching. The maximum strain in crimp region in warp and fill directions is only 0.0065 mm/mm and 0.0025 mm/mm, respectively. These strain values are negligible when compared with the strain at failure. As the strain increases, the yarns in the loading direction are extended, and when fully straightened (ε=0.01 to 0.02), the fabric exhibits a linear response with no visible failure signs. The Young's modulus (elastic stiffness) is defined by the slope of the stress-strain curve in this region. Both the crimp and pre-peak regions are fitted by linear curves to obtain corresponding stiffnesses [9]. As the stress level reaches the strength of the constituent yarns, the yarns in the loading direction start to fail, resulting in a dramatic decrease in the fabric load-carrying capacity until reaching a transition point at about 200 MPa (the end of linear post-peak region) where the yarns/fibers are broken. After that the stress decreases gradually to zero when the strain increases up to about 0.2 mm/mm, representing the nonlinear post-peak region where the failed yarns/fibers slip out of the fabric and the load is carried by the friction between sliding fibers (ε=0.02 to 0.04). The toughness of the fabric is defined by the area under the entire stress-strain curve.

Analysis of the stress versus strain curves in both warp and fill directions for both specimen sizes (50 mm × 200 mm and 25 mm × 200 mm), indicates that the pre-peak elastic stiffness (Young's modulus) of warp direction is almost identical to that of fill direction, and the stiffness in the crimp region for warp and fill directions is as much as 6% and 20% of the elastic stiffness (Young's modulus) in pre-peak region, respectively. The absolute value of the stiffness in linear post-peak region of warp and fill directions is 2.2 and 5.6 times of the elastic stiffness in pre-peak region. Comparing the stress-strain behavior between warp and fill directions, the major difference is the crimp strain, tensile strength (peak stress) and the ultimate strain (strain at peak stress) in both directions. The crimp strain in warp direction is about 2.6 times larger than that of fill direction. The tensile strength in warp direction is approximately 10~15% lower than that in fill direction, while the ultimate strain in warp direction is approximately 7~12% higher than that in fill direction. This is due to the fact that the warp yarns have sustained more damage from weaving process and have higher initial crimps. The stress-strain curves of specimens tested are highly repeatable for both sizes and directions.

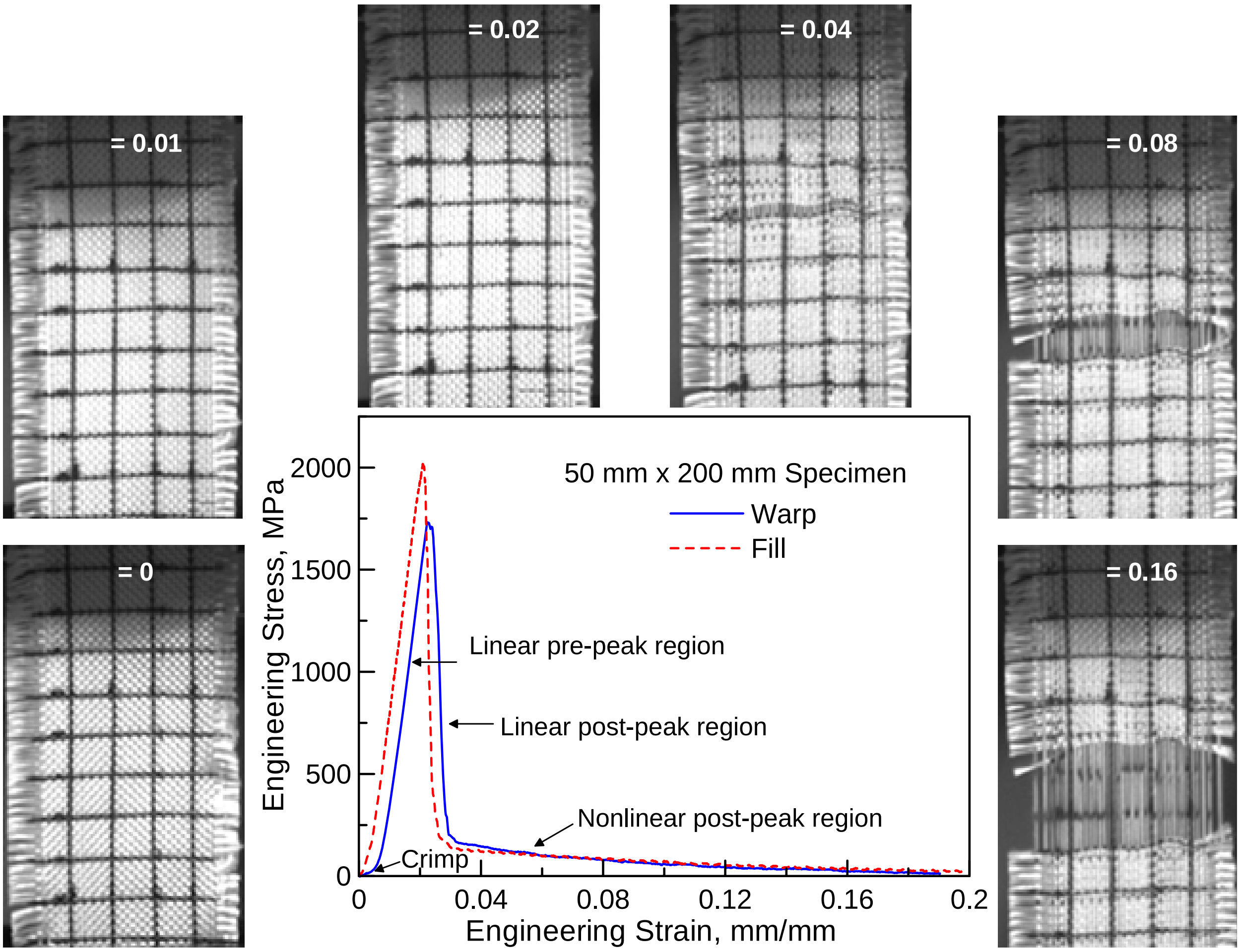

Figure 3. Typical stress-strain relationship and fabric deformation under quasi-static uniaxial tension

Table 1 Summary of Tensile Properties of Kevlar 49 Fabric

Specimen Size (mm × mm)	Material Direction	Tensile Strength (MPa)	Young's Modulus (GPa)	Toughness (MPa)	Ultimate Strain (mm/mm)
50×200	Warp	1748 ± 56	117.2 ± 3.3	32.4 ± 3.0	0.0223 ± 0.0012
	Fill	2013 ± 44	117.1 ± 3.0	33.9 ± 1.3	0.0201 ± 0.0010
25×200	Warp	1859 ± 109	117.9 ± 2.5	32.9 ± 1.4	0.0215 ± 0.0015
	Fill	2055 ± 72	119.7 ± 4.0	33.2 ± 1.2	0.0200 ± 0.0009
25×280	Warp*	1776 ± 100	126.5 ± 4.6	26.9 ± 1.7	0.0197 ± 0.0014
25×355	Warp*	1811 ± 61	132.1 ± 5.8	27.1 ± 1.8	0.0181 ± 0.0008

*These tests were stopped once the load acting on the specimen fell below 222N.

Tables 1 summarizes the tensile properties of both specimen sizes in both warp and fill directions. There is no apparent size effect in terms of Young's modulus, toughness and ultimate strain, but the average tensile strength of 50 mm wide specimens is slightly lower (2~6%) than those of 25 mm wide specimens in both directions. For longer specimens (25 × 280 mm and 25 × 355 mm), the tests were stopped once the load on the specimen fell below 222N (corresponding to approximately 10% maximum strain). Toughness in these samples is underestimated as much as 16~20% lower than those of 200 mm long specimens. However, the toughness remains almost same when the gage length increases from 280 mm to 355 mm, so does the tensile strength, Young's modulus, and ultimate strain, indicating that gage length effect on the fabric's mechanical properties is negligible.

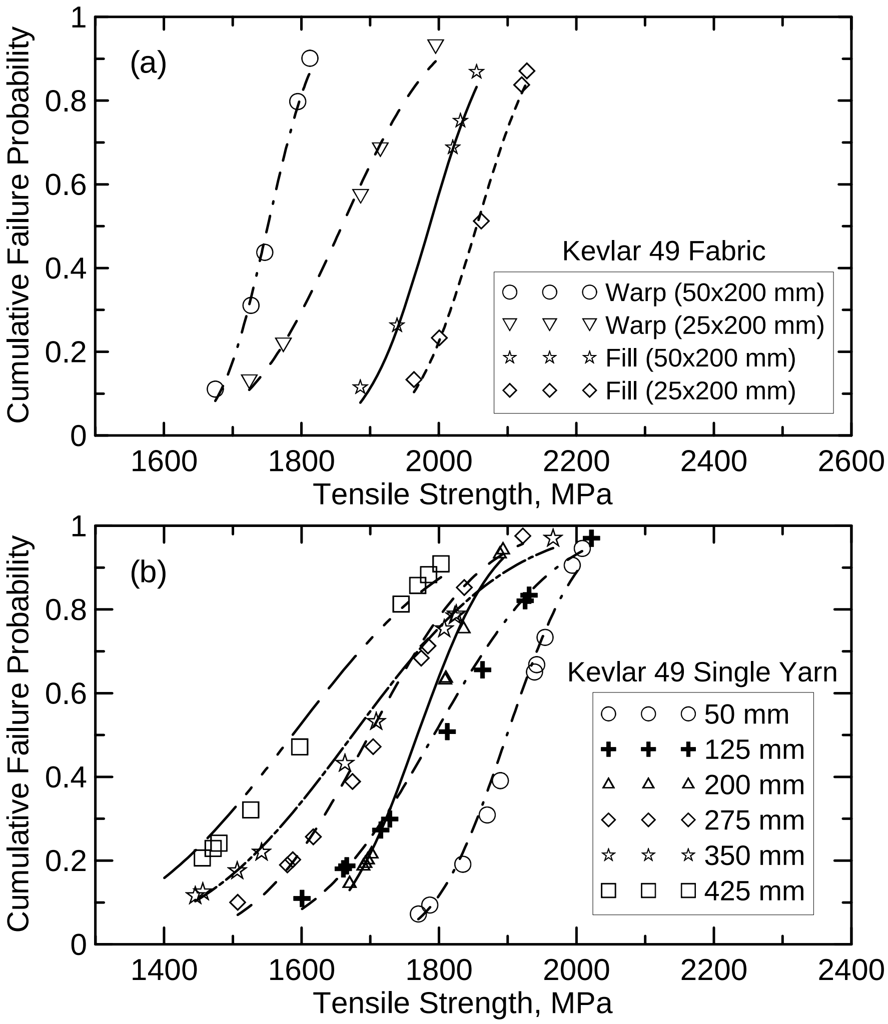

Figure 4. Comparison of cumulative failure probability versus tensile strength: (a) fabric and (b) single yarn under quasi-static loading

Weibull parameters were obtained using a 2-parameter Weibull equation:

$$P_f(\sigma) = 1 - \exp\left[-\left(\frac{\sigma}{\sigma_0}\right)^m\right] \tag{1}$$

where σ_0 is the characteristic yarn strength and m is the shape parameter, characterizing the spread in the distribution of strengths. P_f was estimated using the following equation:

$$P_f = \frac{i}{N+1} \tag{2}$$

where N is the total number of tests and i is the current test number [15].

Figure 4a and b shows the Weibull curve fitting to experimental data of both fabric and single yarn samples, respectively. The fabric data clearly indicate that the fabric breaks at lower stress in warp direction than in fill direction, and wider samples (50 mm) have lower tensile strength. For the single yarn data, as the gage length increases, the cumulative probability plot shifts towards lower stress values, which is a clear indicator of dependence of tensile strength on the gage length. The Weibull parameters identified from both fabric and single yarn tests are presented in Table 2.

Table 2. Weibull Parameters of Kevlar 49 Fabric and Single Yarn under Quasi-Static Loading

	Fabric				Single Yarn					
Size (mm)	25 × 200		50 × 200		50	125	200	275	350	425
Material Direction	Warp	Fill	Warp	Fill	Warp					
σ_0 (MPa)	1857	2064	1759	2001	1933	1829	1795	1724	1726	1652
m	13.3	27.0	27.5	27.4	21.7	11.5	14.3	11.9	7.9	8.8

3.2. Dynamic response

Figure 5(a-d) shows the dependence of the dynamic material properties of Kevlar 49 fabric, defined in terms of Young's modulus, tensile strength, maximum strain and toughness on strain rates, respectively. There is an apparent dependence of the dynamic material properties on the strain rates discussed as follows: For 25 mm gage length specimen, the Young's modulus increases from 120 ± 14 GPa at initial strain rate of 30 s^{-1} to 131 ± 23 and 147 ± 10 GPa at strain rates of 100 s^{-1}, and 170 s^{-1} respectively. The tensile strength increases from 1489 ± 54 MPa at a strain rate of 30 s^{-1} to 1968 ± 109 and 2340 ± 134 MPa at strain rates of 100 s^{-1}, and 170 s^{-1} respectively. Maximum strain increases from 2.92 ± 0.17% to 3.27 ± 0.32% and then to 3.66 ± 0.27%, and toughness increases from 24.6 ± 2.6 MPa to 30.6 ± 1.5 MPa and to 41.4 ± 4.8 MPa when the strain rate increases from 30 to 100 and then to 170 s^{-1}. For 50 mm gage length specimen, the Young's modulus increases from 127 ± 16 GPa to 144 ± 12 GPa and then to 162 ± 11 GPa, the tensile strength increases from 1677 ± 136 MPa to 1954 ± 104 MPa and then to 2108 ± 83 MPa, the maximum strain increases from 2.58 ± 0.34% to 2.82 ± 0.18% and then to 2.83 ± 0.28%, and toughness increases from 21.6 ± 3.8 MPa to 22.2 ± 3.3 MPa and then to 25.8 ± 1.8 MPa when the strain rate increases from 25 to 60 and then to 100 s^{-1}.

Figure 6(a-d) shows the dependence of the dynamic material properties of Kevlar 49 single yarn on the strain rate. There is an apparent dependence of the dynamic material properties on the strain rate; however there is no clear dependence between the properties and gage lengths investigated. For the

25 mm gage length specimen, the Young's modulus increases from 109 ± 11 GPa at a strain rate of 30 s^{-1} to 111 ± 10 and 128 ± 11 GPa at strain rates of 50 s^{-1}, and 100 s^{-1} respectively. The tensile strength increases from 1622 ± 104 MPa at a strain rate of 30 s^{-1} to 1675 ± 51 and 1707 ± 82 MPa at strain rates of 50 s^{-1}, and 100 s^{-1}, respectively. Maximum strain increases from 0.0245 ± 0.003 mm/mm to 0.0253 ± 0.0017 mm/mm and then to 0.0282 ± 0.0022 mm/mm, and toughness increases from 20.1 ± 2.6 to 20.5 ± 1.4 MPa and to 26.0 ± 4.3 MPa when the strain rate increases from 30 to 50 and then to 100 s^{-1}. For the 50 mm gage length specimen, the Young's modulus increases marginally from 118 ± 28 to 121 ± 22 GPa when the strain rate increases from 20 to 60 s^{-1}. While the tensile strength increases by as much as 23.5% from 1579 ± 100 to 1874 ± 110 MPa, the maximum strain increases about 15% from 0.0217 ± 0.003 mm/mm to 0.025 ± 0.0026 mm/mm, and toughness increases about 29 % from 18.8 ± 2.5 MPa to 24.3 ± 4.0 MPa.

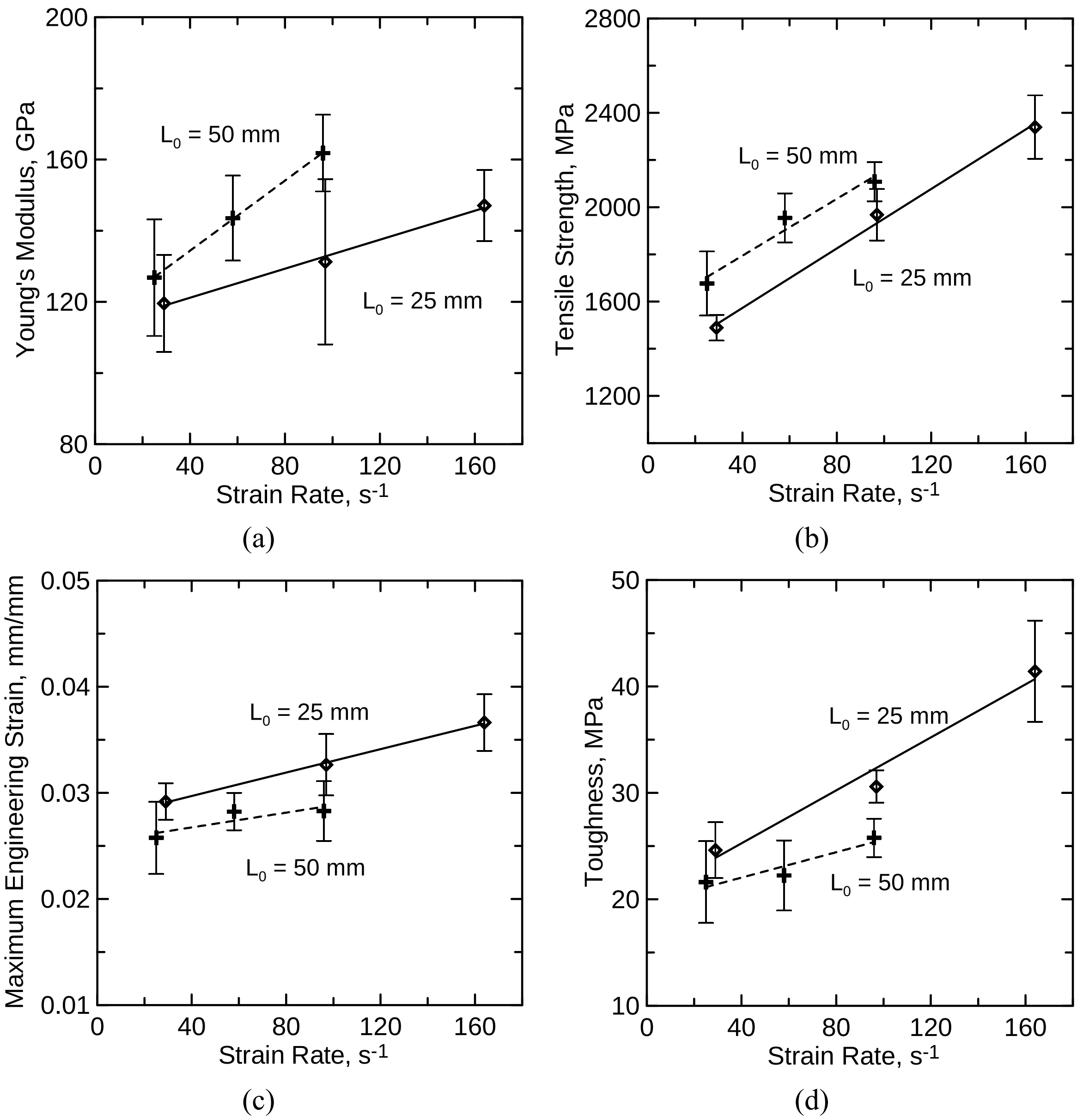

Figure 5. Strain rate effect on the dynamic material properties of Kevlar 49 fabric: (a) Young's modulus, (b) tensile strength, (c) maximum strain, and (d) toughness. L_0 is the gage length.

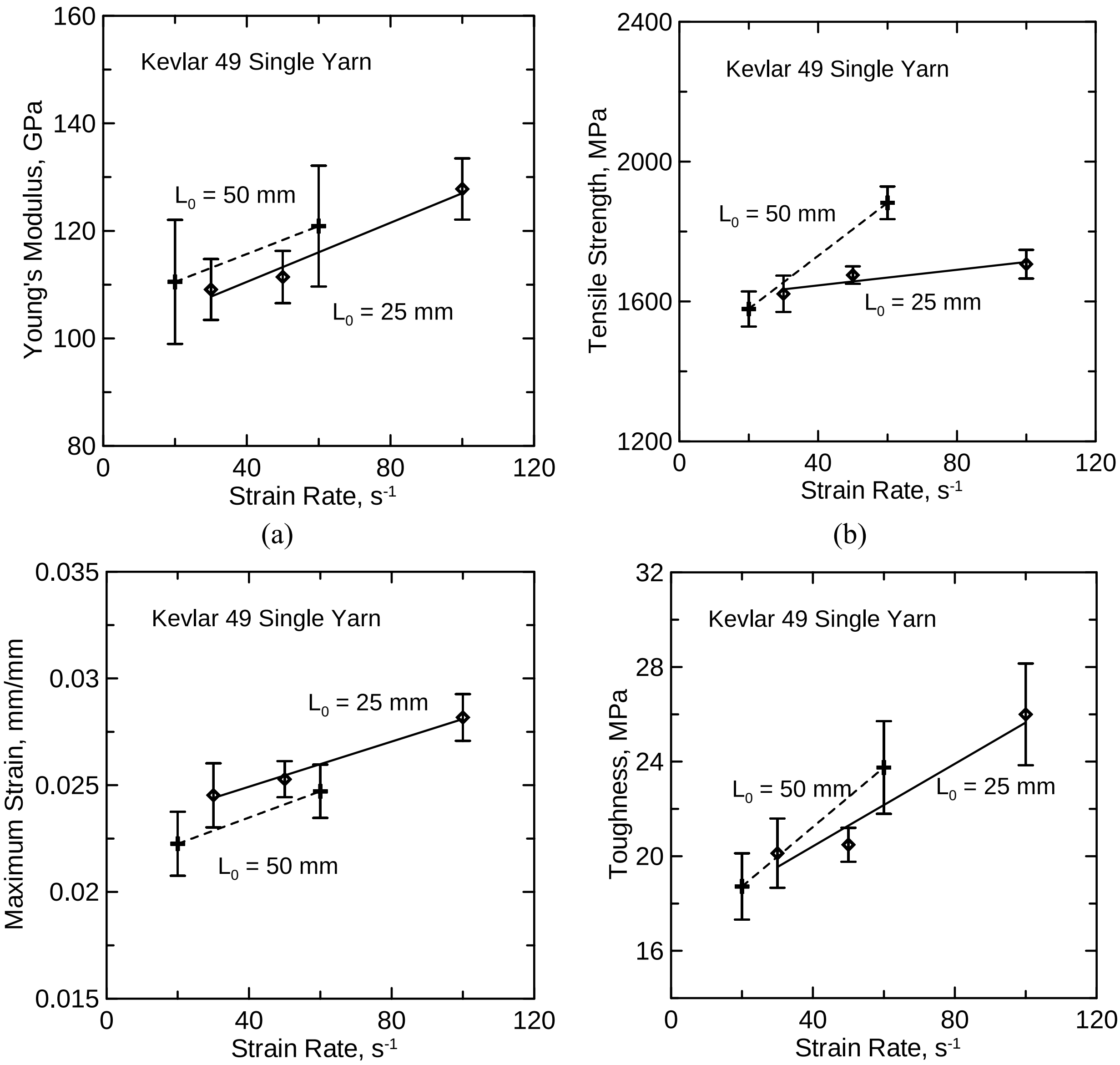

Figure 6. Strain rate effect on the dynamic material properties of single yarn: (a) Young's modulus, (b) tensile strength, (c) maximum strain, and (d) toughness

4. Conclusions

This work investigated the mechanical behaviors of Kevlar 49 fabric and single yarn under quasi-static and dynamic tensile loadings. Weibull parameters have been obtained to characterize the considerable scatter in the mechanical properties due to different amount and distribution of imperfections in the fabric and yarn specimens. The following conclusions can be reached:

(1) Under quasi-static loading, the stress-strain response of Kevlar 49 fabric exhibits non-linear and orthogonal behavior in both warp and fill directions, and the fabric can deform up to 20% before the stress decreases to zero. The Young's modulus is almost identical to one another in both directions. The major difference between warp and fill directions is the crimp strain, the tensile

strength and the ultimate strain. The tensile strength of single yarn decreases with increasing gage length.

(2) Under dynamic loading, Young's modulus, tensile strength, maximum strain and toughness of the fabric and yarn increase with increasing strain rate over the strain rate range from 20 to 170 s^{-1}. However, based on the current results, it is not clear what the effect of the gage length is on the dynamic properties.

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