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Plain-Woven, 600-Denier Kevlar KM2 Fabric Under Quasistatic, Uniaxial Tension

by Martin N. Raftenberg, Mike Scheidler,
Thomas J. Moynihan, and Charles A. Smith

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14. ABSTRACT

We analyzed data from quasistatic, uniaxial tension tests on single-ply specimens of plain-woven, 600-denier KM2. Failure strains were found to range from 0.120 to 0.144 for warp-loaded and from 0.143 to 0.160 for fill-loaded tests. Failure stresses (strengths) ranged from 0.424 to 0.543 GPa for warp-loaded and from 0.593 to 0.642 GPa for fill-loaded tests. A least-squares fit, in the form of a rational function, was obtained to the second Piola-Kirchhoff stress vs. Green-St. Venant strain data for a representative warp-direction and a representative fill-direction test. In addition, averaged least-square fits to all the warp data and to data from four out of five fill tests were obtained, also in the form of a rational function. These fits are intended to inform constitutive modeling in numerical simulations.

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Kevlar KM2, body armor, personal protection, constitutive model, Instron test

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Contents

List of Figures

List of Tables

1. Introduction

We performed quasistatic, uniaxial tension tests on single-ply specimens of plain-woven, 600-denier, Kevlar KM2. Each specimen contained 33 yarns, for a width of 24.7 mm.

The tests were performed with an Instron machine. The specimen was clamped at each end by a vice. The initial separation of the two vices was 50.8 mm. This constitutes the gauge length, L_0, of the test. The speed of vice separation was held constant at 2.12 mm/s. A load cell was used to measure the force F applied to the specimen corresponding to each imposed vice separation, Δ.

In five tests, W1 through W5, the specimen's largest dimension was aligned with its warp yarns, and the specimen was pulled along its warp yarns. In the other five tests, F1 through F5, the long dimension was aligned with the fill yarns, and the specimen was pulled along its fill yarns. Data for F vs. Δ are plotted in figure 1 for the warp series and in figure 2 for the fill series.

The remainder of this report deals with processing of the data in figures 1 and 2. In section 2.1, the Green-St. Venant strain tensor and the second Piola-Kirchhoff stress tensor are evaluated. These evaluations require the introduction of constitutive and kinematic assumptions. Values for failure strain and failure stress are presented for each test. In section 2.2, a least-squares fit in the form of a ratio of polynomials (rational function) is presented for a stress-strain curve from a representative warp test, a representative fill test, the combined data from all warp tests, and the combined data from all fill tests, minus one outlier. These analytical fits are intended to inform constitutive modeling for numerical simulations. Section 3 discusses the failure strain and failure stress results in the context of data from plain-woven, 600-denier, Kevlar KM2 that appeared in Mulkern and Raftenberg[1] and Raftenberg and Mulkern.[2]

2. Results

2.1 Calculation of Stress and Strain

Each single-ply specimen consisted of two families of yarns, warp, and fill (weft). These families were initially mutually orthogonal and are assumed to have remained mutually orthogonal throughout the tension test. In-plane material coordinates X_1 and X_2 are defined in figure 3 as aligned with the two families of yarns. The tensile loading is applied along X_1.

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[1] Mulkern, T. J.; Raftenberg, M. N. *Kevlar KM2 Yarn and Fabric Strength Under QuasiStatic Tension*; ARL-TR-2865; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, October 2002.

[2] Raftenberg, M. N.; Mulkern, T. J. *QuasiStatic Uniaxial Tension Characteristics of Plain-Woven Kevlar KM2 Fabric*; ARL-TR-2891; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, December 2002.

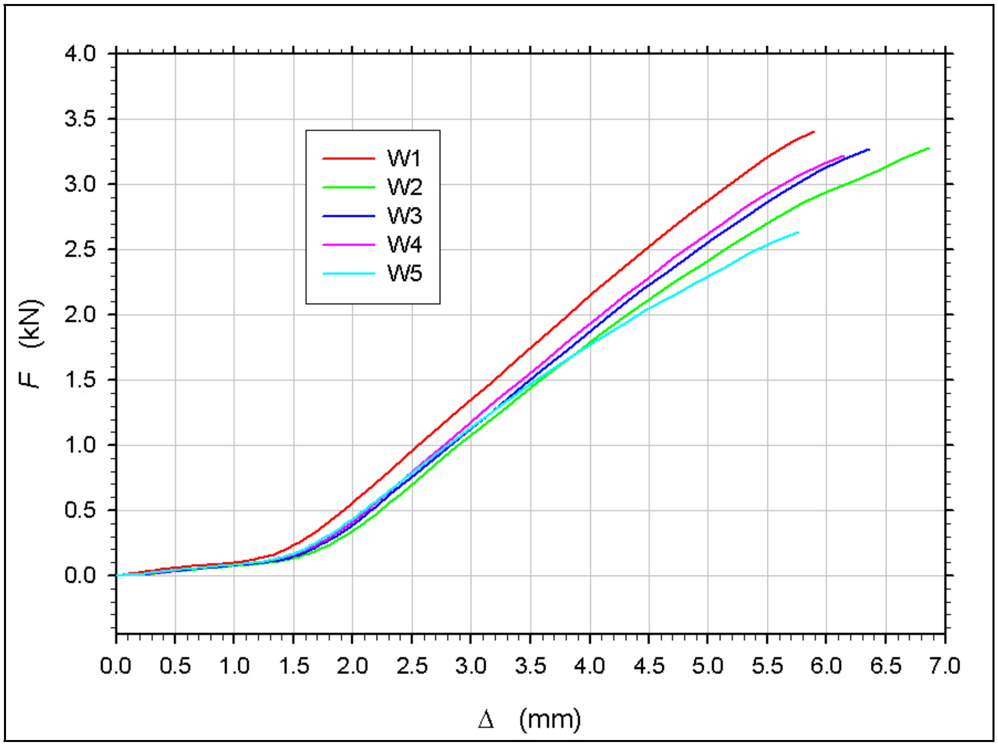

Figure 1. Force-displacement data for a ply under quasistatic, uniaxial tension along the warp direction.

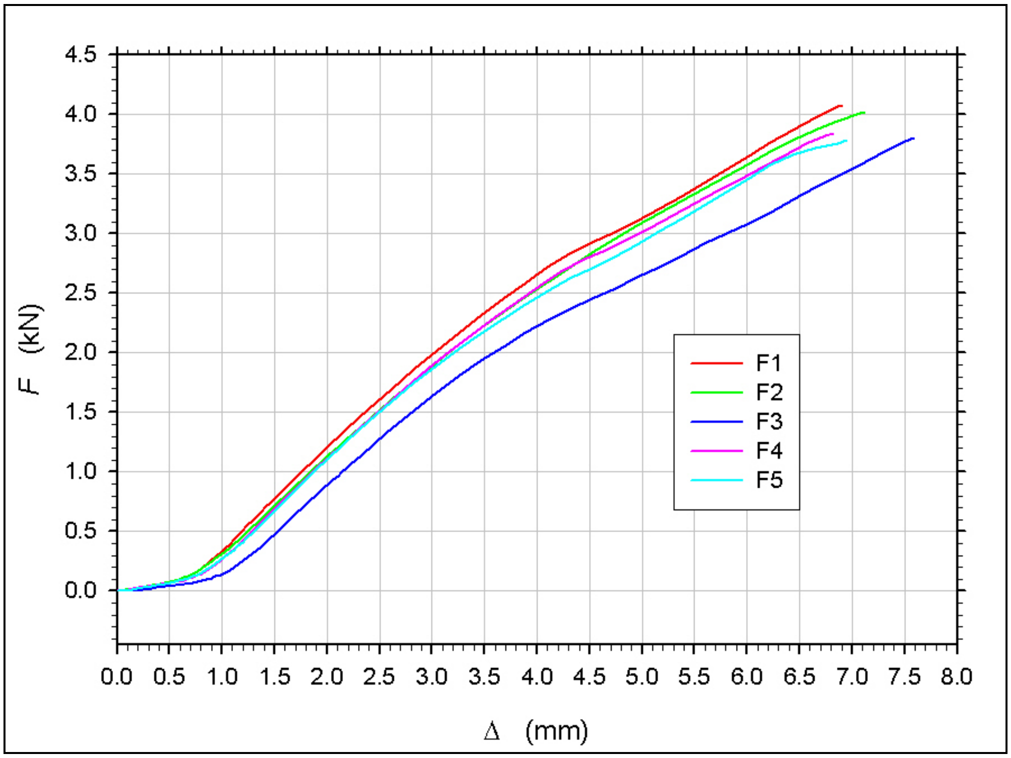

Figure 2. Force-displacement data for a ply under quasistatic, uniaxial tension along the fill direction.

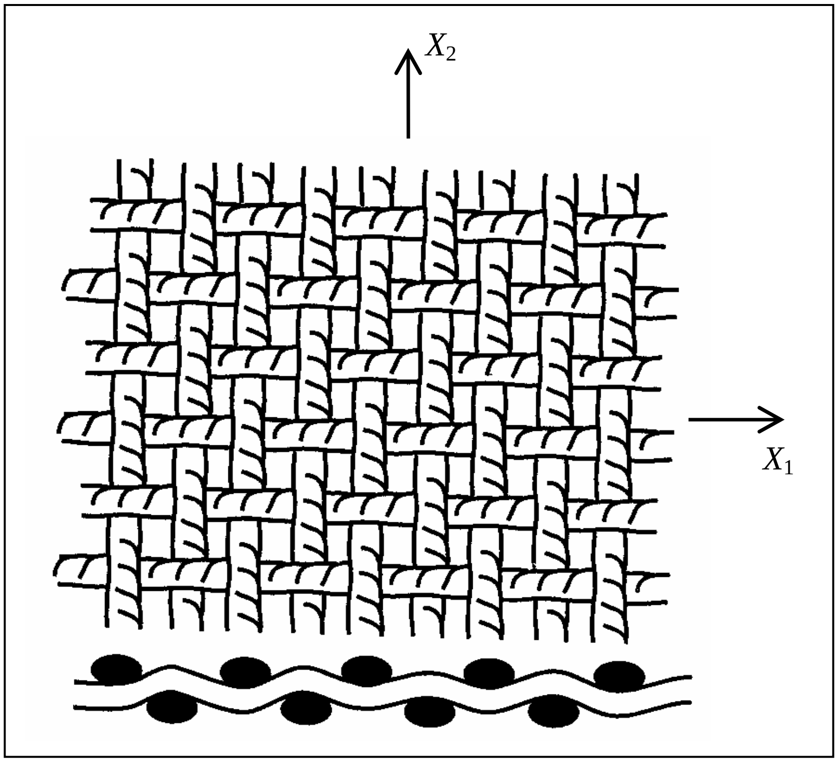

Figure 3. Sketch of the plain-weave construction of the vest.

Hence, in tests W1–W5, X_1 is identified with the warp direction and X_2 with the fill. In tests F1–F5, this identification is reversed. Material coordinate X_3 is orthogonal to both X_1 and X_2. The vest, consisting of 28 plies of plain-woven, 600-denier Kevlar KM2 enclosed in a Cordura case, is envisioned as a homogeneous, orthotropic continuum. Its axes of material symmetry coincide with X_1, X_2, and X_3.

In the remainder of section 2.1, the notation is adopted from Malvern,[3] where discussion of the following definitions can be found. The first Piola-Kirchhoff stress tensor $\mathbf{T^0}$ throughout the duration of each uniaxial tension test was

$$\mathbf{T^0}(t) = \frac{F(t)}{A_0}\begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}. \tag{1}$$

Here, A_0 is the undeformed cross-sectional area of the single-ply specimen. The specimen's undeformed width was 33 yarn diameters, or 24.7 mm. The undeformed thickness of the entire 28-ply vest was measured with a micrometer to be 6.35 mm. The thickness attributed to a single ply is therefore (neglecting the contribution from the Cordura case) 0.227 mm. Hence, A_0 is assigned the value of 5.61 (mm)^2.

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[3] Malvern, L. E. *Introduction to the Mechanics of a Continuous Medium*. Prentice-Hall: Englewood Cliffs, NJ, 1969.

The second Piola-Kirchhoff stress tensor, S, is defined by

$$\mathbf{S} = \mathbf{T}^{\mathbf{0}} \cdot \mathbf{F}^{-T} \quad , \tag{2}$$

where the deformation gradient tensor, F, is defined by

$$\mathbf{F} = \frac{\partial \mathbf{x}}{\partial \mathbf{X}} \quad . \tag{3}$$

F at time t describes the instantaneous mapping from material coordinates **X** to laboratory coordinates **x**. At time $t = 0$, X_1, X_2, and X_3 are coaligned with laboratory coordinates x_1, x_2, and x_3, respectively. The Green-St. Venant (Lagrangian) strain tensor, **E**, is defined in terms of **F** by

$$\mathbf{E} = \frac{1}{2}\left(\mathbf{F}^{T} \cdot \mathbf{F} - \mathbf{I}\right) \quad , \tag{4}$$

where **I** is the identity tensor.

We introduce the constitutive assumption of component decoupling, so that

$$\begin{aligned} S_{11} &= \phi_{11}(E_{11}), \\ S_{22} &= \phi_{22}(E_{22}), \\ S_{33} &= \phi_{33}(E_{33}), \\ S_{12} &= \phi_{12}(E_{12}), \\ S_{23} &= \phi_{23}(E_{23}), \\ S_{31} &= \phi_{31}(E_{31}). \end{aligned} \tag{5}$$

That is, the S_{11} component of second Piola-Kirchhoff stress is a function only of E_{11}, and similarly for the other components. This constitutive assumption makes plausible the kinematic assumption that a condition of uniaxial strain was maintained throughout the test. That is, motion of each material point is assumed to be describable throughout the test by

$$\begin{aligned} x_1(X_1, t) &= X_1\left[1 + \frac{\Delta(t)}{L_0}\right], \\ x_2 &\equiv X_2, \\ x_3 &\equiv X_3. \end{aligned} \tag{6}$$

Corresponding to equation 6, equation 3 yields

$$\mathbf{F}(t) = \begin{bmatrix} F_{11}(t) & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad , \tag{7}$$

where

$$F_{11}(t) = 1 + \frac{\Delta(t)}{L_0} \quad . \tag{8}$$

The Green-St. Venant strain is then determined from equation 4 to be

$$\mathbf{E}(t) = \begin{bmatrix} E_{11}(t) & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} , \tag{9}$$

where

$$E_{11}(t) = \frac{\Delta(t)}{L_0} + \frac{1}{2}\left[\frac{\Delta(t)}{L_0}\right]^2 \quad . \tag{10}$$

The second Piola-Kirchhoff stress is determined from equation 2 to be

$$\mathbf{S}(t) = \begin{bmatrix} S_{11}(t) & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} , \tag{11}$$

where

$$S_{11}(t) = \frac{F(t)}{A_0\left[1 + \dfrac{\Delta(t)}{L_0}\right]} \quad . \tag{12}$$

Equations 10 and 12 are used to convert the force-displacement curves of figures 1 and 2 into the stress-strain curves of figures 4 and 5. Also, the displacement and force at the time of specimen rupture are converted to failure strain, E_{11}^{fail}, and failure stress (strength), S_{11}^{fail}, by means of equations 10 and 12, respectively. The results are listed in table 1. In this table, and throughout the remainder of this report, the “11” subscript has been dropped from the notation. The scalars S and E denote the component of the second Piola-Kirchhoff stress and the Lagrangian strain, respectively, along the direction of applied tensile loading, and S^{fail} and E^{fail} denote the values corresponding to material failure.

2.2 Least-Square Fits to Stress-Strain Curves

The stress-strain curves in figures 4 and 5 were each fitted with the rational function

$$S(E) = \frac{aE + bE^2 + cE^3 + dE^4}{1 + eE + fE^2} \quad ; 0 \le E \le E^{\mathrm{fail}} \quad . \tag{13}$$

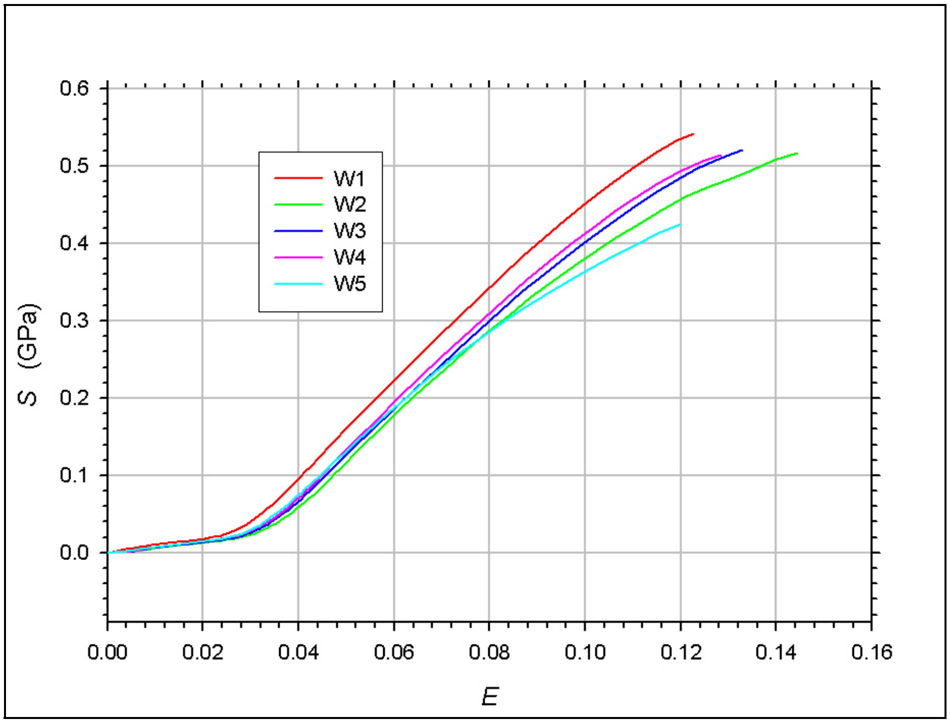

Figure 4. Second Piola-Kirchhoff stress vs. Green-St. Venant strain for a ply under quasistatic, uniaxial tension along the warp direction.

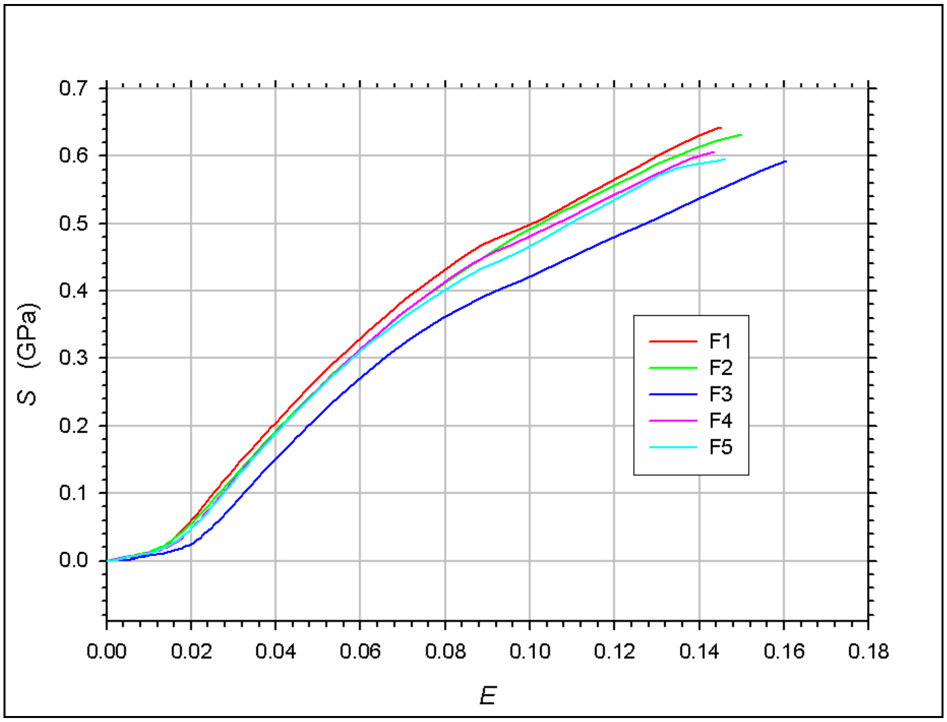

Figure 5. Second Piola-Kirchhoff stress vs. Green-St. Venant strain for a ply under quasistatic, uniaxial tension along the fill direction.

Table 1. Failure strain and failure stress (strength) from each test.

Test	E^{fail}	S^{fail} (GPa)
W1	0.122633	0.542566
W2	0.144261	0.516930
W3	0.132930	0.520462
W4	0.128275	0.514715
W5	0.119819	0.424321
F1	0.145151	0.642427
F2	0.149961	0.631463
F3	0.160437	0.592621
F4	0.143361	0.605060
F5	0.146129	0.596035

Coefficients a, b, c, d, e, and f were evaluated by a nonlinear least squares error procedure. *Mathematica* software[4] was employed. The resulting fits are presented in table 2 and in figures 6–13. For each of these four fits, the two poles in equation 13 occur at complex values of E, so the rational function properly remains bounded.

Table 2. Least-squares fit parameters.

Coefficients	W3	W1–5	F2	F1,2,4,5
a (GPa)	1.35322	1.65620	1.79587	0.872878
b (GPa)	–98.8705	–128.102	–204.612	–57.6990
c (GPa)	2727.95	3881.13	14539.8	7214.87
d (GPa)	–4898.41	–10674.6	–33428.5	–14475.3
e	–22.0527	–15.6910	–34.3400	–28.6378
f	465.297	476.711	2137.94	1266.84
E^{fail}	0.132930	0.129584	0.149961	0.146151

2.2.1 Warp Direction

In figure 4, the stress-strain data from the five warp-direction tests display some variation from test to test. Test W3 was deemed to be representative of the other four and it was fitted in table 2 and figure 6. The W3 fit is seen to closely follow the data overall, although there is some curvature deviation in the region of small strain (see figure 7). Figures 8 and 9 re-present the figure 4 data from all five warp tests over the entire strain range and a small-strain range, respectively. The “W3” fit of data from test W3 alone has been reproduced from figures 6 and 7. To this has been added a fit, labeled “W1–5,” to all data from the five warp tests. The coefficients to this second fit are added to table 2. In the table, E^{fail} for fit “W1–5” has been averaged over the five tests. Figure 9 shows that this averaged fit, while generally following the data closely, also displays some curvature deviation at small strain. For strains of about 0.2, the fit W1–5 lies at the edge of the experimental data, whereas fit W3 lies slightly below the data.

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[4] Wolfram, S. *The Mathematica Book*; 4th ed.; Cambridge University Press: Cambridge, UK, 1999.

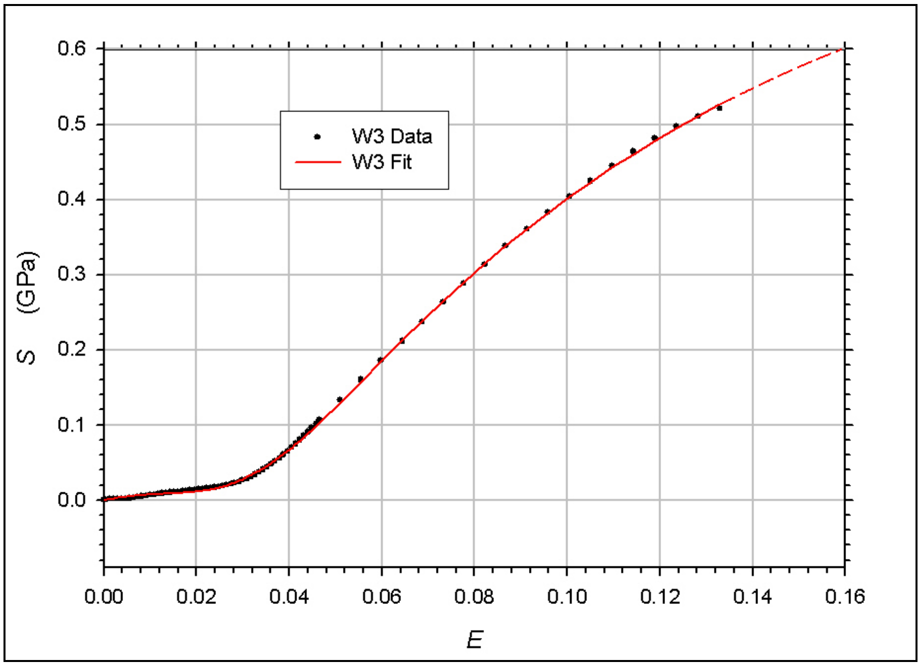

Figure 6. Least-squares fit for second Piola-Kirchhoff stress vs. Green-St. Venant strain from test W3.

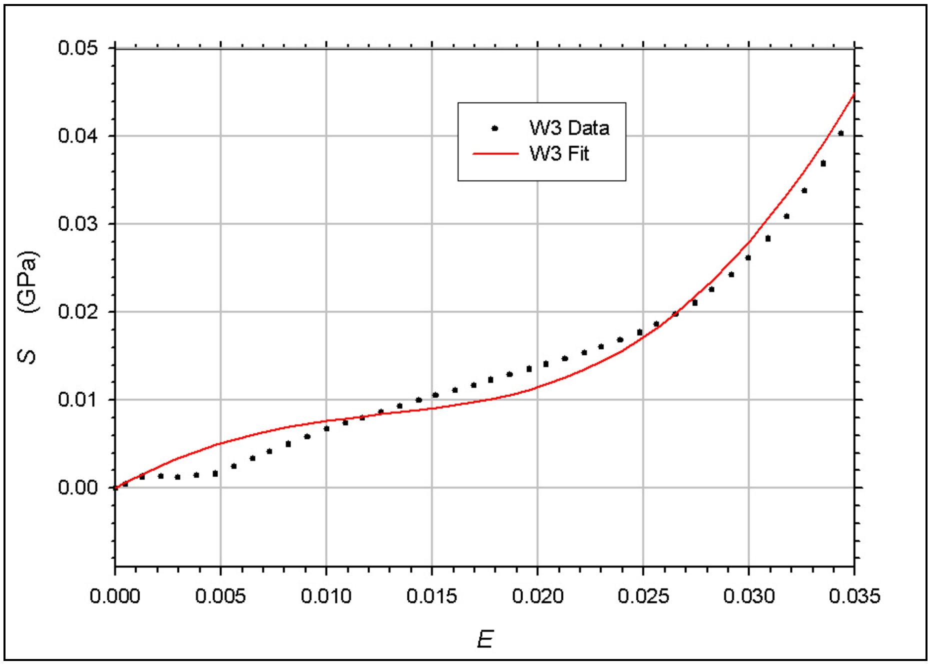

Figure 7. Least-squares fit for second Piola-Kirchhoff stress vs. Green-St. Venant strain from test W3 in the small strain range.

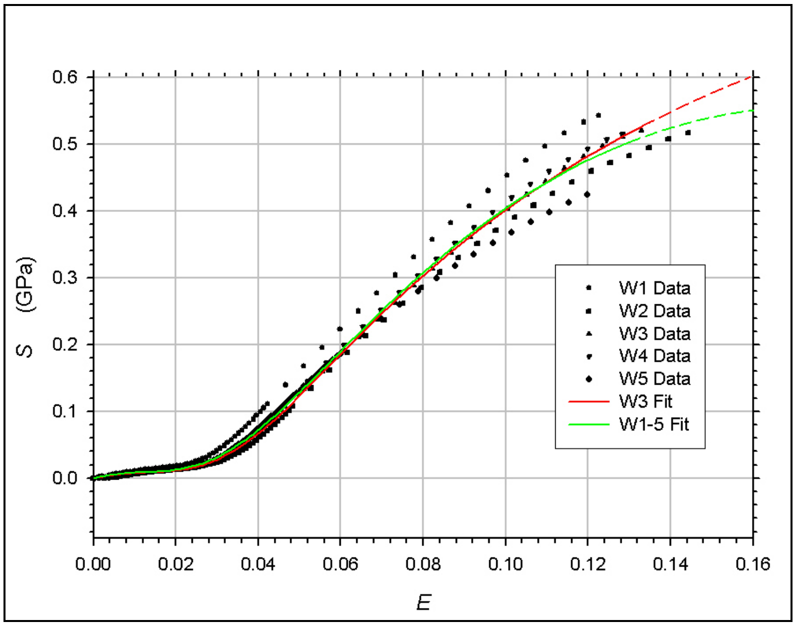

Figure 8. Least-squares fit for second Piola-Kirchhoff stress vs. Green-St. Venant strain from test W3 and from the averaged tests W1 through W5.

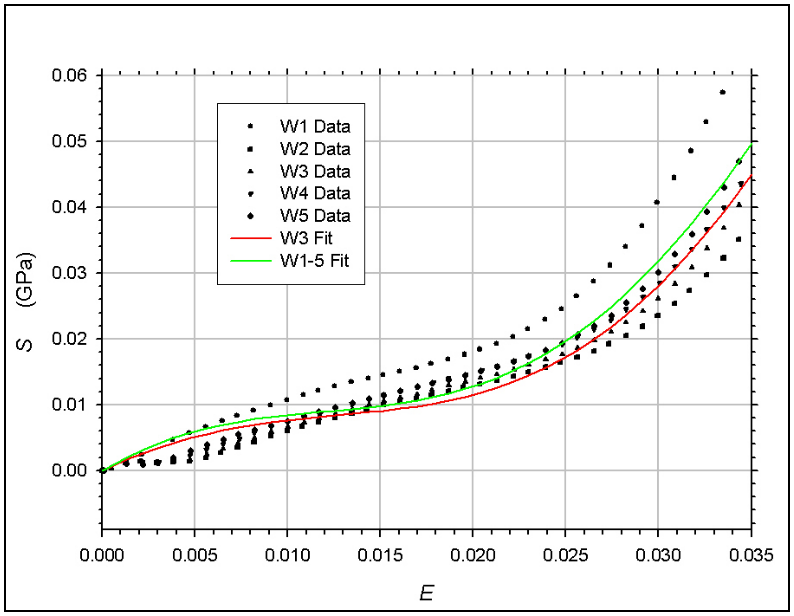

Figure 9. Least-squares fit for second Piola-Kirchhoff stress vs. Green-St. Venant strain from test W3 and from the averaged tests W1 through W5 in the small-strain range.

2.2.2 Fill Direction

In figure 5 the stress-strain data from the five fill-direction tests are presented. Test F2 was deemed to be representative and it was fitted in table 2 and figures 10 and 11 for the entire strain range and the small-strain range, respectively. The F2 fit is seen to closely follow the data overall, including in the region of small strain.

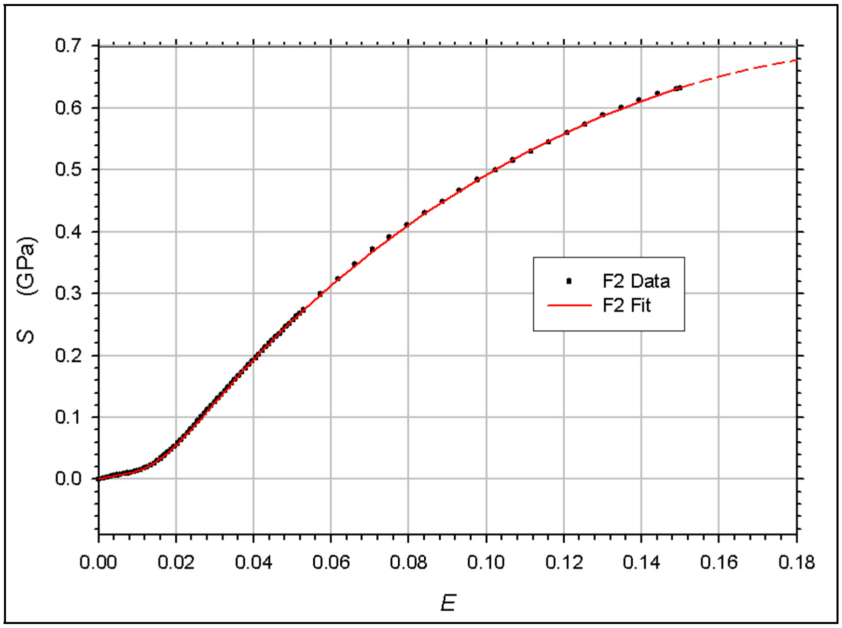

Figure 10. Least-squares fit for second Piola-Kirchhoff stress vs. Green-St. Venant strain from test F2.

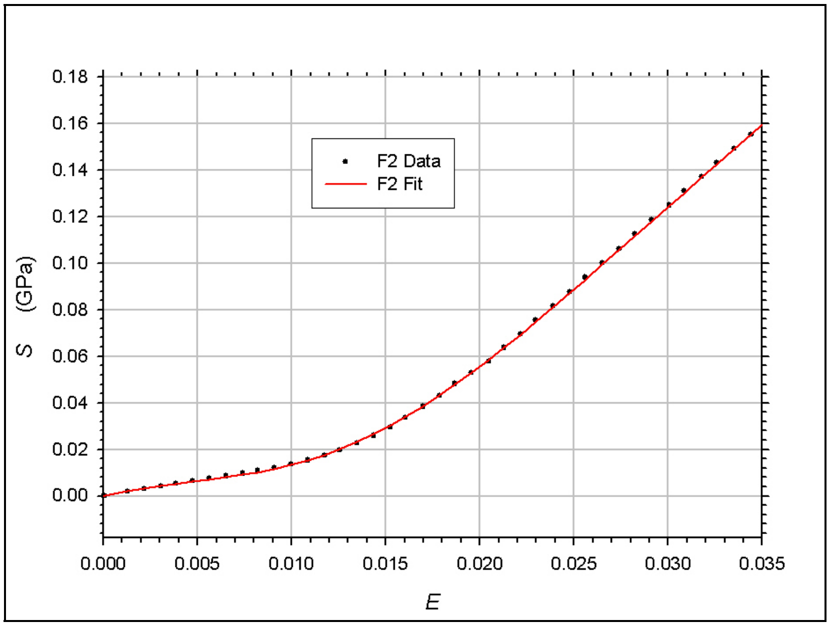

Figure 11. Least-squares fit for second Piola-Kirchhoff stress vs. Green-St. Venant strain from test F2 in the small-strain range.

In figure 12 data from four fill tests, namely F1, F2, F4, and F5, have been included in the single fit. The fifth test, F3, was rejected as an outlier based on its relatively large deviations from the other tests in figure 5. The coefficients are presented in table 2. In the table, E^{fail} for this averaged fit "F1,2,4,5" has been averaged over the four tests. Figure 13 shows that this averaged fit generally follows the data at small strain.

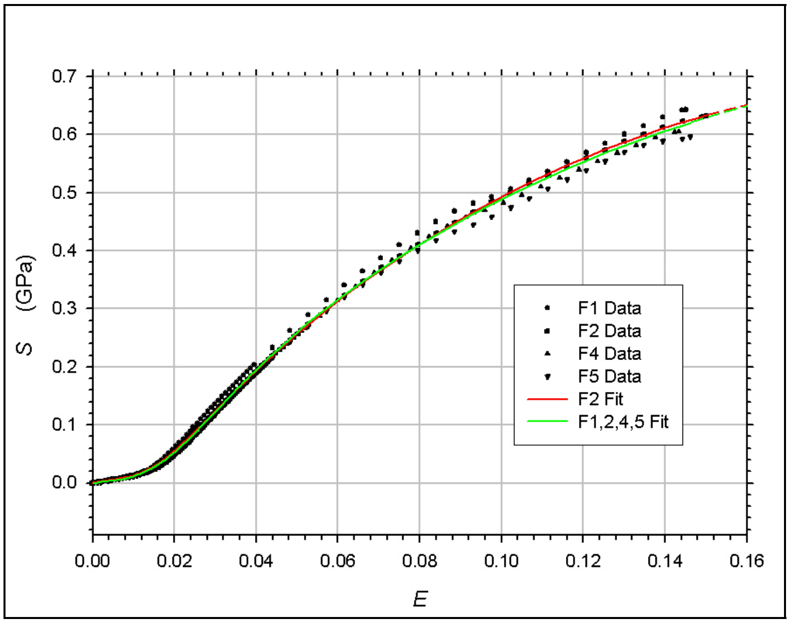

Figure 12. Least-squares fit for second Piola-Kirchhoff stress vs. Green-St. Venant strain from tests F1, F2, F4, and F5 and from test F2.

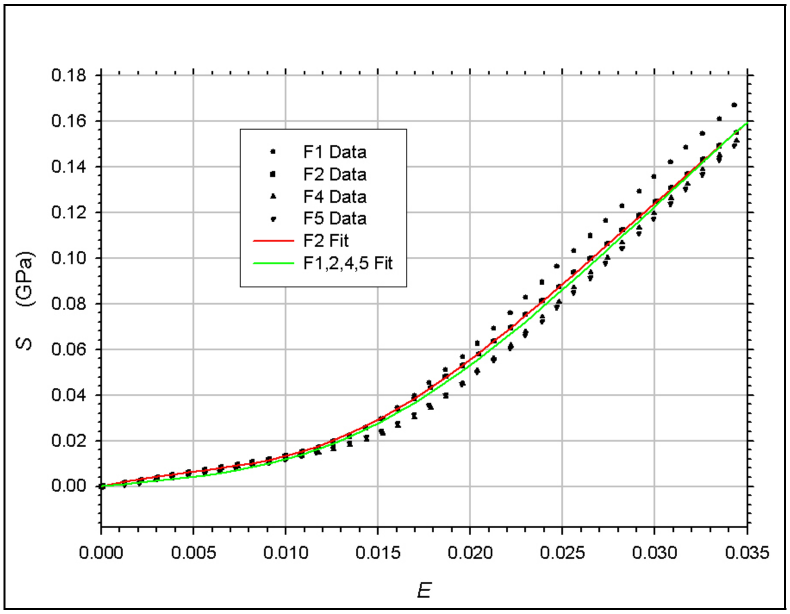

Figure 13. Least-squares fit for second Piola-Kirchhoff stress vs. Green-St. Venant strain from tests F1, F2, F4, and F5 and from test F2 in the small-strain range.

In figures 12 and 13, the averaged fit F1,2,4,5 and the F2 fit are seen to agree closely with each other. Both fits fall within the range of experimental stress data throughout the strain domain.

3. Discussion

Mulkern and Raftenberg[1] also presented strength data for single plies of plain-woven, 600-denier KM2. Those tests were performed with larger specimens, 50.8 mm in width and 254 mm in initial separation between the two clamps. Strength results in table 5 of Mulkern and Raftenberg range from 2.07 to 2.33 GPa for warp-loaded specimens and 2.47–2.77 GPa for fill-loaded specimens. Before comparing these numbers to those in our table 1, the former must be adjusted to account for the different evaluation of cross-sectional area A_0 that was applied in the earlier report. Since the main goal in Mulkern and Raftenberg was to compare the plain-woven single-ply strength to single-yarn strength, the effective thickness of the ply was evaluated based on the cross-sectional area occupied by the yarns. This resulted in an effective ply thickness of 0.0606 mm, substantially smaller than the 0.227 mm obtained in section 2.1 of the present report. The ratio of the two thicknesses is 3.75.

The strengths in table 5 of Mulkern and Raftenberg are divided by 3.75 to give strength ranges from 0.552 to 0.621 GPa for warp-loaded tests and from 0.659 to 0.739 GPa for fill-loaded tests. Our strength results in table 1 range from 0.424 to 0.543 GPa for warp-loaded and from 0.593 to 0.642 GPa for fill-loaded tests. Hence, our strength results in table 1 are consistently smaller than those reported in table 5 of Mulkern and Raftenberg. This discrepancy may reflect differences in the two sets of specimens. Alternatively, this discrepancy may reflect a systematic error in one set of experiments, e.g., slippage at a clamp.

Our failure strain results in table 1 can be compared with results in another report on plain-woven 600-denier KM2, Raftenberg and Mulkern.[2] Since the gauge length in Raftenberg and Mulkern was not determinable, no strains were reported. However, the crosshead displacements at failure, plotted in figure 13 of Raftenberg and Mulkern, clearly show larger values for the warp-loaded tests than for the fill-loaded tests. This trend was attributed to the presence of greater initial crimping in the warp than in the fill yarns. In contrast, our table 1 shows larger failure strains for the fill-oriented tests than for the warp-oriented tests. This trend in our table 1 is therefore inconsistent with that reported in Raftenberg and Mulkern. The explanation for this discrepancy is also unclear. Differences between the two sets of specimens or a systematic error in one set, such as slippage at a clamp, are two possible sources.

4. Summary

We analyzed data from quasistatic, uniaxial tension tests on single-ply specimens of plain-woven, 600-denier KM2. Failure strains were found to range from 0.120 to 0.144 for warp-loaded and from 0.143 to 0.160 for fill-loaded tests. Failure stresses (strengths) ranged from 0.424 to 0.543 GPa for warp-loaded and from 0.593 to 0.642 GPa for fill-loaded tests. A least-squares fit, in the form of a rational function, was obtained to the second Piola-Kirchhoff stress vs. Green-St. Venant strain data for a representative warp-direction and a representative fill-direction test. In addition, averaged least-square fits of all the warp data and of data from four out of five fill tests were obtained, also in the form of a rational function. These fits are intended to inform constitutive modeling in numerical simulations.

List of Symbols, Abbreviations, and Acronyms

A_o	initial cross-sectional area of the smaller platen
$\mathbf{E}$	Green-St. Venant (Lagrangian) strain tensor
E_{ij}	component *ij* of $\mathbf{E}$
E_{11}, E	normal component of the Green-St. Venant (Lagrangian) strain along the load direction
E_{11}^{fail}, E^{fail}	the values of E_{11}, E corresponding to specimen rupture in the tension test
$\mathbf{F}$	deformation gradient tensor
F	tensile force applied to the fabric specimen
$\mathbf{I}$	identity tensor
L_0	specimen gauge length (initial separation between the two grips)
$\mathbf{S}$	second Piola-Kirchhoff stress tensor
S_{ij}	component *ij* of $\mathbf{S}$
S_{11}, S	normal component of the second Piola-Kirchhoff stress along the load direction
S_{11}^{fail}, S^{fail}	the values of S_{11}, S corresponding to specimen rupture in the tension test
$\mathbf{T}^{\mathbf{0}}$	first Piola-Kirchhoff stress tensor
$\mathbf{X}$	material coordinate vector
X_1, X_2, X_3	material coordinates
a, b, c, d, e, f	coefficients in a fit to S vs. E
t	time
$\mathbf{x}$	spatial coordinate vector
x_1, x_2, x_3	spatial (laboratory) coordinates
Δ	relative displacement of the two grips
ϕ_{ij}	constitutive function relating S_{ij} to E_{ij}

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