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Transverse Compression Response of a Multi-Ply Kevlar Vest

by Martin N. Raftenberg, Michael J. Scheidler, and Paul Moy

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14. ABSTRACT

Each of the two 38 × 38-cm square panels, consisting of 28 plies of plain-woven 600-denier Kevlar KM2 and a Cordura case, was loaded in quasistatic, transverse compression by means of an Instron machine. Constitutive assumptions were introduced to allow for calculation of Green-St. Venant strain, second Piola-Kirchhoff stress, and Cauchy stress. A least squares fit in the form of a rational function was obtained for each second Piola-Kirchhoff stress vs. Green-St. Venant strain curve.

15. SUBJECT TERMS

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

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1. Introduction

A "soft" body-armor vest is typically composed of multiple plies of plain-woven Kevlar* fabric. When a bullet strikes, the vest undergoes out-of-plane displacement, during which its warp and fill yarns are placed in tension. In this sense, the vest behaves structurally, at least in part, as an anisotropic membrane. In addition to in-plane tension of the yarns, those yarns in the region of impact also undergo transverse compression. The processes of yarn axial tension and transverse compression both contribute to the spatial and temporal spreading of the load transmitted to the torso backing the vest, as well as to energy extraction from the bullet. The transverse compression contribution has been generally neglected by fabric modelers, but its relative importance has apparently not been studied to date. The relative importance of transverse compression is likely to grow when the armor is backed by the human torso or some surrogate thereof as opposed to unbacked, since such backings impede out-of-plane motion.

In the present study, quasistatic, transverse compression tests were performed on a square specimen composed of 28 plies of plain-woven Kevlar KM2 enclosed in a Cordura* case. The tests are described in section 2. Force-deflection data are presented in section 3.1 and converted to stress and strain in section 3.2. This conversion required constitutive assumptions for the fabric material. Section 3.2 also presents least squares fits to stress-strain curves in the form of a rational function. The resulting analytical representations are intended to inform constitutive modeling of the vest as an orthotropic material. Section 4 contains a brief summary.

2. Methods

Square panels with a 38 cm edge length were purchased from Point Blank Corporation. The panels consisted of 28 plies of 600-denier Kevlar KM2 enclosed in a Cordura case. The 28 plies were stitched together at each of the four corners of the panel. The stitching crossed the corner diagonally and was offset about 2 cm from the corner. The initial thickness of the specimen was measured to be 6.35 mm.

An Instron 4505 testing machine† was used with a load cell rated at 100 kN. A portion of the vest was sandwiched between two platens, one with a 51-mm diameter and the other with a 152-mm diameter. The platens were smooth and no lubrication was applied. A constant crosshead displacement rate of 0.0212 mm/s was imposed.

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*Kevlar and Cordura are registered trademarks of DuPont.

†Further reading can be found in: Instron Corporation. *The Series 4500 Floor Model Load Frame, Operators Guide*. Manual no. M10-4500-5, Issue B, Canton, MA: Instron, June 1988.

Two compression tests were performed on fabric specimens. In both tests, a crosshead velocity of 0.0212 mm/s was maintained until the 100-kN load-cell capacity was reached. In test 1, the panel was loaded at its center. In test 2, the load was applied at a location about 10 cm from the center and 12 and 13 cm from the two nearest edges of the panel. In order to quantify the machine compliance contribution to the total crosshead displacements in tests 1 and 2, a third compression test was performed without a fabric specimen present.

3. Results and Discussion

3.1 Force and Displacement

Measurements of the load cell force, F, as a function of the imposed crosshead displacement, Δ, are presented from three tests in figure 1. Tests 1 and 2 included a fabric specimen, and the third test did not. In figure 1, for each force F, the crosshead displacement in the third test has been subtracted from the results for tests 1 and 2. The positive curvature ($d^2F/d\Delta^2 > 0$) exhibited by the two data curves in figure 1 corresponds to an increasing stiffness with increasing load. A contribution to this stiffness increase is the progressive squeezing out of air.

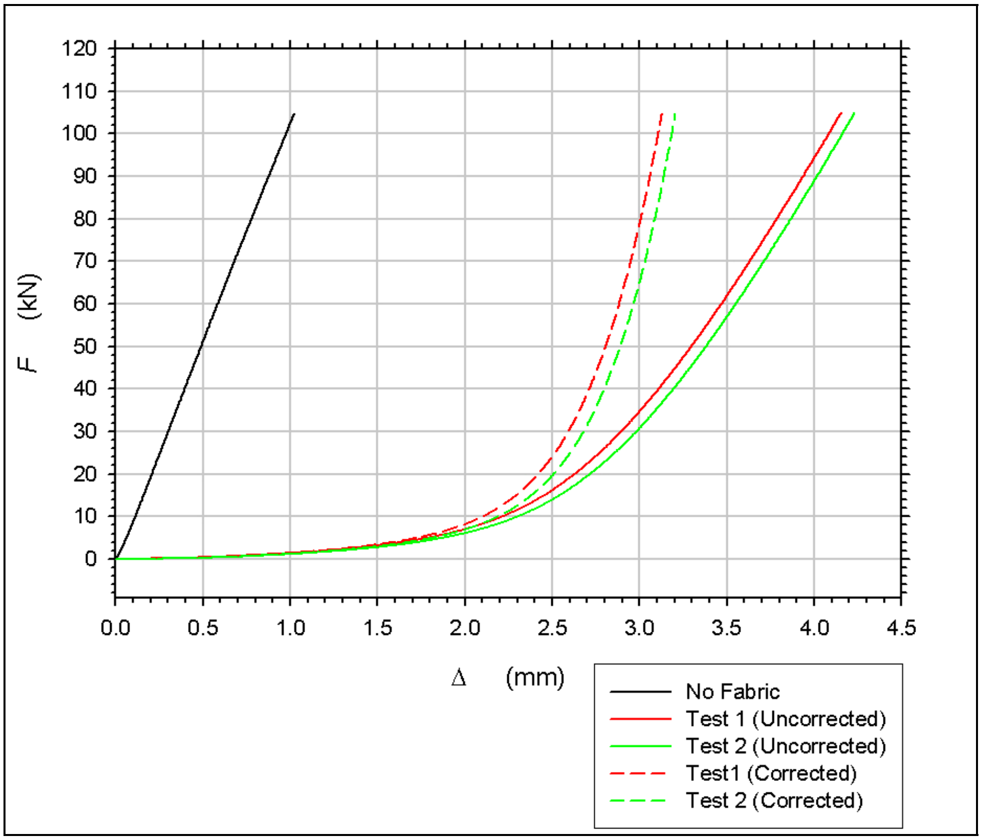

Figure 1. Compressive force-crosshead displacement data for the vest under quasistatic, transverse compression.

3.2 Stresses and Strain

In order to relate load cell force and crosshead displacement to stress and strain, we introduce constitutive and kinematics assumptions. We adopt the notation in Malvern (1969).

The entire 28-ply vest is modeled as a homogeneous, orthotropic continuum. Cartesian material coordinates X_1, X_2, and X_3 are defined in figure 2. The plane $X_3 = 0$ coincides with one free surface of the vest. The vest has initial thickness L_0, so the plane $X_3 = L_0$ coincides with the opposite free surface. In the case of our specimen, L_0 is 6.35 mm. As shown in figure 3, the X_1 and X_2 axes are aligned with the warp and fill yarns, respectively (neglecting the yarns' initial crimp). X_1, x_2, and x_3 are the corresponding coordinates of the deformed material; thus they coincide with X_1, X_2, and X_3 coordinates in the undeformed state.

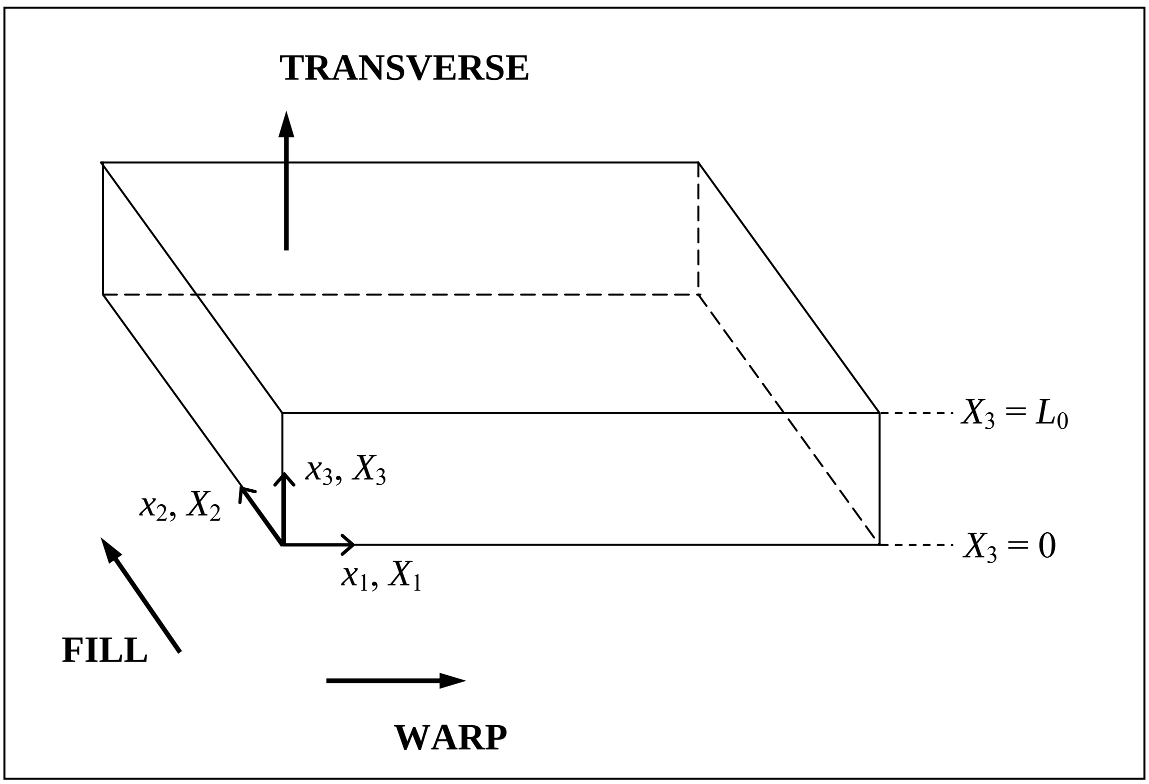

Figure 2. The vest in its undeformed configuration, with the coordinate system indicated.

The deformation gradient tensor, **F**, is given by

$$\mathbf{F} = \frac{\partial \mathbf{x}}{\partial \mathbf{X}} \, , \tag{1}$$

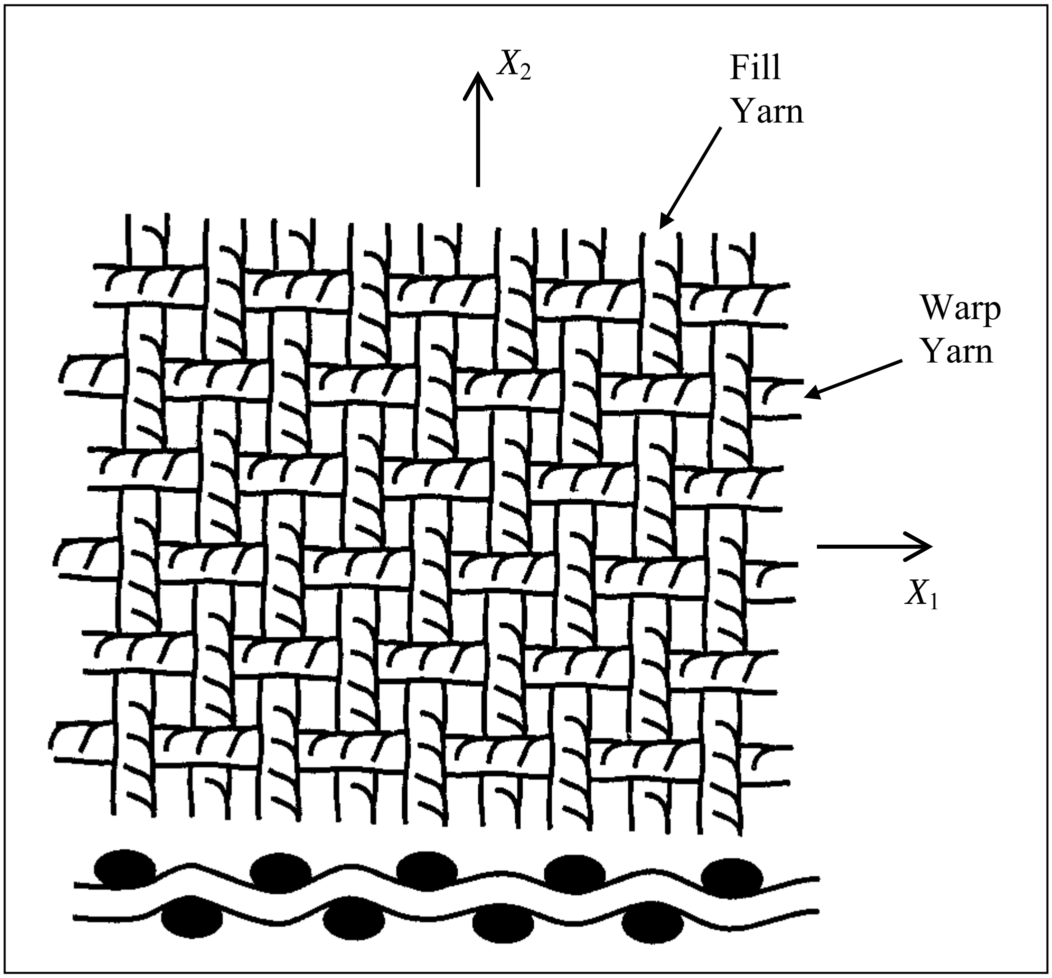

Figure 3. Sketch of the plain-weave construction of the vest.

Where $\mathbf{X} = (X_1, X_2, X_3)$ and $\mathbf{x} = (x_1, x_2, x_3)$. The Green-St. Venant strain tensor, $\mathbf{E}$, defined by

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

has six independent components. E_{11}, E_{22}, and E_{33} represent the normal strains along the coordinate axes. E_{12} is the in-plane shear between warp and fill yarns, and E_{23} and E_{31} are the transverse shear strains.

Let $\mathbf{T}$, $\mathbf{T^0}$, and $\mathbf{S}$ denote the Cauchy, first Piola-Kirchoff, and second Piola-Kirchoff stress tensors, respectively. They are interrelated by

$$\mathbf{S} = \mathbf{T^0} \cdot \mathbf{F}^{-T} \tag{3}$$

and

$$\mathbf{T} = \frac{\mathbf{F} \cdot \mathbf{S} \cdot \mathbf{F}^T}{J} \ , \tag{4}$$

where

$$J = \det \mathbf{F} \ . \tag{5}$$

The six components of the second Piola-Kirchhoff stress, resolved along the coordinate axes, are S_{11}, S_{22}, S_{33}, S_{12}, S_{23}, and S_{31}.

We assume that the entire vest (all 28 plies) can be represented as a homogeneous, orthotropic, hyperelastic continuum. In terms of the X_1, X_2, and X_3 coordinates, we further assume constitutive decoupling of the form

$$\begin{aligned} S_{11} &= \phi_{11}\left(E_{11}\right) \\ S_{22} &= \phi_{22}\left(E_{22}\right) \\ S_{33} &= \phi_{33}\left(E_{33}\right) \\ S_{12} &= \phi_{12}\left(E_{12}\right) \\ S_{23} &= \phi_{23}\left(E_{23}\right) \\ S_{31} &= \phi_{31}\left(E_{31}\right), \end{aligned} \tag{6a}$$

where

$$\phi_{11}(0) = \phi_{22}(0) = \phi_{33}(0) = \phi_{12}(0) = \phi_{23}(0) = \phi_{31}(0) = 0 \ . \tag{6b}$$

That is, the vest's warp, fill, and transverse normal responses and its three shear responses are all mutually decoupled. This decoupling assumption is motivated by the plain-weave construction of each ply of the vest, which is sketched in figure 3. In-plane tensile loading of the warp (fill) yarns produces relatively little deformation of the orthogonal family of fill (warp) yarns. The amount of coupling under quasistatic, biaxial, in-plane tension has been measured and found to be small in fabrics other than Kevlar (e.g., Kageyama et al. [1988]) for plain-woven wool. No such biaxial study has been documented for Kevlar. Similarly (and more relevant to this report), the presence of the initial gaps between yarns motivates the assumption that compressive normal loading in the transverse direction produces relatively little elongation of the warp and fill yarns. (Admittedly, figure 3 greatly exaggerates the size of these gaps in the case of our vest.)

The elasticity assumption has been adopted by most constitutive modelers of Kevlar (e.g., Johnson et al. [1999] and Walker [1999]). To our knowledge, all published constitutive data for woven Kevlar fabric have been quasistatic. Hence, there are no available data on which to directly base an inelastic model for Kevlar.

The constitutive decoupling assumptions of equation 6 ensure that conditions of uniaxial stress and uniaxial strain occur simultaneously, i.e., that uniaxial stress implies uniaxial strain, and vice versa. For a general specimen material, the smooth platens would make the uniaxial stress condition plausible for the early stage of a transverse compression test. Friction between specimen and platens would increase continuously throughout the test, eventually leading to an approximation of uniaxial strain. For our decoupled material of equation 6, the conditions of uniaxial stress and strain would both apply early in the test as well as late in the test. We further assume that both conditions applied throughout the transverse compression tests on fabric.

The condition of uniaxial stress implies that the first Piola-Kirchhoff stress tensor, $\mathbf{T^0}$, in the region between the platens was given by

$$\mathbf{T^0} = -\frac{F}{A_0}\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} . \tag{7}$$

Here, A_0 is the initial area of the smaller platen and F is again the load cell force taken positive in compression. Uniaxial strain implies that deformation within the vest throughout the transverse compression test can be described by

$$\begin{aligned} x_1 &= X_1 \\ x_2 &= X_2 \\ x_3 &= X_3\left(1-\delta\right). \end{aligned} \tag{8}$$

Here, δ is the nominal strain in the transverse direction, taken to be positive in compression. It is measured by the crosshead displacement scaled by the vest's initial thickness, or

$$\delta = \frac{\Delta}{L_0} . \tag{9}$$

Note that $\delta \rightarrow 1$ as $\Delta \rightarrow L_0$. Substitution of equations 8 and 9 into equations 1–5 yields the following evaluations for **F**, **E**, **S**, and **T**:

$$\mathbf{F} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1-\delta \end{bmatrix} , \tag{10}$$

$$\mathbf{E} = \left(-\delta + \frac{\delta^2}{2} \right)\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} , \tag{11}$$

$$\mathbf{S} = -\frac{F}{A_0(1-\delta)}\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} , \tag{12}$$

and

$$\mathbf{T} = -\frac{F}{A_0}\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} = \mathbf{T^0} \ . \tag{13}$$

In particular, the transverse normal components of the Green-St. Venant strain, the second Piola-Kirchhoff stress, and the Cauchy stress are

$$E_{33} = -\delta + \frac{\delta^2}{2} \ , \tag{14}$$

$$S_{33} = -\frac{F}{A_0(1-\delta)} = \frac{T_{33}}{1-\delta} \ , \tag{15}$$

and

$$T_{33} = -\frac{F}{A_0} \ . \tag{16}$$

Note from equation 9 that $\delta \rightarrow 1$ as $\Delta \rightarrow L_0$. This limit corresponds to the vest compressed to zero thickness and hence constitutes an unreachable upper bound on δ. In a compression test δ is therefore restricted to the range $0 < \delta < 1$. Further note from equation 14 that $E_{33} \rightarrow -1/2$ as $\delta \rightarrow 1$, so that $-1/2$ constitutes a lower bound on E_{33}. Since $0 < \delta < 1$ in compression, we have from equations 15 and 16 that $-S_{33} > -T_{33}$ in these tests (recall that stress is positive in tension). S_{33} and T_{33} are plotted as functions of E_{33} in figures 4 and 5, respectively.

The curves for tests 1 and 2 in figure 4 can be closely approximated by a function of the form

$$S_{33} = \frac{aE_{33} + bE_{33}^{\ 2} + cE_{33}^{\ 3} + d\,E_{33}^{\ 4}}{(1+2E_{33})^2\,(1+e\,E_{33} + f\,E_{33}^{\ 2})} \ . \tag{17}$$

Note that this functional form, with its singularity at $E_{33} = -1/2$, insures the required condition of unbounded stress as $E_{33} \rightarrow -1/2$. We used Mathematica (Wolfram, 1999) to evaluate the six coefficients, *a*, *b*, *c*, *d*, *e*, and *f*, by applying a nonlinear least squares procedure to the global error. The resulting coefficient values for the two tests are given in table 1. The resulting fits are plotted along with the data in figures 6–8 for test 1 and figures 9–11 for test 2. In figures 6 and 9, the stress is plotted on a log scale; note that the S_{33} fit does indeed become unbounded as $E_{33} \rightarrow -1/2$.

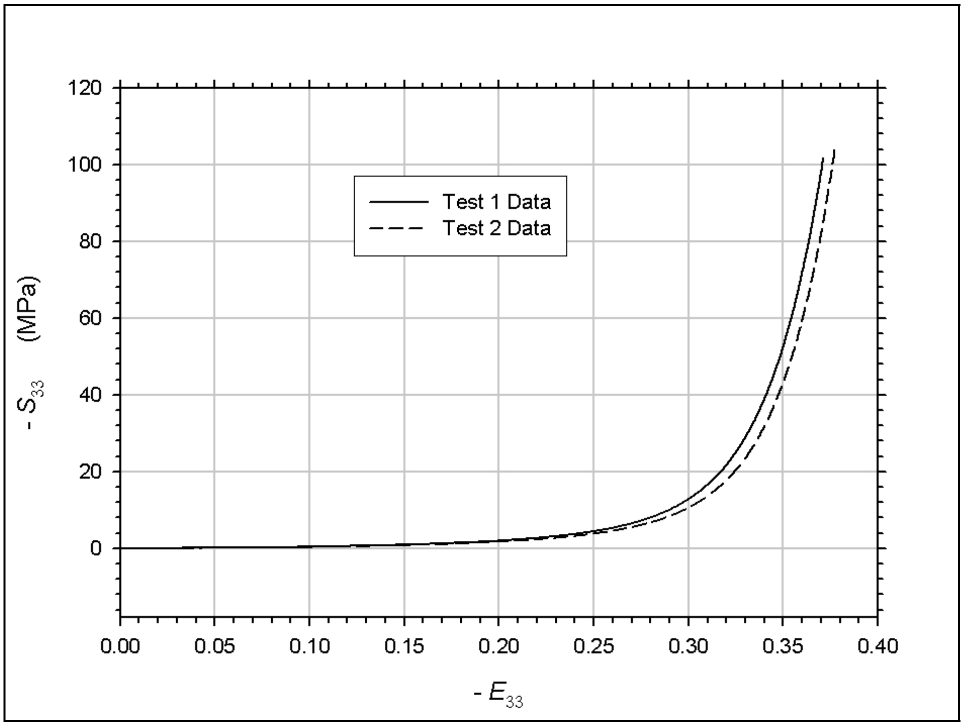

Figure 4. Second Piola-Kirchhoff stress vs. Green-St. Venant strain for the vest under quasistatic, transverse compression in tests 1 and 2.

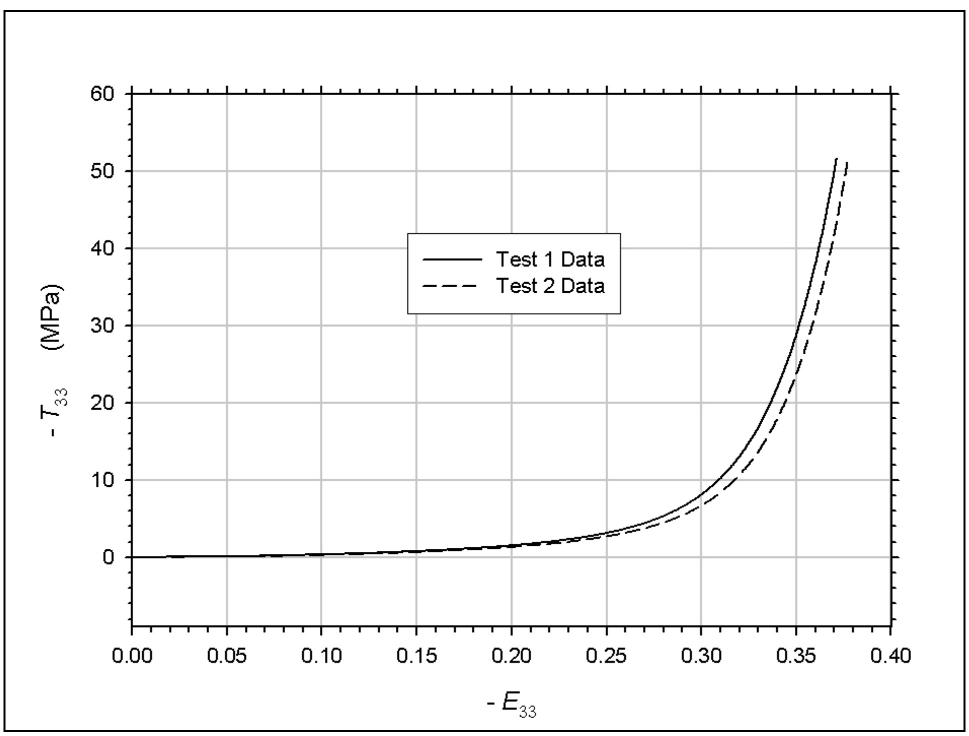

Figure 5. Cauchy stress vs. Green-St. Venant strain for the vest under quasistatic, transverse compression in tests 1 and 2.

Table 1. Least squares fit parameters.

Coefficient	Test 1	Test 2
a (MPa)	1.25770	0.550219
b (MPa)	–7.68533	–13.3413
c (MPa)	–71.1591	–86.6872
d (MPa)	–135.116	–146.099
e	4.74248	4.65902
f	6.00453	5.78536

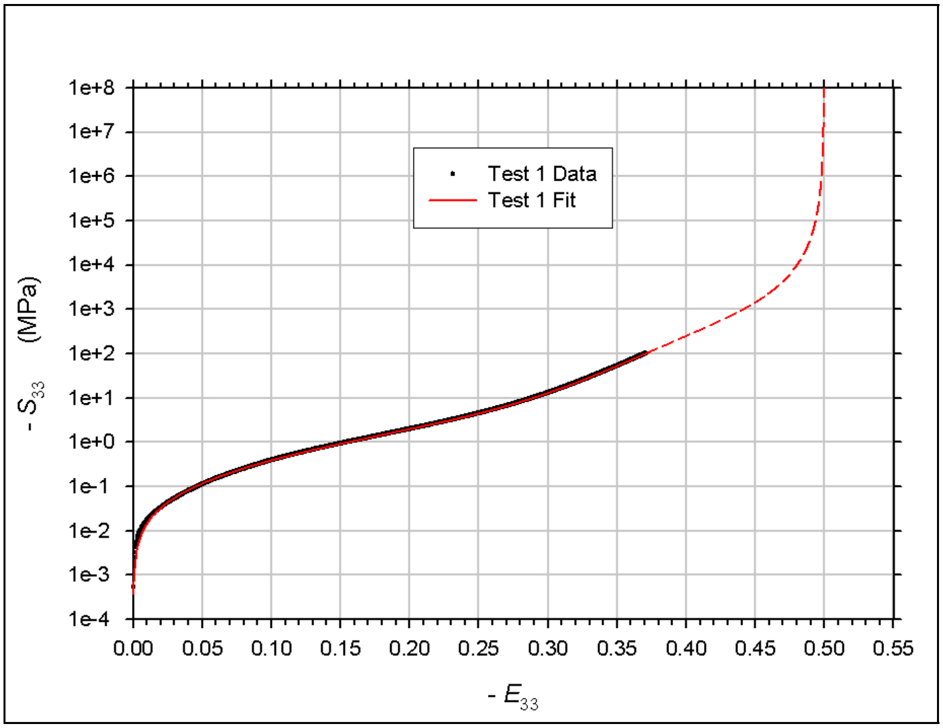

Figure 6. Second Piola-Kirchhoff stress vs. Green-St. Venant strain for the vest under quasistatic, transverse compression in test 1.

The quantity dS_{33}/dE_{33} provides a measure of the fabric's transverse stiffness and constitutes a nonlinear elastic modulus. From equation 17,

$$\frac{dS_{33}}{dE_{33}} = \frac{F_1 - F_2}{F_3} \quad , \tag{18a}$$

where

$$F_1 = (1+2E_{33})^2 \, (1+e\,E_{33} + f\,E_{33}{}^2)\,(a+2bE_{33}+3cE_{33}{}^2+4d\,E_{33}{}^3) \; , \tag{18b}$$

$$F_2 = (1+2E_{33})^2 \, (aE_{33}+bE_{33}{}^2+cE_{33}{}^3+d\,E_{33}{}^4)[4+e+2(3e+f)E_{33}+8f\,E_{33}{}^2] \; , \tag{18c}$$

and

$$F_3 = (1+2E_{33})^4 \, (1+e\,E_{33} + f\,E_{33}{}^2)^2 \; . \tag{18d}$$

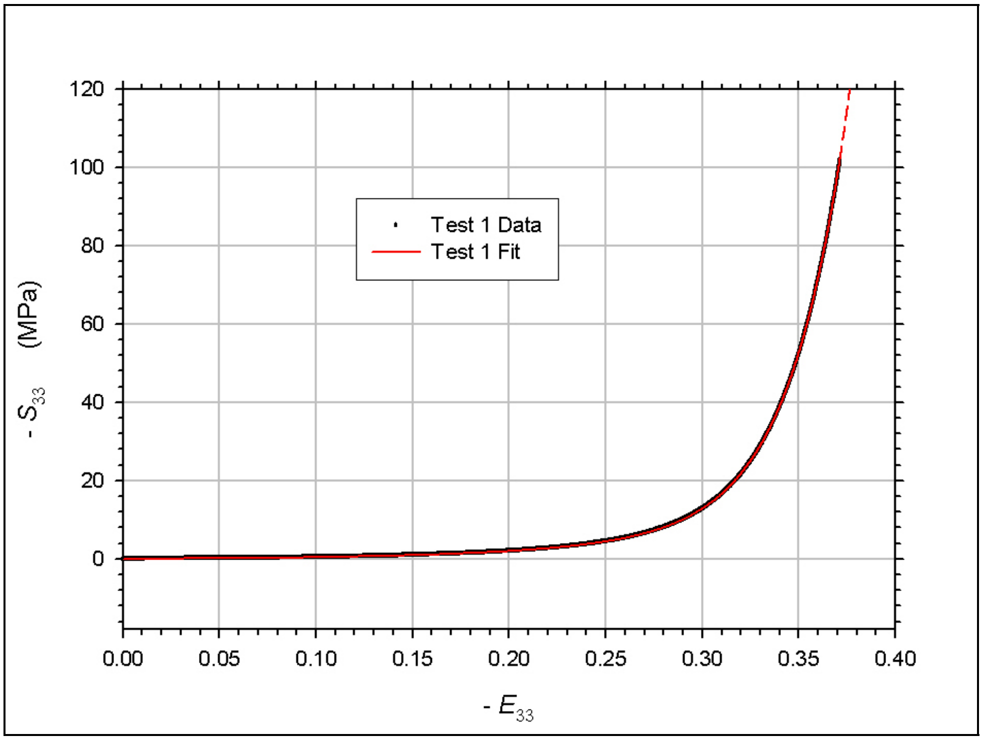

Figure 7. Second Piola-Kirchhoff stress vs. Green-St. Venant strain for the vest under quasistatic, transverse compression in test 1.

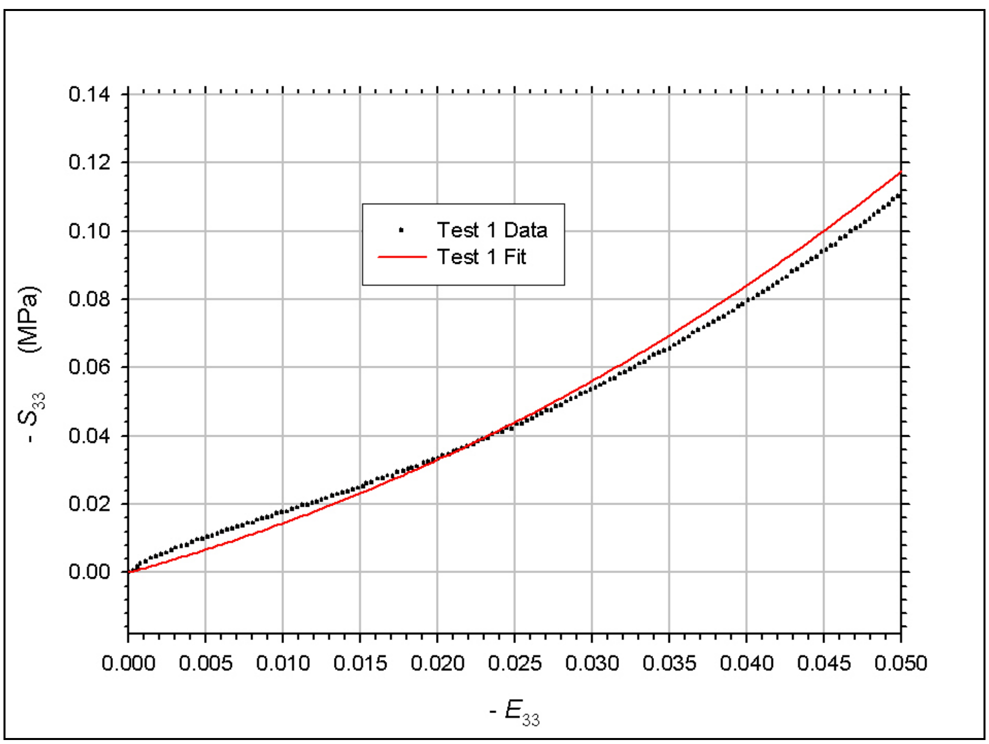

Figure 8. Second Piola-Kirchhoff stress vs. Green-St. Venant strain for the vest under quasistatic, transverse compression for the small-strain range in test 1.

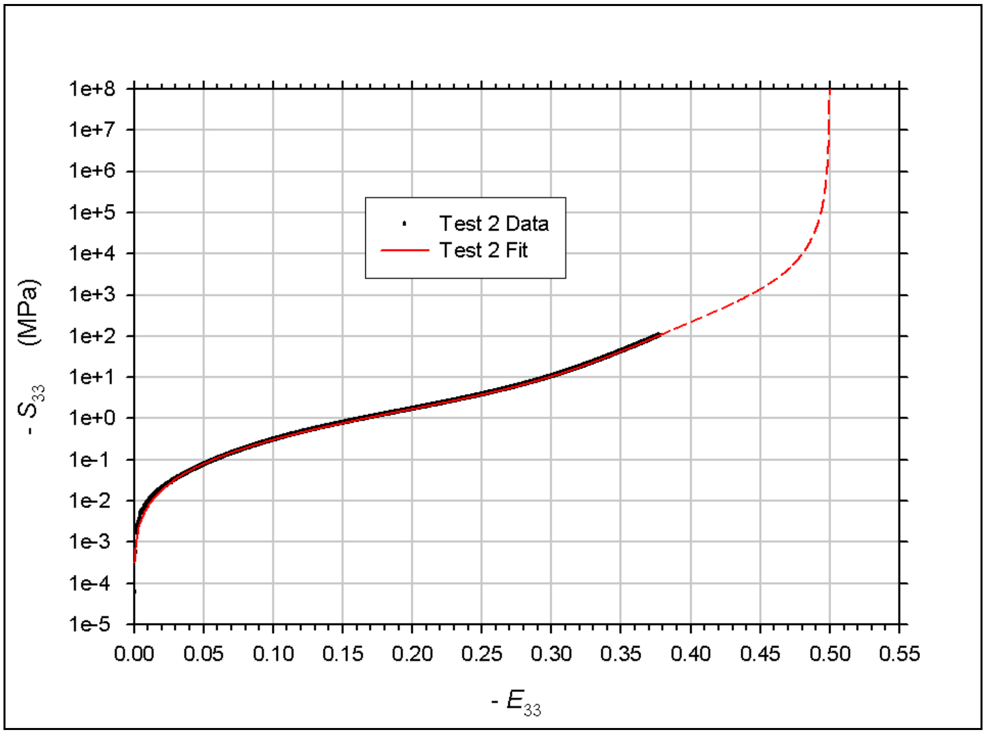

Figure 9. Second Piola-Kirchhoff stress vs. Green-St. Venant strain for the vest under quasistatic, transverse compression in test 2.

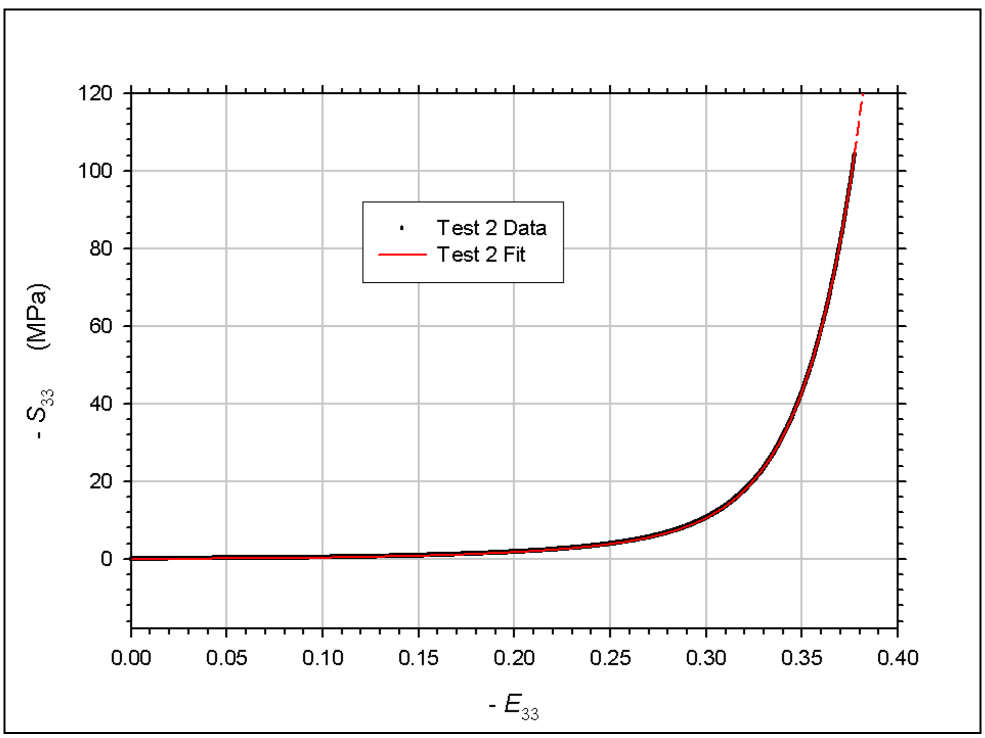

Figure 10. Second Piola-Kirchhoff stress vs. Green-St. Venant strain for the vest under quasistatic, transverse compression in test 2.

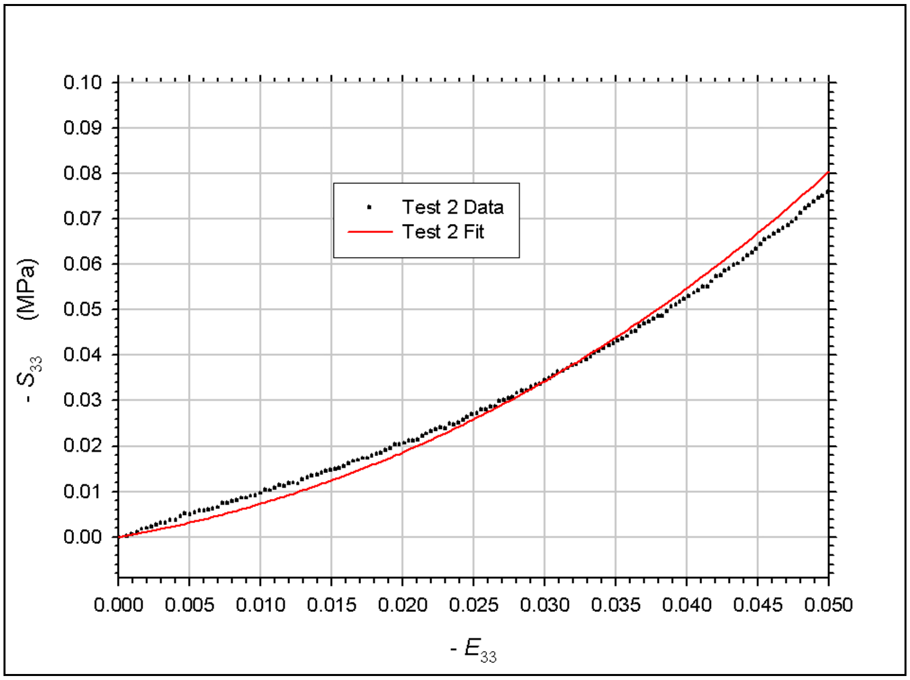

Figure 11. Second Piola-Kirchhoff stress vs. Green-St. Venant strain for the vest under quasistatic, transverse compression for the small strain range in test 2.

The quantity dS_{33}/dE_{33} is evaluated from the fits to tests 1 and 2. The results are presented in figure 12.

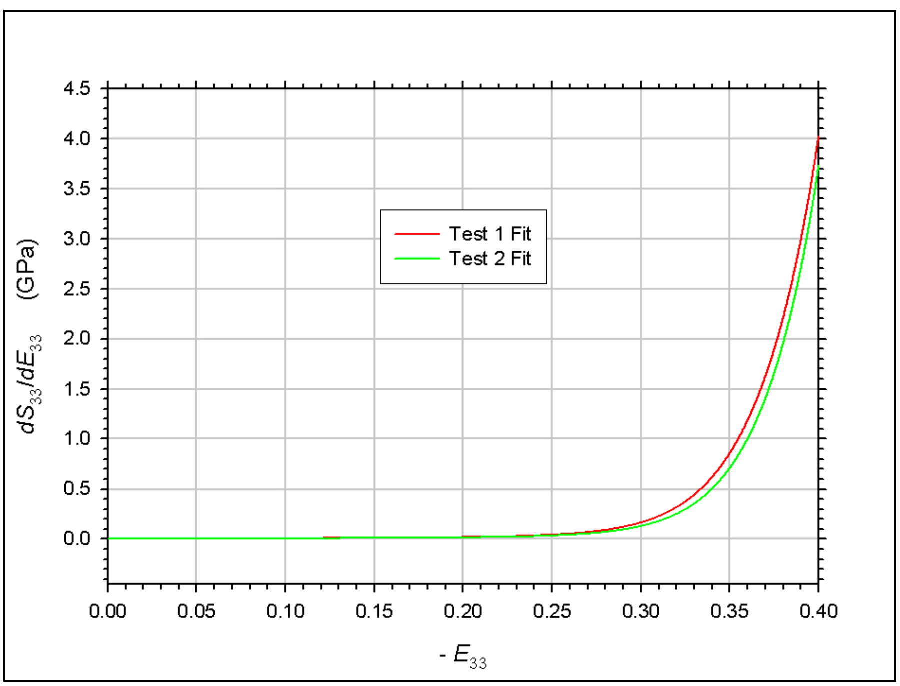

Figure 12. Elastic modulus based on second Piola-Kirchhoff stress vs. Green-St. Venant strain for the vest under quasistatic, transverse compression.

4. Summary

The 38 × 38-cm square test panels consisted of 28 plies of plain-woven, 600-denier Kevlar KM2 enclosed in a Cordura case. Each of the two panels was loaded in quasistatic, transverse compression by means of an Instron machine.

Force-displacement data are presented in figure 1. Constitutive assumptions were introduced to allow for calculation of Green-St. Venant strain, second Piola-Kirchhoff stress, and Cauchy stress. A least squares fit in the form of a rational function was obtained to each second Piola-Kirchhoff stress-Green-St. Venant strain curve. These fits are described in equation 17 and in table 1. The fits are differentiated to obtain a measure of transverse stiffness.

5. References

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List of Symbols, Abbreviations, and Acronyms

A_0	initial cross-sectional area of the smaller platen
$\mathbf{E}$	Green-St. Venant (Lagrangian) strain tensor
E_{ij}	component *ij* of **E**
E_{33}	transverse normal component of the Green-St. Venant strain
$\mathbf{F}$	deformation gradient tensor
F	compressive force applied to the fabric specimen
$\mathbf{I}$	identity tensor
L_0	fabric specimen (vest) initial thickness
$\mathbf{T}$	Cauchy stress tensor
T_{33}	transverse normal component of the Cauchy stress
$\mathbf{S}$	second Piola-Kirchhoff stress tensor
S_{ij}	component *ij* of **S**
S_{33}	transverse normal component of the second Piola-Kirchhoff stress
$\mathbf{T}^{\mathbf{0}}$	first Piola-Kirchhoff stress tensor
X_1, X_2, X_3	material coordinates
a, *b*, *c, d, e, f*	coefficients in a fit to S_{33} vs. E_{33}
x_1, x_2, x_3	deformed coordinates
Δ	crosshead displacement
δ	crosshead displacement scaled by the vest's initial thickness
ϕ_{ij}	constitutive function relating S_{ij} to E_{ij}

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