ARMY RESEARCH LABORATORY

Transverse Compression Response of a Multi-Ply Kevlar Vest

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

ARL-TR-3343 **September 2004**

NOTICES

Disclaimers

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Citation of manufacturer's or trade names does not constitute an official endorsement or approval of the use thereof.

Destroy this report when it is no longer needed. Do not return it to the originator.

Army Research Laboratory

Aberdeen Proving Ground, MD 21005-5066

ARL-TR-3343 **September 2004**

Transverse Compression Response of a Multi-Ply Kevlar Vest

Martin N. Raftenberg, Michael J. Scheidler, and Paul Moy
Weapons and Materials Research Directorate, ARL

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED (From - To)**
September 2004	Final	April 2003–August 2004

4. TITLE AND SUBTITLE
Transverse Compression Response of a Multi-Ply Kevlar Vest

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Martin N. Raftenberg, Michael J. Scheidler, and Paul Moy

5d. PROJECT NUMBER
1L162618AH80

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
ATTN: AMSRD-ARL-WM-TD
Aberdeen Proving Ground, MD 21005-5066

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-3343

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

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

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
					Martin N. Raftenberg
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** (*Include area code*)
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL	34	410-306-0949

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Contents

List of Figures

List of Tables

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.

*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.

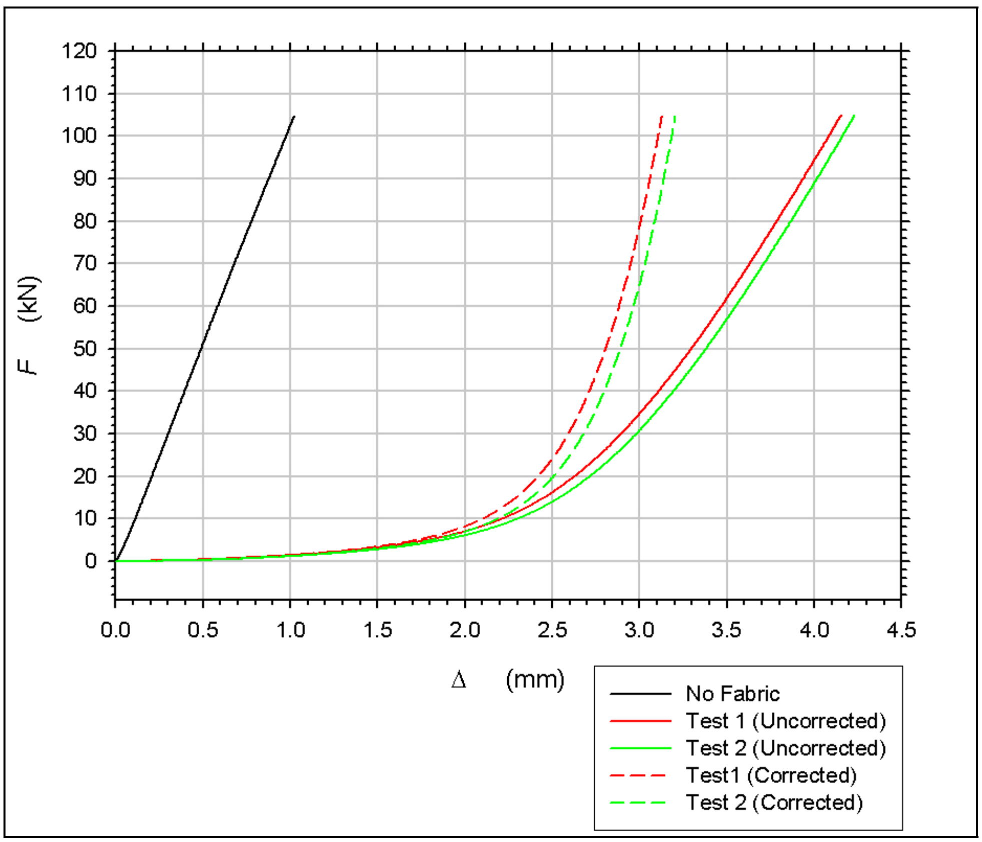

Figure 1. Compressive force-crosshead displacement data for the vest under quasistatic, transverse compression.

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.

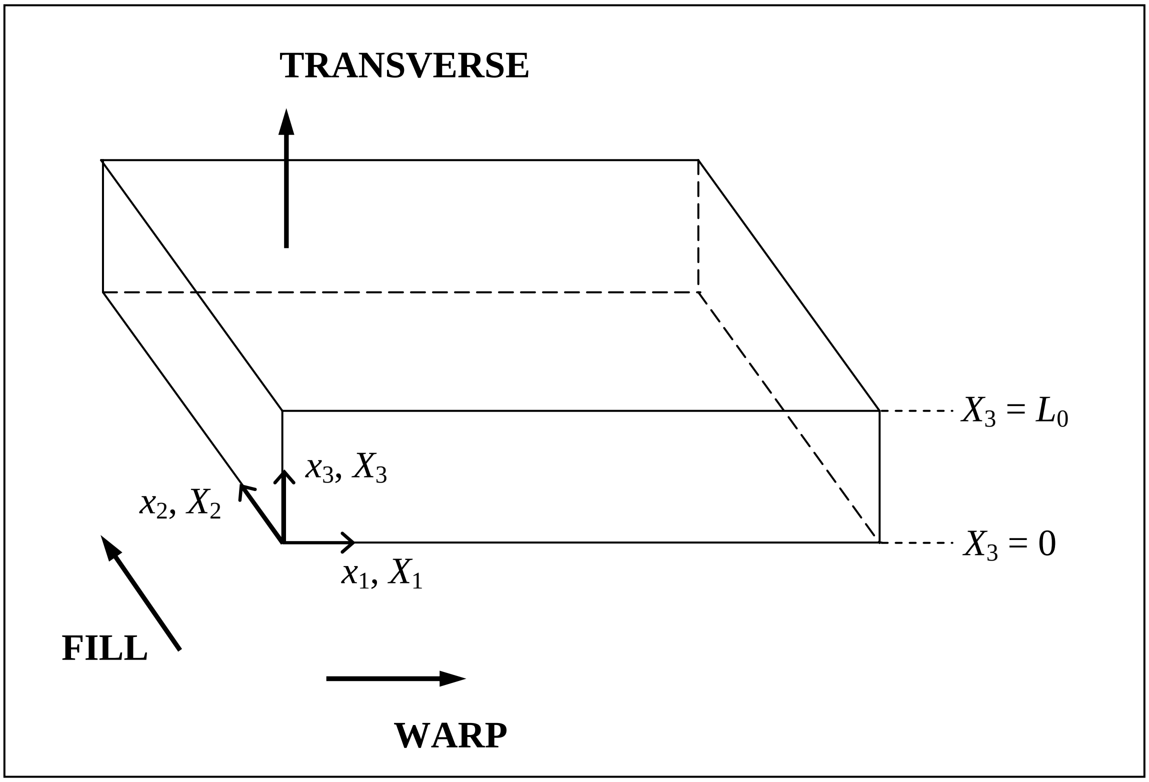

Figure 2. The vest in its undeformed configuration, with the coordinate system indicated.

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

$$\mathbf{F} = \frac{\partial \mathbf{x}}{\partial \mathbf{X}} \ , \qquad (1)$$

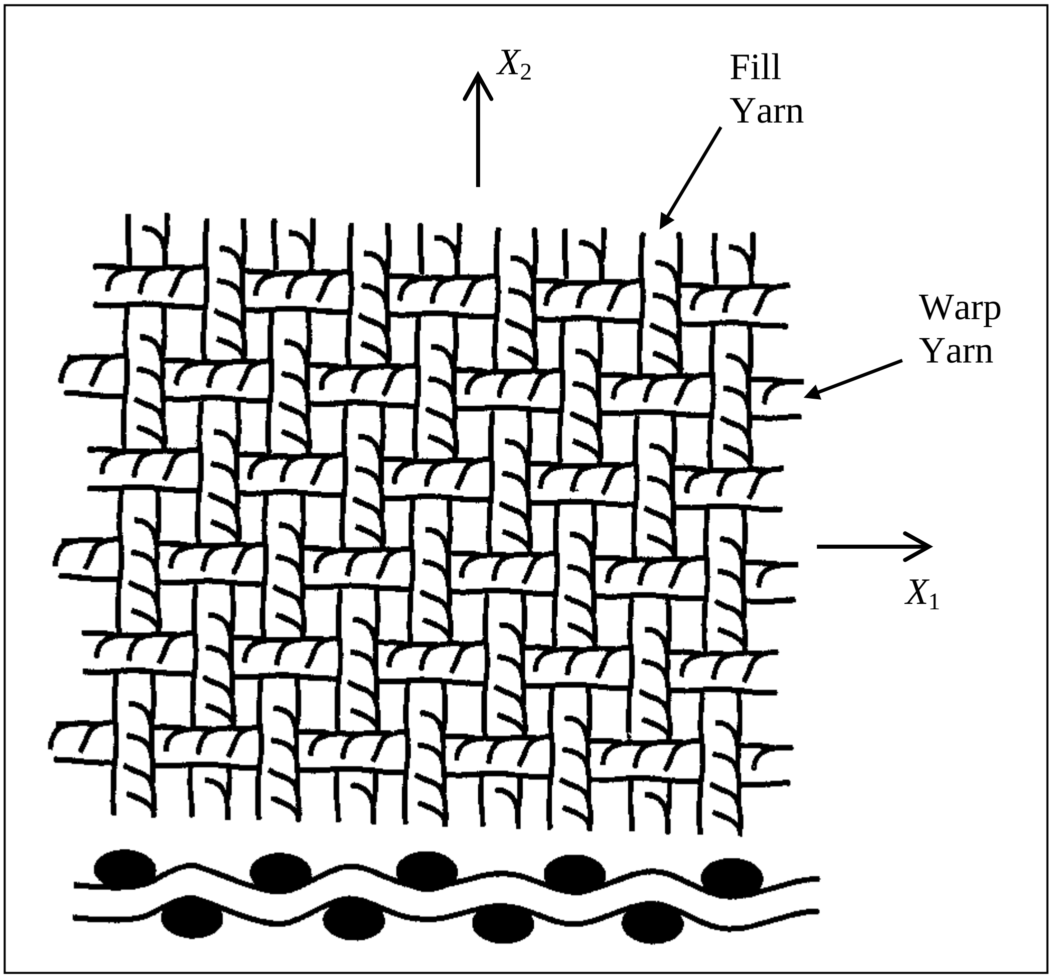

Figure 3. Sketch of the plain-weave construction of the vest.

Where $\mathbf{X} = (X_1, X_2, X_3)$ and $\mathbf{x} = (x_1, x_2, x_3)$. The Green-St. Venant strain tensor, **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 **T**, $\mathbf{T^0}$, and **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 $\delta \to 1$ as $\Delta \to L_0$. 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 $E_{33} \to -1/2$ as $\delta \to 1$, 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

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

Note that this functional form, with its singularity at $E_{33} = -1/2$, insures the required condition of unbounded stress as $E_{33} \to -1/2$. 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 $E_{33} \to -1/2$.

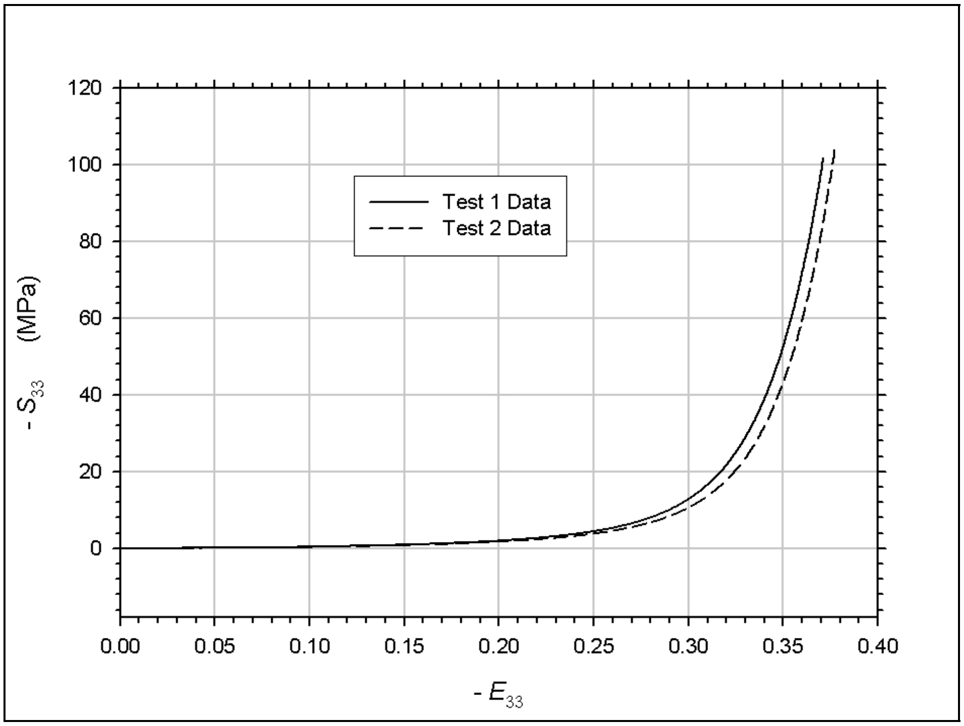

Figure 4. Second Piola-Kirchhoff stress vs. Green-St. Venant strain for the vest under quasistatic, transverse compression in tests 1 and 2.

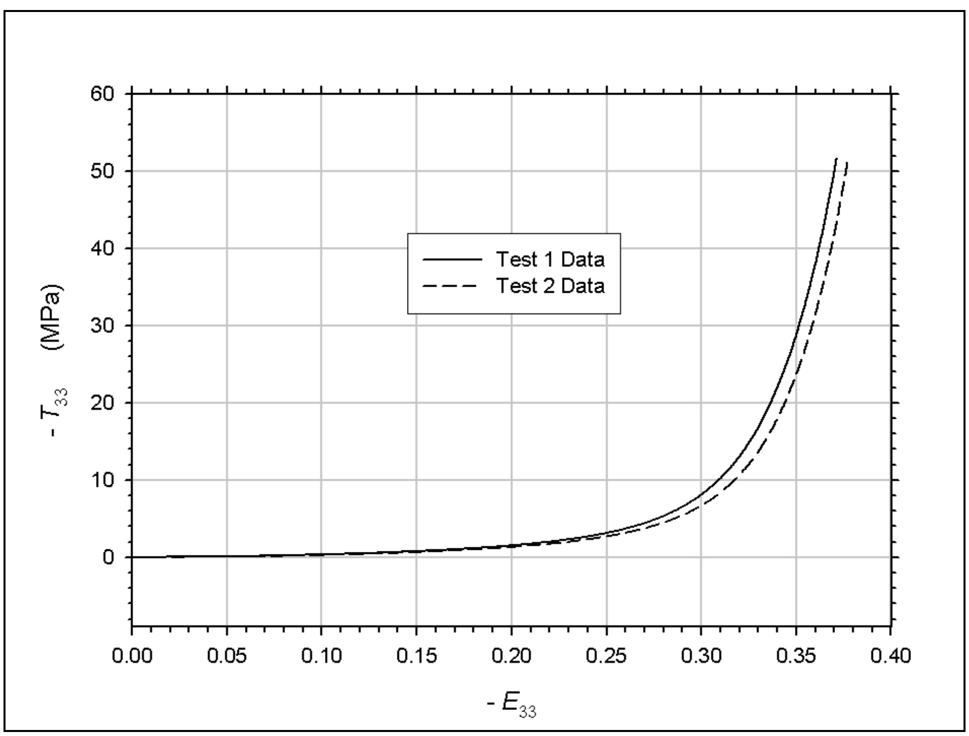

Figure 5. Cauchy stress vs. Green-St. Venant strain for the vest under quasistatic, transverse compression in tests 1 and 2.

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

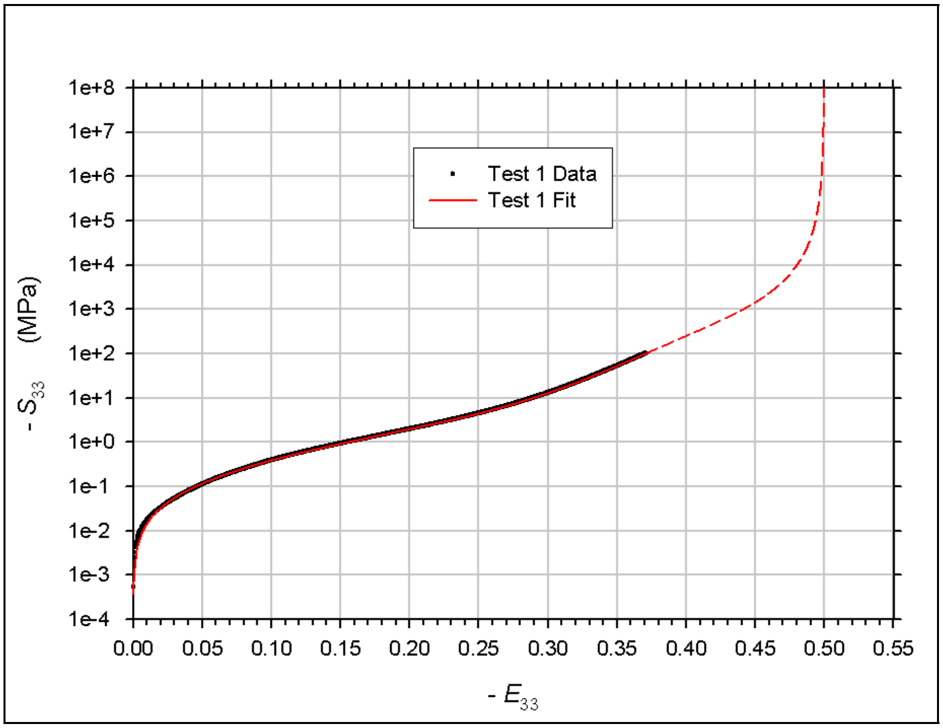

Figure 6. Second Piola-Kirchhoff stress vs. Green-St. Venant strain for the vest under quasistatic, transverse compression in test 1.

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

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

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

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

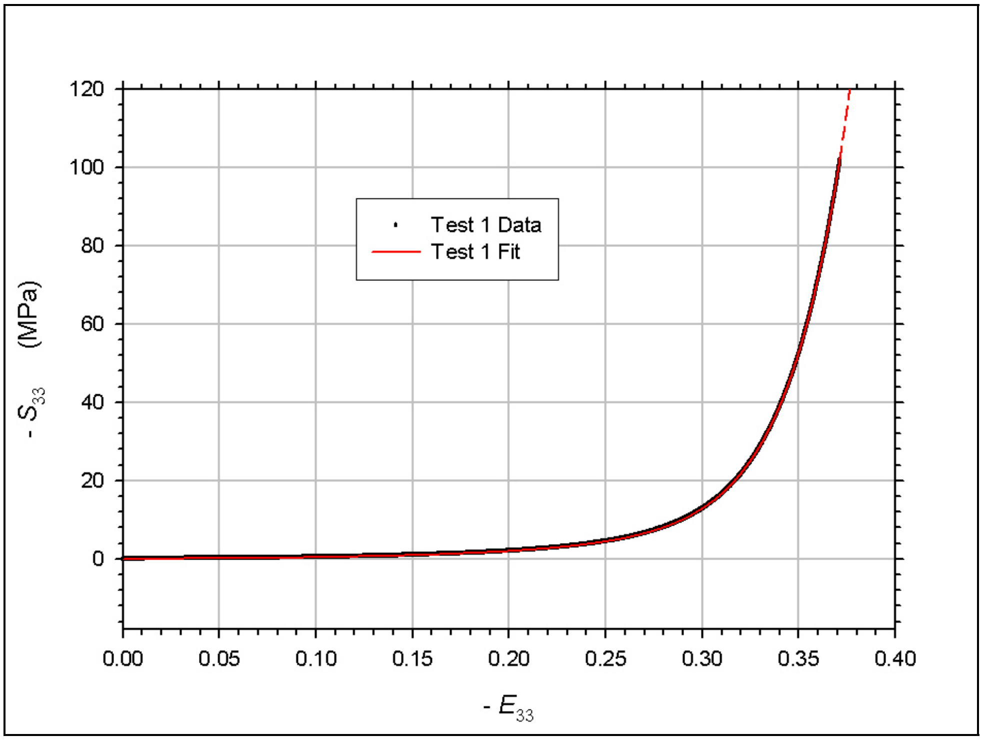

Figure 7. Second Piola-Kirchhoff stress vs. Green-St. Venant strain for the vest under quasistatic, transverse compression in test 1.

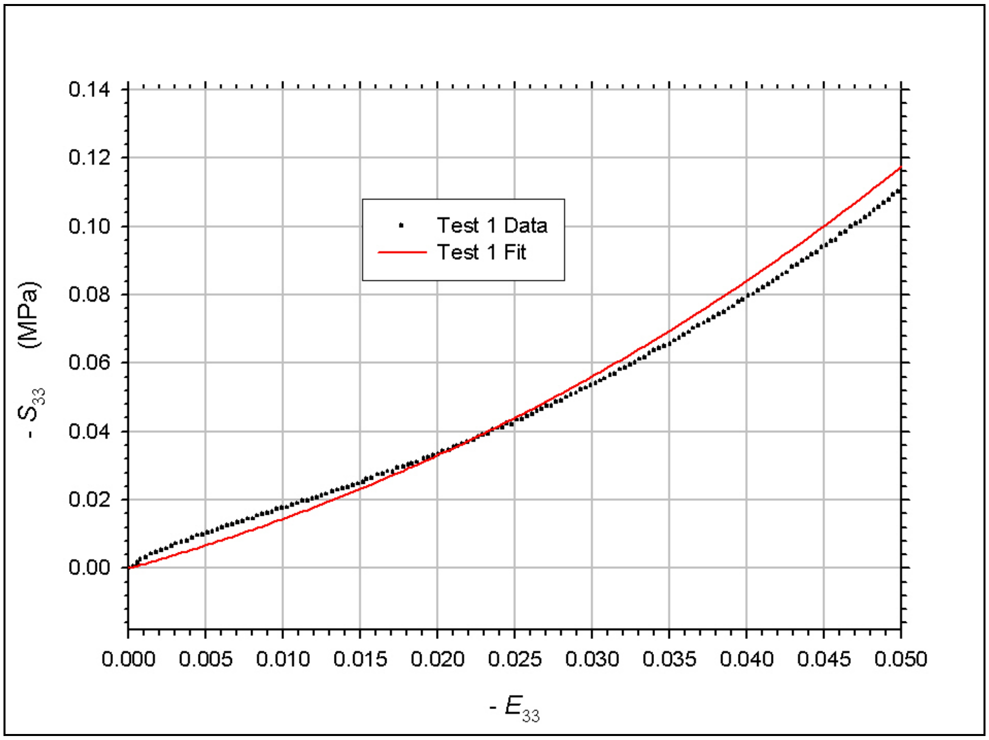

Figure 8. Second Piola-Kirchhoff stress vs. Green-St. Venant strain for the vest under quasistatic, transverse compression for the small-strain range in test 1.

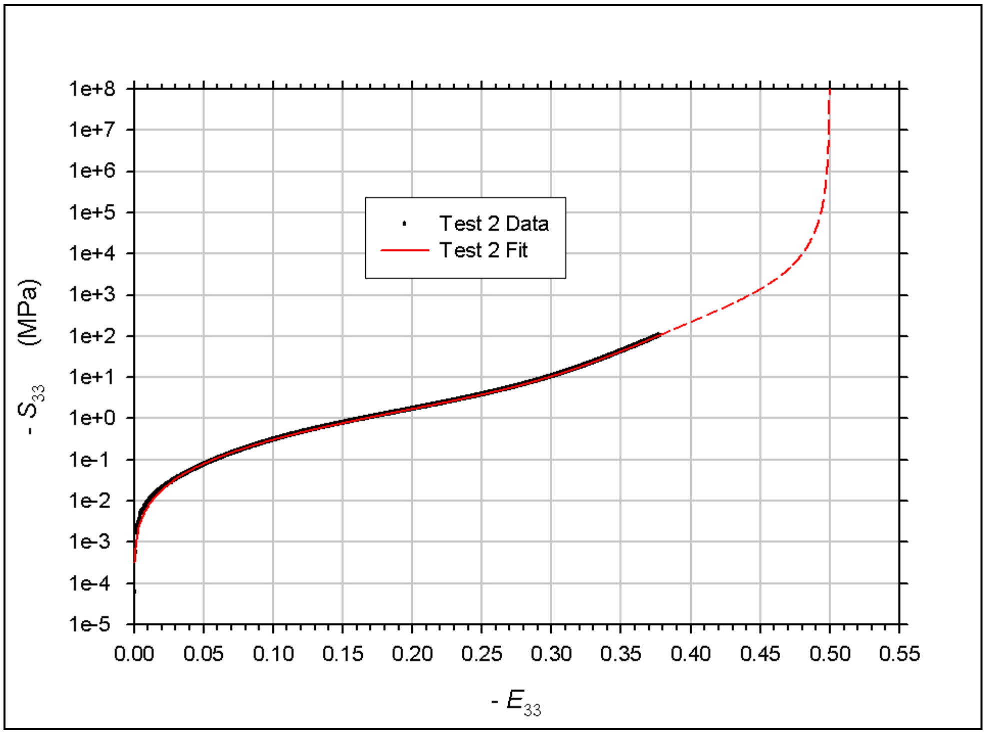

Figure 9. Second Piola-Kirchhoff stress vs. Green-St. Venant strain for the vest under quasistatic, transverse compression in test 2.

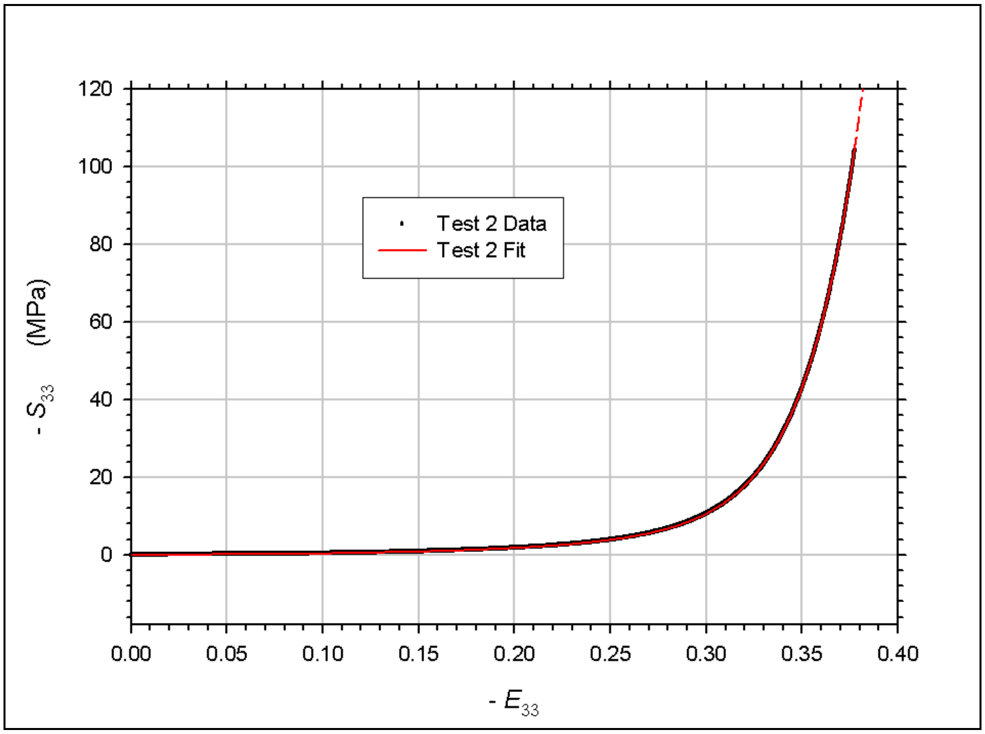

Figure 10. Second Piola-Kirchhoff stress vs. Green-St. Venant strain for the vest under quasistatic, transverse compression in test 2.

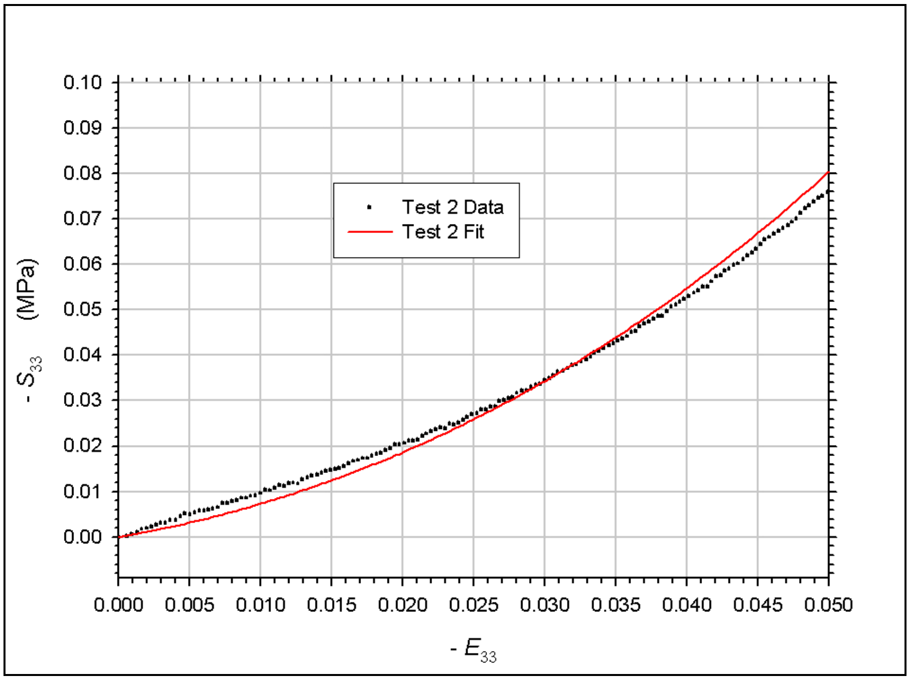

Figure 11. Second Piola-Kirchhoff stress vs. Green-St. Venant strain for the vest under quasistatic, transverse compression for the small strain range in test 2.

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

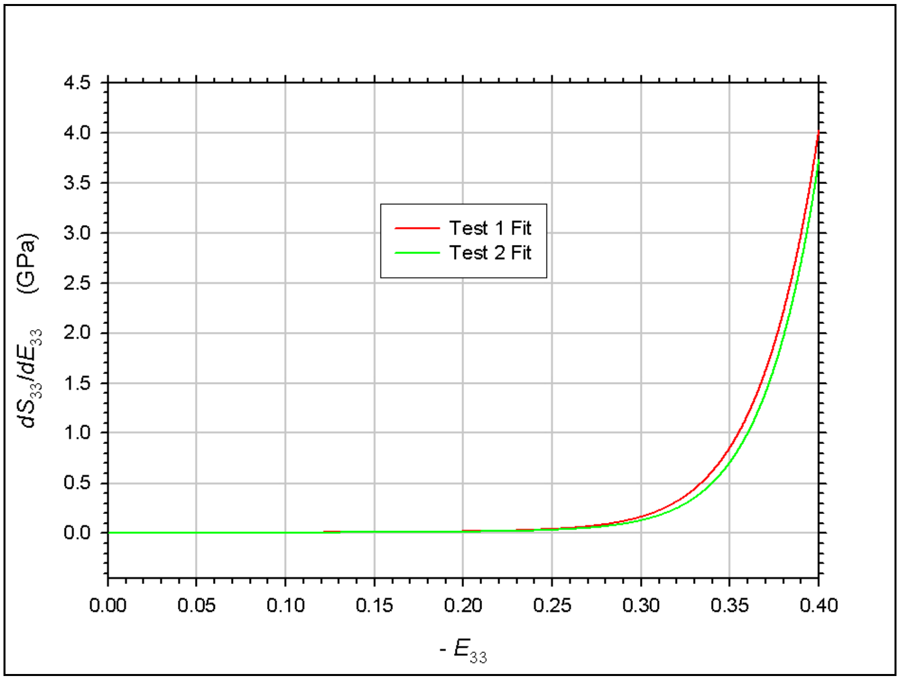

Figure 12. Elastic modulus based on second Piola-Kirchhoff stress vs. Green-St. Venant strain for the vest under quasistatic, transverse compression.

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

Johnson, G. R.; Beissel, S. E.; Cunniff, P. M. A Computational Model for Fabrics Subjected to Ballistic Impact. *18th International Symposium on Ballistics*; Vol. 2, Reinecke, W. G., Ed.; Technomic Publishing: Lancaster, PA, 1999; pp 962–969.

Kageyama, M.; Kawabata, S.; Niwa, M. The Validity of a Linearizing Method for Predicting the Biaxial-Extension Properties of Fabrics. *Journal of the Textile Institute* **1988**, *79*, 543–567.

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

Walker, J. D. Constitutive Model for Fabrics With Explicit Static Solution and Ballistic Limit. *Proceedings of the 18th International Symposium on Ballistics*; Vol. 2, Reinecke, W. G., Ed.; Technomic Publishing: Lancaster, PA, 1999; pp 1231–1238.

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

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
$\mathbf{T^0}$	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}

NO. OF COPIES	ORGANIZATION
1 (PDF ONLY)	DEFENSE TECHNICAL INFORMATION CTR DTIC OCA 8725 JOHN J KINGMAN RD STE 0944 FORT BELVOIR VA 22060-6218
1	US ARMY RSRCH DEV & ENGRG CMD SYSTEMS OF SYSTEMS INTEGRATION AMSRD SS T 6000 6TH ST STE 100 FORT BELVOIR VA 22060-5608
1	INST FOR ADVNCD TCHNLGY THE UNIV OF TEXAS AT AUSTIN 3925 W BRAKER LN STE 400 AUSTIN TX 78759-5316
1	US MILITARY ACADEMY MATH SCI CTR EXCELLENCE MADN MATH THAYER HALL WEST POINT NY 10996-1786
1	DIRECTOR US ARMY RESEARCH LAB IMNE AD IM DR 2800 POWDER MILL RD ADELPHI MD 20783-1197
3	DIRECTOR US ARMY RESEARCH LAB AMSRD ARL CI OK TL 2800 POWDER MILL RD ADELPHI MD 20783-1197
3	DIRECTOR US ARMY RESEARCH LAB AMSRD ARL CS IS T 2800 POWDER MILL RD ADELPHI MD 20783-1197

NO. OF COPIES	ORGANIZATION
	ABERDEEN PROVING GROUND
1	DIR USARL AMSRD ARL CI OK TP (BLDG 4600)

NO. OF COPIES	ORGANIZATION
10	DIR ARO A RAJENDRAN A CROWSON B LAMATTINA D KISEROW D STEPP H EVERETT J PRATER G ANDERSON J CHANG TECH LIB PO BOX 12211 RTP NC 27709-2211
14	US ARMY NATICK SOLDIER CTR R KINNEY J WARD P CUNNIFF M MAFFEO J SONG S WACLAWIK J F MACKIEWICZ J ZHENG W ZUKAS W HASKELL W NYKVIST S BEAUDOIN L PISCITELLE W ZUKAS 15 KANSAS ST NATICK MA 01760
2	WALTER REED ARMY HOSPITAL PULMONARY MEDICINE COL M MAYORGA LTC J PARKER 6900 GEORGIA AVE WASHINGTON DC 20307-5001
1	US ARMY MEDICAL RSRCH AND MATERIEL COMMAND MILITARY OPERATIONAL MEDICINE RESEARCH PROG LTC K FRIEDL FORT DETRICK MD 21702-5012
2	PM SOLDIER SYS W BROWER S PINTER 10125 KINGMAN RD FT BELVOIR VA 22060-5820

NO. OF COPIES	ORGANIZATION
1	US ARMY COLD REGIONS RSCH & ENGRNG LAB P DUTTA 72 LYME RD HANOVER NH 03755
1	USA SBCCOM PM SOLDIER SPT AMSSB PM RSS A J CONNORS KANSAS ST NATICK MA 01760-5057
2	USA SBCCOM MATERIAL SCIENCE TEAM AMSSB RSS J HERBERT M SENNETT KANSAS ST NATICK MA 01760-5057
1	DIRECTOR US ARMY RESEARCH LAB AMSRL CP CA D SNIDER 2800 POWDER MILL RD ADELPHI MD 20783-1197
1	DIRECTOR US ARMY RESEARCH LAB AMSRL SS SD H WALLACE 2800 POWDER MILL RD ADELPHI MD 20783-1197
2	DIRECTOR US ARMY RESEARCH LAB AMSRL SS SE DS R REYZER R ATKINSON 2800 POWDER MILL RD ADELPHI MD 20783-1197
1	DIRECTOR US ARMY RESEARCH LAB AMSRL WM MB A FRYDMAN 2800 POWDER MILL RD ADELPHI MD 20783-1197
1	COMMANDER US ARMY MATERIEL CMD AMXMI INT 5001 EISENHOWER AVE ALEXANDRIA VA 22333-0001

NO. OF COPIES	ORGANIZATION
1	TACOM ARDEC M MINISI AMSTA AR CCL B PICATINNY ARSENAL NJ 07806
3	COMMANDER US ARMY ARDEC AMSTA AR CC M PADGETT J HEDDERICH H OPAT PICATINNY ARSENAL NJ 07806-5000
2	COMMANDER US ARMY ARDEC AMSTA AR AE WW E BAKER J PEARSON PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR FSE PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR TD PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR CCH P J LUTZ PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR FSF T C LIVECCHIA PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA ASF PICATINNY ARSENAL NJ 07806-5000

NO. OF COPIES	ORGANIZATION
13	COMMANDER US ARMY ARDEC AMSTA AR CCH A F ALTAMURA M NICOLICH M PALATHINGUL D VO R HOWELL A VELLA M YOUNG L MANOLE S MUSALLI R CARR M LUCIANO E LOGSDEN T LOUZEIRO PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR QAC T C J PAGE PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR M D DEMELLA PICATINNY ARSENAL NJ 07806-5000
3	COMMANDER US ARMY ARDEC AMSTA AR FSA A WARNASH B MACHAK M CHIEFA PICATINNY ARSENAL NJ 07806-5000
2	COMMANDER US ARMY ARDEC AMSTA AR FSP G M SCHIKSNIS D CARLUCCI PICATINNY ARSENAL NJ 07806-5000

NO. OF COPIES	ORGANIZATION
2	COMMANDER US ARMY ARDEC AMSTA AR CCH C H CHANIN S CHICO PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR QAC T D RIGOGLIOSO PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR WET T SACHAR BLDG 172 PICATINNY ARSENAL NJ 07806-5000
1	US ARMY ARDEC INTELLIGENCE SPECIALIST AMSTA AR WEL F M GUERRIERE PICATINNY ARSENAL NJ 07806-5000
10	COMMANDER US ARMY ARDEC AMSTA AR CCH B P DONADIA F DONLON P VALENTI C KNUTSON G EUSTICE K HENRY J MCNABOC G WAGNECZ R SAYER F CHANG PICATINNY ARSENAL NJ 07806-5000
1	PM ARMS SFAE GCSS ARMS BLDG 171 PICATINNY ARSENAL NJ 07806-5000

NO. OF COPIES	ORGANIZATION
6	COMMANDER US ARMY ARDEC AMSTA AR CCL F PUZYCKI R MCHUGH D CONWAY E JAROSZEWSKI R SCHLENNER M CLUNE PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR WEA J BRESCIA PICATINNY ARSENAL NJ 07806-5000
1	PM MAS SFAE AMO MAS PICATINNY ARSENAL NJ 07806-5000
1	PM MAS SFAE AMO MAS CHIEF ENGINEER PICATINNY ARSENAL NJ 07806-5000
1	PM MAS SFAE AMO MAS PS PICATINNY ARSENAL NJ 07806-5000
2	PM MAS SFAE AMO MAS LC PICATINNY ARSENAL NJ 07806-5000
2	PM MAS SFAE AMO MAS MC PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC PRODUCTION BASE MODERN ACTY AMSMC PBM K PICATINNY ARSENAL NJ 07806-5000

NO. OF COPIES	ORGANIZATION
2	PM MAS SFAE AMO MAS SMC PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY TACOM PM COMBAT SYSTEMS SFAE GCS CS 6501 ELEVEN MILE RD WARREN MI 48397-5000
1	COMMANDER US ARMY TACOM AMSTA SF WARREN MI 48397-5000
3	NAVAL RSRCH LAB MULTIFUNCTIONAL MAT BR CODE 6350 R EVERETT P MATIC C SIMMONDS WASHINGTON DC 20375
2	NAVAL SURFACE WARFARE CTR DAHLGREN DIV CODE G06 TECH LIBRARY CODE 323 17320 DAHLGREN RD DAHLGREN VA 22448
1	NAVAL SURFACE WARFARE CTR CRANE DIVISION M JOHNSON CODE 20H4 LOUISVILLE KY 40214-5245
2	NAVAL SURFACE WARFARE CTR U SORATHIA C WILLIAMS CD 6551 9500 MACARTHUR BLVD WEST BETHESDA MD 20817
2	COMMANDER NAVAL SURFACE WARFARE CTR CARDEROCK DIVISION R PETERSON CODE 2020 M CRITCHFIELD CODE 1730 BETHESDA MD 20084
1	NAVAL SURFACE WARFARE CTR CARDEROCK DIVISION R CRANE CODE 2802 3A LEGGETT CIR BETHESDA MD 20054-5000

NO. OF COPIES	ORGANIZATION
8	NAVAL SURFACE WARFARE CTR J FRANCIS CODE G30 D WILSON CODE G32 R D COOPER CODE G32 J FRAYSSE CODE G33 E ROWE CODE G33 T DURAN CODE G33 L DE SIMONE CODE G33 R HUBBARD CODE G33 DAHLGREN VA 22448
1	AFRL MLSS R THOMSON 2179 12TH ST RM 122 WRIGHT PATTERSON AFB OH 45433-7718
2	AFRL F ABRAMS J BROWN BLDG 653 2977 P ST STE 6 WRIGHT PATTERSON AFB OH 45433-7739
1	NATIONAL INST OF JUSTICE S NEWETT 810 SEVENTH ST NW WASHINGTON DC 20531
4	UNIV OF VA IMPACT BIOMECHANICS LAB J CRANDALL D BASS R SALZAR W PILKEY 1011 LINDEN AVE CHARLOTTESVILLE VA 22902
1	ARMED FORCES INSTITUTE OF PATHOLOGY ORTHOPAEDICS CAPT M DE MAIO 6825 16TH ST NW WASHINGTON DC 20306-6000
1	USAARL B J MCENTIRE BLDG 6901 PO BOX 620577 FORT RUCKER AL 36362-0577

NO. OF COPIES	ORGANIZATION
3	ARMY HIGH PERFORMANCE COMPUTING CENTER T J HOLMQUIST G R JOHNSON S BEISSEL 1200 WASHINGTON AVE SOUTH MINNEAPOLIS MN 55415
1	NATIONAL INST OF JUSTICE OFFICE OF LAW ENFCMNT K HIGGINS BLDG 225 RM A323 GAITHERSBURG MD 20899
1	NIST OLES K D RICE GAITHERSBURG MD 20899
2	HONEYWELL INTL L WAGNER A BHATNAGAR 15801 WOODS EDGE RD COLONIAL HEIGHTS VA 23834
4	SIMULA J COLTMAN R HUYETT J MEARS R MONKS 10016 S 51ST ST PHOENIX AZ 85044
4	WAYNE STATE UNIV BIOENGINEERING CTR A KING K H YANG M WILHELM C BIR 818 W HANCOCK DETROIT MI 48202
3	DARPA/DSO S G WAX S VANFOSSEN L CHRISTODOULOU 3701 NORTH FAIRFAX DR ARLINGTON VA 22203-1714

NO. OF COPIES	ORGANIZATION
3	OFC OF NAVAL RSRCH K PRUSACYK D SIEGEL CODE 351 J KELLY 800 N QUINCY ST ARLINGTON VA 22217-5660
1	VIRGINIA POLYTECH INST IMPACT BIOMECHANICS LAB MECHANICAL ENGINEERING S M DUMA BLACKSBURG VA 24061
1	UNIVERSITY OF ALABAMA ENGINEERING MECHANICS S E JONES PO BOX 870278 TUSCALOOSA AL 34587-0278
2	NORTHWESTERN UNIV MECHANICAL ENGRNG W K LIU C BRINSON EVANSTON IL 60208
1	NORTHWESTERN UNIVERSITY CIVIL ENGRNG T BELYTSCHKO EVANSTON IL 60208
1	UNIV OF MISSOURI ROLLA CIVIL ENGINEERING DEPT W SCHONBERG ROLLA MO 65409-0030
5	UNIV OF DELAWARE CTR FOR COMPOSITE MTRLS J GILLESPIE B GAMA M SANTARE D HEIDER N J WAGNER 201 SPENCER LABORATORY NEWARK DE 19716
3	JHU MECH ENG K T RAMESH J F MOLINARI A DOUGLAS LATROBE HALL 3400 N CHARLES ST BALTIMORE MD 21218

NO. OF COPIES	ORGANIZATION
1	MIT MTRLS SCI AND ENG DEPT D ROYLANCE CAMBRIDGE MA 02139
3	MIT MECHANICAL ENG DEPT M BOYCE S SOCRATE I HUNTER CAMBRIDGE MA 02139
1	MIT CHEMISTRY DEPT T SWAGER 77 MASSACHUSSETTS AVE CAMBRIDGE MA 02139-4307
3	SRI INTERNATIONAL D A SHOCKEY D C ERLICH J W SIMONS 333 RAVENSWOOD AVE MENLO PARK CA 94025-3493
2	UC SAN DIEGO MECH AEROSPACE ENGRNG S NEMAT NASSER M A MEYERS 9500 GILMAN DR LA JOLLA CA 92093
1	N C STATE UNIV DEPT MECH AND AEROSPACE ENGINEERING M ZIKRY BOX 7910 RALEIGH NC 27695-7910
1	UNIV OF CINCINNATI COLLEGE OF ENGRNG A TABIEI 787 RHODES HALL PO BOX 210070 CINCINNATI OH 45221-0070
1	UNIV OF ARIZONA MECHANICAL ENGRNG W CHEN PO BOX 210119 TUCSON AZ 85721

NO. OF COPIES	ORGANIZATION
1	CALIFORNIA INST OF TECH AERONAUTICS AND APPLIED MECHANICS M ORTIZ PASADENA CA 91125
3	U C BERKELEY MECHANICAL ENGR DEPT D STEIGMANN P PAPADOPOULOS B NADLER 6133 ETCHVERRY BERKELEY CA 94720
2	UNIVERSITY OF ROCHESTER MECHANICAL ENGR DEPT D J QUESNEL A L LERNER ROCHESTER NY 14627-0132
4	FOSTER-MILLER K KASTURI W KONG M ROYLANCE J TING 350 SECOND AVE WALTHAM MA 02451
1	DYNA EAST CORP W FLIS 3620 HORIZON DR KING OF PRUSSIA PA 19406-2647
2	SOUTHWEST RSRCH INST ENGR AND MAT SCI DIV C E ANDERSON J WALKER 6220 CULEBRA RD PO DRAWER 28510 SAN ANTONIO TX 78228-0510
2	UNIV OF TEXAS AT AUSTIN INSTITUTE FOR ADV TECH S BLESS S SATAPATHY 4030 2 W BRAKER LN AUSTIN TX 78759
1	LIVERMORE SOFTWARE TECH CORP J O HALLQUIST 2876 WAVERLY WY LIVERMORE CA 94550-1740

NO. OF COPIES	ORGANIZATION
1	PURDUE UNIV AERO & ASTRO C T SUN W LAFAYETTE IN 47907-1282
1	APPLIED RSRCH ASSOCIATES L A BROWN 1848 LOCKHILL SELMA RD SUITE 102 SAN ANTONIO TX 78213
1	JAYCOR CORP J STUHMILLER 9775 TOWNE CENTRE DR SAN DIEGO CA 92121
1	DOMINCA N WINFREE 12111 RANCHITOS RD NE ALBUQUERQUE NM 87122
1	NAVAL POSTGRADUATE SCHL MECH ENG Y KWON 700 DYER RD BLDG 245 MONTEREY CA 93943-5146
1	APPLIED RSRCH ASSOCIATES D E GRADY SUITE A 220 4300 SAN MATEO BLVD NE ALBUQUERQUE NM 87110
1	MINING SAFETY APPLIANCES CO T J MOYNIHAN P O BOX 439 PITTSBURGH PA 15230-0439
3	DUPONT SPRUANCE PLANT H H YANG 5401 JEFFERSON DAVIS HWY RICHMOND VA 23234
1	UNIV OF MASSACHUSETTS TEXTILE SCIENCES S B WARNER NORTH DARTMOUTH MA 02747
1	CORNELL UNIV THEORET APPLIED MECHANICS S L PHOENIX 321 THURSTON HALL ITHACA NY 14853

NO. OF COPIES	ORGANIZATION
1	INTERNATIONAL RESEARCH ASSOC D L ORPHAL 4450 BLACK AVE STE E PLEASANTON CA 94566
3	MICHIGAN STATE UNIV MECHANICAL ENGINEERING W R YU F POURBOGHRAT M ZAMPALONI EAST LANSING MI 48824
7	DIR LLNL M J MURPHY D LASSILLA M FINGER R CHRISTENSEN S DETERESA F MAGNESS TECH LIB PO BOX 808 LIVERMORE CA 94550
4	DIRECTOR SANDIA NATIONAL LABS M KIPP E HERTEL R BRANNON TECH LIB PO BOX 5800 ALBUQUERQUE NM 87185-5800
3	DIRECTOR SANDIA NATIONAL LABS APPLIED MECHANICS DEPT MS 9042 J HANDROCK Y R KAN J LAUFFER PO BOX 969 LIVERMORE CA 94551-0969
3	DIR LANL D A MANDEL G T GRAY TECH LIB PO BOX 166 LOS ALAMOS NM 87454
1	USA SPCL OPNS SGM L K JELLSON PO BOX 70660 FT BRAGG NC 28307-5000

NO. OF COPIES	ORGANIZATION
1	US ARMY NGIC T SHAVER 2055 BOULDERS RD CHARLOTTESVILLE VA 22911-8318

ABERDEEN PROVING GROUND

NO. OF COPIES	ORGANIZATION
1	US ARMY MATERIEL SYSTEMS ANALYSIS ACTIVITY P DIETZ 392 HOPKINS RD AMXSY TD APG MD 21005-5071
1	US ARMY ATC W C FRAZER CSTE DTC AT AC I 400 COLLERAN RD APG MD 21005-5059
111	DIR USARL AMSRD CI HC AMSRD CS IO FI M ADAMSON AMSRD SL R SAUCIER D BELY R HENRY AMRSD SL BE W BRUCHEY E DAVIS AMSRD WM J MCCAULEY J SMITH M ZOLTOSKI AMSRD WM B A HORST AMSRD WM BA D LYON AMSRD WM BC J NEWILL P PLOSTINS A ZIELINSKI AMSRD WM BF S WILKERSON AMSRD WM M J BEATTY B BURNS T HADUCH AMSRD WM MA M BRATCHER D DESCHEPPER L GHIORSE P MOY (10 CPS) S MCKNIGHT C PERGANTIS E WETZEL AMSRD WM MB T BOGETTI L BURTON W DRYSDALE B FINK D HOPKINS R LIEB J TZENG AMSRD WM MC B F HART E RIGAS W SPURGEON AMSRD WM MD B CHEESEMAN E CHIN P DEHMER R DOOLEY G GAZONAS J LASALVIA J MONTGOMERY W ROY B SCOTT D SPAGNUOLO S WALSH C F YEN AMSRD WM TA M BURKINS N GNIAZDOWSKI W GOOCH T HAVEL C HOPPEL E HORWATH T JONES M NORMANDIA B RICKTER AMSRD WM TB P BAKER R BITTING L LOTTERO AMSRD WM TC K KIMSEY L MAGNESS D SCHEFFLER S SCHRAML W WALTERS R COATES AMSRD WM TD M N RAFTENBERG (20 CPS) E RAPACKI

NO. OF
COPIES ORGANIZATION

T WEERISOORIYA
S SCHOENFELD
S BILYK
M SCHEIDLER (5 CPS)
T BJERKE
Y HUANG
D CASEM
J CLAYTON
H MEYER
AMSRD CI HC
R NAMBURU
C ZOLTANI

NO. OF COPIES	ORGANIZATION
1	TNO TPD K SMORENBURG P O BOX 155 2600 AD DELFT THE NETHERLANDS
2	P ROUVET J DA CUNHA DGA/ETBS/SDT/EXT BOURGES FRANCE
1	P CHANTERET INSTITUT SAINT-LOUIS MULHOUSE FRANCE
1	RAFAEL BALLISTICS CTR M MAYSELESS PO BOX 2250 HAIFA ISRAEL
2	DSTL BIOMEDICAL SCIENCES W TAM G COOPER PORTON DOWN SALISBURY WILTSHIRE SP4 0JQ UNITED KINGDOM
2	UNIV OF WATERLOO MECHANICAL ENGNRG M J WORSWICK D CRONIN 200 UNIVERSITY AVE WEST WATERLOO ONTARIO N2L3G1 CANADA
2	DLO R&P P GOTTS P M KELLY SKIMMINGDISH LANE CAVERSFIELD BICESTER OXON OX27 ATS UNITED KINGDOM
1	TECHNION MECHANICAL ENG DEPT S BODNER HAIFA 3200 ISRAEL

NO. OF COPIES	ORGANIZATION
5	CRANFIELD UNIV ENGINEERING SYSTEMS DEPT I HORSFALL M J IREMONGER C A COULDRICK E LEWIS C WATSON SHRIVENHAM SWINDON SN6 8LA UNITED KINGDOM
3	TNO PML J VAN BREE T VERHAGEN H HUISJES P O BOX 45 2280 AA RIJSWIJK THE NETHERLANDS
3	DREV D BOURGET A DUPUIS S OUELLET 2459 BOULEVARD PIEXI NORD VAL BELAIR QUEBEC QC G37 IX5 CANADA
1	DYNEEMA M VAN ES P O BOX 6510 6401 JH HEERLEN THE NETHERLANDS
1	ARL ERO S SAMPATH AERO MECH ENG 223 MARYLEBONE RD LONDON NW1 5TH UNITED KINGDOM
1	UNIV OF BRITISH COLUMBIA METALS AND MATERIALS ENG R VAZIRI FRANK FORWARD BLDG 309 6350 STORES RD VANCOUVER BC V6T 124 CANADA

NO. OF COPIES	ORGANIZATION
6	NATIONAL UNIV SINGAPORE V P W SHIM C T LIM K J FOO S Y YONG V B C TAN T E TAY MECHANICAL ENGINEERING 10 KENT RIDGE CRESCENT SINGAPORE 119260 SINGAPORE
1	DUPONT UK LTD S REBOUILLAT MAYDOWN RESEARCH CENTER LONDONDERRY BT 47 ITU UNITED KINGDOM
1	INSTITUTE CHEMICAL PHYSICS S BAZHENOV KOSYGIN STREET 4 117 977 MOSCOW RUSSIA
1	UNIV POLITECNICA MADRID B PARGA-LANDA ARQUITECTURA CONSTRUC ETSI NAVALES 28040 MADRID SPAIN
1	UNIV POLITECNICA MADRID F HERNANDEZ-OLIVARES CONSTRUC TEC ARQUITEC ETS ARQUITECTURA AV JUAN DE HERRERA 4 28040 MADRID SPAIN
1	TNO DEFENSE RESEARCH R IJSSELSTEIN PO BOX 6006 2600 J A DELFT THE NETHERLANDS
1	AMC SCI & TECH CTR EUROPE T J MULKERN POSTFACH 81 55247 MAINZ KASTEL GERMANY

NO. OF COPIES	ORGANIZATION
1	LAB DE MECANIQUE PHYSIQUE Q GRIMAL LMP CNRS ESA 7052 UNIVERSITE DE PARIS 12 VAL DE MARNE 61 AVE DU GENERAL DE GAULLE 94010 CRETEIL CEDEX FRANCE
2	DSTO WEAPONS SYSTEM DIVISION J J WANG N BURMAN 307 EPO PO BOX 1500 SALISBURY SA 5108 AUSTRALIA
2	DSTO AERONAUT MARINE RESEARCH H H BILLON D J ROBINSON PO BOX 4331 MELBOURNE 3001 VICTORIA AUSTRALIA
1	DSTL FORT HALSTEAD P N JONES SEVEN OAKS KENT TN 147BP UNITED KINGDOM
3	WILLIAM LEE INNOVATION CENTRE UMIST COLIN CORK PO BOX 88 MANCHESTER M60 10D UNITED KINGDOM
1	UNIV OF WITWATERSRAND B W SKEWS MECHANICAL ENGINEERING JOHANNESBURG SOUTH AFRICA

INTENTIONALLY LEFT BLANK.