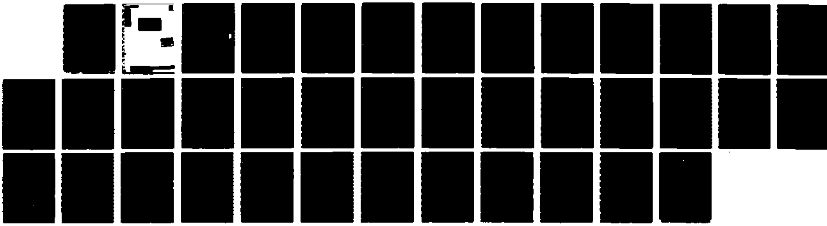
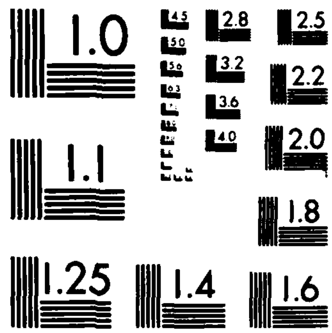
AD-A184 637 PLASTICITY OF FIBROUS COMPOSITES(U) RENSSELAER POLYTECHNIC INST TROY NY DEPT OF CIVIL ENGINEERING G J DVORAK MAY 87 ARO-20061 1-EG DAAG29-83-K-0171 1/1

UNCLASSIFIED F/G 11/4 NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

PLASTICITY OF FIBROUS COMPOSITES

by

George J. Dvorak

ARO 20061.1-EG
ARO 22538.1-EG
2

PLASTICITY OF FIBROUS COMPOSITES

by

George J. Dvorak

Final Report

May 1987

U.S. Army Research Office

Grants

DAAG29-83-K-0171-2983

and

DAAG29-85-K-0011

Department of Civil Engineering
Rensselaer Polytechnic Institute

FOREWORD

This program was initially conducted under grant DAAG29-83-K-0171-2983 to the University of Utah, as a joint effort of two principal investigators: Dr. George J. Dvorak in Utah, and Dr. Aris Phillips at Yale University. This grant was in effect from 10/10/83 until 8/31/84. Thereafter the work continued under grant DAAG29-85-K0011 to the Rensselaer Polytechnic Institute, which was in effect from 10/22/84 until 2/28/87. After the untimely death of Dr. Phillips in August of 1985, the work was directed by Dr. Dvorak. The entire experimental program was performed in Dr. Phillips' laboratory at Yale University.

Table of Contents

		Page
1.	Statement of the Problem.	1
2.	Summary of the Most Important Results	4
	2.1 Preliminaries.	4
	2.2 Bounds on Instantaneous Overall Properties	4
	2.3 Experimental Results	9
	2.4 A Bimodal Plasticity Theory of Fibrous Composites. . . .	11
	2.5 Significance of the Results.	14
	2.6 References	14
	2.7 Figures.	17
3.	List of Publications.	29
4.	List of Scientific Personnel and Degrees Granted.	31

1. STATEMENT OF THE PROBLEM

The purpose of this research program was to establish experimentally verified constitutive relations for isothermal elastic-plastic behavior of metal matrix fibrous composite materials. The theoretical part of the work was concerned with development of new constitutive models of elastic-plastic fibrous composite materials. Our goal was to identify modeling techniques which would permit derivation of overall instantaneous mechanical properties of the aggregate in terms of microstructural geometry and the properties of the phases. Since most fibers remain elastic until failure, the inelastic overall strains are caused by plastic deformation of the matrix. Therefore, an important objective was to find connections between the elastic-plastic deformation of the neat matrix and the composite, and to develop models which would utilize such connections in predictions of the overall response. Also, among the possible approaches to the problem, it was necessary to identify those which would offer a guarantee of accuracy in applications involving incremental loading which could be verified experimentally.

The experimental component of the research program consisted of measurements of initial and subsequent yield surfaces and total strains on matrix and composite specimens subjected to complex incremental loading sequences. The material selected for the experiments was the 6061Aℓ/B system. Tubular specimens (diameter 1.5 in.; wall thickness 0.050 in., length 8 in.) were manufactured by diffusion bonding of unidirectionally reinforced sheets by Amercom, Inc. of Chatsworth, CA. In the finished form, the composite tubes had seven layers of fiber in their wall, the fibers were aligned in the direction parallel to tube axis; the fiber volume fraction was $c_f = 0.45$. Neat matrix specimen tubes were manufactured from 6061 aluminum foil, by the same diffusion bonding process as the composite tubes. Three composite tubes and three matrix tubes were used. All specimens were annealed before testing.

The testing program consisted of incremental loading of the tubes by axial force, internal pressure, and axial torque. An MTS closed-loop, electrohydraulic testing machine, with computer controls and data readout, was used in the experiments. The test system performed combined incremental loading of the tubular specimens along a prescribed loading path. All tests were performed under load control. Data readout devices were used to record the three cylindrical stress components (normal stresses in axial and hoop directions, and longitudinal shear stresses) and the three corresponding total strains at each load increment.

The experimental program was conducted in several stages. The first stage served to characterize the elastic-plastic deformation of the 6061-0 aluminum matrix. The results showed that the elastic-plastic behavior of the matrix material was qualitatively similar to that of commercially pure aluminum. The latter was studied extensively by Phillips and coworkers; their results were utilized in our investigation.

The next stage of the program was dedicated to an exploratory investigation of elastic-plastic behavior of the composite material. The results showed several important aspects of composites plasticity which were not observed before, or predicted by earlier constitutive models. These results were utilized, in part, in model development.

The final and most extensive part of the experimental program consisted of verification of constitutive models. In particular, this part of the program served to confirm the validity of the bimodal plasticity theory of fibrous composites which is described in more detail in the sequel. It also provided experimental support for the periodic hexagonal array model which was developed in the theoretical part of the program.

2. SUMMARY OF THE MOST IMPORTANT RESULTS

2.1 Preliminaries

During the initial part of this study we extended some earlier results on plasticity of fibrous composites, in anticipation of their possible utility in the present investigation. In particular, the plasticity theory of fibrous composites based on the Vanishing Fiber Diameter (VFD) model, which was originally developed in a stress space formulation [1-3], was recast in terms of plasticity theory in strain space [4]. In this formulation one can calculate the macroscopic stress increments, as well as local strains while the fibrous aggregate is subjected to a prescribed deformation history; i.e., the instantaneous overall stiffness matrix is found at each loading step. This offers an advantage in certain numerical calculations, e.g., in those based on the finite element method, which require the evaluation of instantaneous overall stiffness rather than compliance. The strain-space formulation also permits evaluation of local strain increments in the phases during overall deformation; this result was not available in the earlier stress-space formulation. Implementation of these results into a general purpose finite element program is now in progress.

2.2 Bounds on Instantaneous Overall Pr. perties

The principal theoretical work under this research contract was directed at development of a bounding technique for evaluation of instantaneous stiffness and compliance matrices and local fields in elastic-plastic composite aggregates subjected to uniform overall stress or strain increments. Such bounding techniques have been available for many years for evaluation of overall elastic properties of elastic composites, but not for the elastic-plastic systems. The reasons for this can be summarized as follows:

During elastic deformation of a composite medium the constituent phases are homogeneous, their properties are known constants, and actual local fields or their volume averages can be found for many microstructural geometries from solutions of certain inclusion problems in a representative volume element of the aggregate. Of course, the overall properties are also constant and follow from superposition of results obtained for simple loading states applied to the representative volume. When at least one of the phases deforms plastically, its homogeneity is lost. Local properties become stress-dependent within the phase. This creates a major obstacle in evaluation of local fields. Solutions of inclusion problems become intractable, even in terms of stress or strain averages, because the local constitutive relation for averages or non-uniform fields is not known. This difficulty is sometimes circumvented by assuming that the averages are related in the same way as uniform fields, but this may cause serious errors in the presence of large stress and strain gradients. In any case, the overall properties depend on the applied loading path and their instantaneous values need to be found at many loading points. These considerations indicate the need for a technique which provides upper and lower bounds on the overall properties in each loading step, and thus the estimate of the cumulative error which accrues after many steps of a given path. Finally, the technique must permit, at reasonable cost, evaluation of instantaneous element properties in a finite element program for analysis of composite structures.

In the present work we developed the required procedure from minimum principles of plasticity [5-7], applied to a class of periodic models of binary fibrous and particulate composites. The results are described in references [8] to [10].

The periodic models were developed for a binary composite reinforced with aligned continuous fibers, in which the fiber axes are arranged in a periodic hexagonal array. The fiber cross sections are approximated by n x 6 sided polygons; regular hexagons were used in our implementation. Other periodic geometries e.g., representations of various particulate arrangements, can be obtained by an affine transformation of the regular hexagonal array.

The advantage of the periodic models is that they allow a selection of a small unit cell which, when subjected to appropriate boundary conditions, can represent the mechanical behavior of the composite aggregate. The unit cell is then subdivided into a small number of subelements in which the local fields are regarded as piecewise uniform. The local fields are not known exactly, instead they are approximated by certain admissible trial functions which satisfy certain minimum conditions for energy increments in the unit cell domain. Specific results were found with the displacement and equilibrium formulation of the finite element method.

The minimum principles of plasticity lead to certain energy rate inequalities which permit evaluation of upper and lower bounds on certain terms of the instantaneous stiffness and compliance matrices of the composite aggregate. In particular, if the actual current stress and strain states are known in the representative volume V of the composite, then the energy rate inequalities guarantee that for a given overall strain increment applied to V, the ordered eigenvalues and the diagonal terms, of the actual instantaneous stiffness matrix are bracketed by the calculated bounds. In our implementation we have shown that the bounds are close even for a relatively coarse subdivision of the unit cell. Similarly, one can derive energy rate inequalities which lead to derivation of bounds on the diagonal terms and on the ordered eigen-values of the instantaneous overall compliance matrix.

However, it is important to keep in mind that the minimum principles compare certain energy changes caused in V by overall deformation or stress increments from a current reference state in which the actual local fields are known, or are assumed to be known, together with the actual local properties. Similarly, the resulting bounds on overall instantaneous properties relate the moduli obtained from the approximate solution to those of the actual solution for the given increment from the actual current state. When the incremental loading continues along a finite path, the current state is not known exactly. It is known only in terms of the approximate solution obtained in the last loading step. In particular, the local material properties are known only in terms of certain approximate values calculated in the last loading step. It follows that the approximate solution is not an admissible state, and therefore, rigorous bounds on the actual instantaneous overall properties under incremental loading can not be determined from the minimum principles.

However, the minimum principles can be used to obtain approximate bounds on overall properties. In this case, the current reference state is derived from the approximate incremental solution. For example, in the implementation adopted in our work, the representative volume was divided into representative unit cells, and subelements k subdivided the volume of each phase in the cell. The approximate local fields were prescribed through certain shape functions. Contributions of the subelements to the total energy changes were then found and minimized with respect to the internal nodal displacements. At the end of each load increment, the approximate local properties were calculated in the plastically deforming subelements. These properties were then taken as the reference state of the next loading step. Therefore, in a binary composite where the reinforcement phase is elastic, the minimum principles give bounds on overall properties of an aggregate in which the exact matrix properties have been replaced by those found in the finite element solution.

Two different procedures were developed along these lines. Approximate upper bounds on energy rates were calculated from the displacement formulation of the finite element method, and approximate lower bounds were obtained from the equilibrium formulation. When the phases are elastic, one obtains rigorous bounds on the potential and complementary energies of the representative volume, and rigorous bounds on overall properties. During plastic deformation, the reference states for the upper bound calculation are taken from the previous upper bound steps, and a similar sequence is followed in the lower bound calculation. It remains to be established if either procedure is uniformly convergent. At this time, the results can be regarded as complementary estimates of the actual energy changes.

The periodic hexagonal array model was used in conjunction with the minimum principles to develop a computer program for numerical evaluation of overall strains and local fields in the unit cell. Computational efficiency of the model was a major consideration in this development. In a related project, it was implemented as a subroutine for evaluation of element material matrices in the ABAQUS finite element program. The program was used in practical applications, e.g., in dimensional stability studies of laminated Gr/Aℓ plates.

2.3 Experimental Results

As pointed out in Section 3, the experimental program was conducted in the laboratory of Professor Aris Phillips at Yale University. In the first part of the program, yield surfaces and plastic strains were measured on 6061-0 Aℓ tubes tested in axial tension and torsion. The yield surfaces found had an irregular convex shape which changed significantly during loading. However, apart from the change in shape, and some change in size, the yield surfaces translated in the stress plane, without significant rotation. Also, no cross effects were evident. As a result, the hardening was almost entirely kinematic, and to the first approximation, the translation of the center of the yield surface was equal to the applied stress increment at each loading step. In this and other respects, the results were similar to those obtained earlier by Phillips and coworkers on commercially pure aluminum.

The experiments on annealed fiber reinforced 6061 Aℓ-B tubes started with a series of tests under combined axial tension and torsion loads. As predicted by the VFD model, the yield surfaces were elongated along the axis of the normal stress applied in the fiber direction, and appeared at first to be elliptical. However, a more detailed investigation revealed that the surfaces had an oval shape, with distinct flat branches perpendicular to the longitudinal shear axis. These flat branches were also found in subsequent experiments under combined torsion and internal pressure. Figures 1 to 3 illustrate the initial yield surfaces obtained in these experiments. Also shown in these figures are the yield surfaces calculated from the periodic hexagonal array (PHA) model described in Section 2.2 above, together with the yield surfaces predicted by the bimodal plasticity theory explained in the sequel.

The hardening experiments on the composite tubes showed that the initial yield surfaces in either stress plane exhibited rigid body translation without any rotation. Minor hardening and softening effects were apparent in the changes in size of the subsequent yield surfaces. However, no systematic isotropic hardening or softening was detected.

Hardening behavior of the composite tubes was examined most extensively under internal pressure and torsion, as in Figure 3. The results are shown in Figures 4 to 7. This series of figures shows successive yield surfaces found during loading along a complex loading path. The rigid body translation is clearly evident.

The results also indicate that the translation of the yield surfaces during active loading is identical with the loading path, whenever the loading point is located on the semielliptical branches of the yield surface. Indeed, in such loading steps the loading point remains fixed in the same location of the yield surface. In contrast, when loading takes place on either of the two flat branches of the yield surface, the surface translates only in the direction of the longitudinal shear axis, regardless of the actual direction of the loading vector.

Figures 8 to 10 show results of hardening experiments for combined axial tension and torsion loading. Under these loading conditions, the yield surface again experiences rigid body translation. When loaded at the flat branches, the surface translates only in the direction of the torsion axis. Loading at the end caps of the yield surface also causes rigid body translation, but in contrast with the behavior in the transverse plane, the loading point travels during loading along the semielliptical branch toward one of the flat branches.

Measurement of total and elastic strains made during the loading sequences shown in Figures 4 to 10, indicated that the plastic strain increments are normal to the current yield surface. However, the yield surfaces sometimes show local distortion, and the normality rule then holds for the distorted yield surface.

As expected, the overall deformation of the tube depends strongly on the loading direction. The tube is very stiff under axial normal stress, somewhat less stiff under internal pressure, and rather compliant under torsion loading.

2.4 A Bimodal Plasticity Theory of Fibrous Composites

To provide a phenomenological explanation of the experimental observations, we proposed a new plasticity theory of fibrous composite materials. This theory shows that elastic-plastic response of a composite aggregate reinforced by aligned continuous fibers can be described in terms of two distinct deformation modes.

To illustrate this, imagine that an unreinforced elastic-plastic layer is subjected to incremental loading by macroscopically uniform states of plane stress. At each point of the loading path there is a certain macroscopically uniform plastic strain rate field which may be related, e.g., through Tresca or Mises yield conditions, to a hypothetical family of slip planes and directions on which the overall field is resolved into simple shear deformations. Now, if the layer is reinforced by aligned, elastic fibers, and subjected to the same incremental loading history, plastic slip may still take place on those planes which are parallel to the fiber axis, but not necessarily on planes which intersect the fibers. Slip on the intersecting planes may be impeded to a certain extent, depending on the fiber properties and the state of stress. For example, fibers with large shear stiffness, such as boron, silicon carbide, or alumina (FP), may render all off-axis planes inactive in a wide range of stress states; whereas fibers which are more compliant in shear, such as graphite, may have only a limited effect.

These considerations suggest that elastic-plastic response of the fibrous ply may be analyzed in terms of two distinct deformation modes. In the case of stiff elastic fibers, macroscopic plastic straining will be preferred in certain directions, through local deformation of the matrix interlayers which are, in actual composite systems, only 10-100μ thick. Under such circumstances one expects that simple shear will be the dominant mode of local plastic deformation of the matrix, and that the fiber will not participate in this mode. Therefore, the composite ply may be regarded as an elastic-plastic continuum with slip planes parallel to the fiber axis. Apart from this restriction, the ply deforms plastically in the same way as the matrix, and therefore, this type of deformation is referred to as the matrix-dominated mode.

In systems reinforced by more compliant elastic fibers, and under overall stresses which do not favor the matrix mode, both phases must deform together in the elastic and plastic range. The fiber often has a significant influence on the overall response, hence this case is referred to as the fiber-dominated mode. No particular deformation mechanism is suggested, the mode must be treated as a general case of plastic deformation of a heterogeneous medium.

These considerations led to the development of a bimodal plasticity theory of fibrous composites. The initial formulation of the theory was described in Reference [11]; additional publications will follow. The theory leads to good prediction of initial yield surfaces, as shown in Figures 1 to 3. In these figures the abbreviation MDM indicates branches of the yield surface predicted with the matrix-dominated mode of the bimodal theory. SCM and Voigt symbols indicate the yield surfaces of the fiber-dominated mode, predicted, respectively, with the help of the self-consistent method, and the Voigt approximation. As pointed out before, the PHA model surfaces were calculated using the periodic hexagonal array model described in Section 4.2.

The bimodal theory also provides a connection between matrix and composite hardening. For example, the predominantly kinematic hardening of the matrix, with the translation vector equal to the loading vector, is reflected in the overall behavior of the composite. The composite displays this type of hardening much more clearly than the matrix. This can be attributed to the limitations imposed on <u>in-situ</u> matrix slip systems by the reinforcing fibers.

Work continues on derivation of the connections between the macroscopic and matrix flow rules, and on predictions of the overall plastic strains.

We note that the theory predicts that the matrix dominated deformation mode may exist only in systems reinforced with fibers of high longitudinal shear stiffness (B, SiC, FP) and not in systems with low shear stiffness, such as graphite. This prediction was not experimentally verified in the present program, but it was confirmed by numerical calculations based on the PHA model.

2.5 Significance of the Results

Results obtained in the course of this research established several new areas of understanding of plasticity of metal matrix composites.

First, the PHA model, the bounds it provides on evaluation of overall response, and its implementation into a general purpose program provides for the first time a reliable and practically useful tool for plasticity analysis of metal matrix composite structures.

Next, the experimental studies, which were the first of its kind performed on a metal matrix composite system, revealed many unusual features of composite behavior, particularly the bimodal nature of composite plastic deformation.

Finally, the bimodal plasticity theory, in conjunction with the experimental results, suggests new insights into elastic-plastic behavior of fiber-reinforced metals. These insights will be of value in future investigations of other types of inelastic deformation of fibrous composite systems.

2.6 References

1. G.J. Dvorak, and Y.A. Bahei-El-Din, "Plasticity of Composite Laminates," Research Workshop on Mechanics of Composite Materials, Duke University, October 17-18, 1978, p. 32.

2. G.J. Dvorak, and Y.A. Bahei-El-Din, "Plasticity Analysis of Fibrous Composites," Journal of Applied Mechanics, Vol. 49, June 1982, p. 327.

3. Y.A. Bahei-El-Din, and G.J. Dvorak, "Plasticity Analysis of Laminated Composite Plates," Journal of Applied Mechanics, Vol. 49, December 1982, p. 740.

4. C.J. Wung, and G.J. Dvorak, "Strain-Space Plasticity Analysis of Fibrous Composites," International Journal of Plasticity, Vol. 1, 1985, p. 125.

5. H.J. Greenberg, "Complementary Minimum Principles for an Elastic-plastic Material," Quarterly of Applied Mathematics, Vol. 7, No. 1, 1949, p. 85.

6. D.C. Drucker, "Variational Principles in Mathematical Theory of Plasticity," Calculus of Variations and its Applications, Proceedings of the Eighth Symposium in Applied Mathematics of the American Mathematical Society, edited by L.M. Graves, McGraw-Hill, 1958, p. 7.

7. P.G. Hodge, Jr., "Numerical Applications of Minimum Principles in Plasticity," Engineering Plasticity, edited by J. Heyman and F.A. Leckie, Cambridge University Press, 1968, p. 237.

8. G.J. Dvorak, and J.L. Teply, "Periodic Hexagonal Array Models for Plasticity Analysis of Composite Materials," Plasticity Today: Modeling, Methods and Applications, edited by A. Sawczuk and G. Bianchi, Elsevier, London, 1985, p. 625.

9. J.L. Teply, and G.J. Dvorak, "Dual Estimates of Overall Instantaneous Properties of Elastic-Plastic Composites," Continuum Models of Discrete Systems, edited by A.J.M. Spencer, Balkema Press, Rotterdam, 1987, p. 205.

10. J.L. Teply, and G.J. Dvorak, "Bounds on Overall Instantaneous Properties of Elastic-Plastic Composites," to appear in Journal of the Mechanics and Physics of Solids.

11. G.J. Dvorak, and Y.A. Bahei-El-Din, "A Bimodal Plasticity Theory of Fibrous Composite Materials," to appear in Acta Mechanica.

2.7 Figures

Figure 1. Initial yield surfaces of a B-Aℓ composite in the σ_{21} σ_{11} plane. Comparison of experimental results with yield surfaces derived from the bimodal plasticity theory and from the periodic hexagonal array (PHA) model.

Figure 2. Initial yield surfaces of a B-Aℓ composite in the σ_{21} σ_{22} plane. Comparison of experimental results with yield surface of matrix-dominated mode, and with surfaces derived from the periodic hexagonal array (PHA) model.

Figure 3. Initial yield surface of a B-Aℓ composite tube under internal pressure and torsion. Comparison of experimental results with the yield surface of the matrix-dominated mode.

Figure 4. Subsequent yield surfaces of a B-Aℓ composite tube under internal pressure and torsion.

Figure 5. Subsequent yield surfaces of a B-Aℓ composite tube under internal pressure and torsion.

Figure 6. Subsequent yield surfaces of a B-Aℓ composite tube under internal pressure and torsion.

Figure 7. Subsequent yield surfaces of a B-Aℓ composite tube under internal pressure and torsion.

Figure 8. Initial and subsequent yield surfaces of a B-Aℓ composite.

Figure 9. Translation of the yield surface of a B-Aℓ composite in torsion.

Figure 10. Rigid body translation of the yield surface of a B-Aℓ composite in stress space.

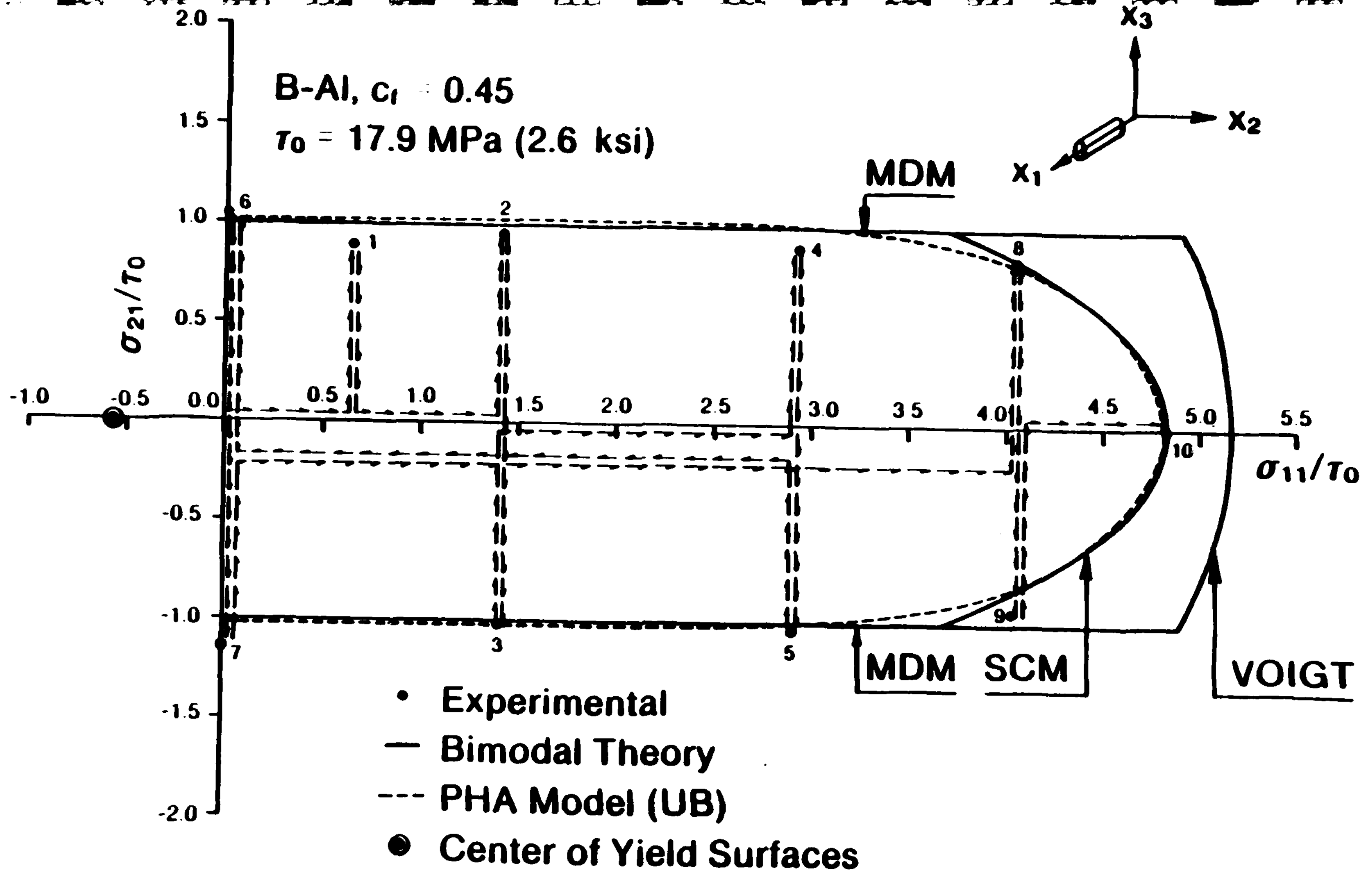


Figure 1. Initial yield surfaces of a B-Al composite in the $\sigma_{21}\ \sigma_{11}$-plane. Comparison of experimental results with yield surfaces derived from the bimodal plasticity theory and from the periodic hexagonal array (PHA) model.

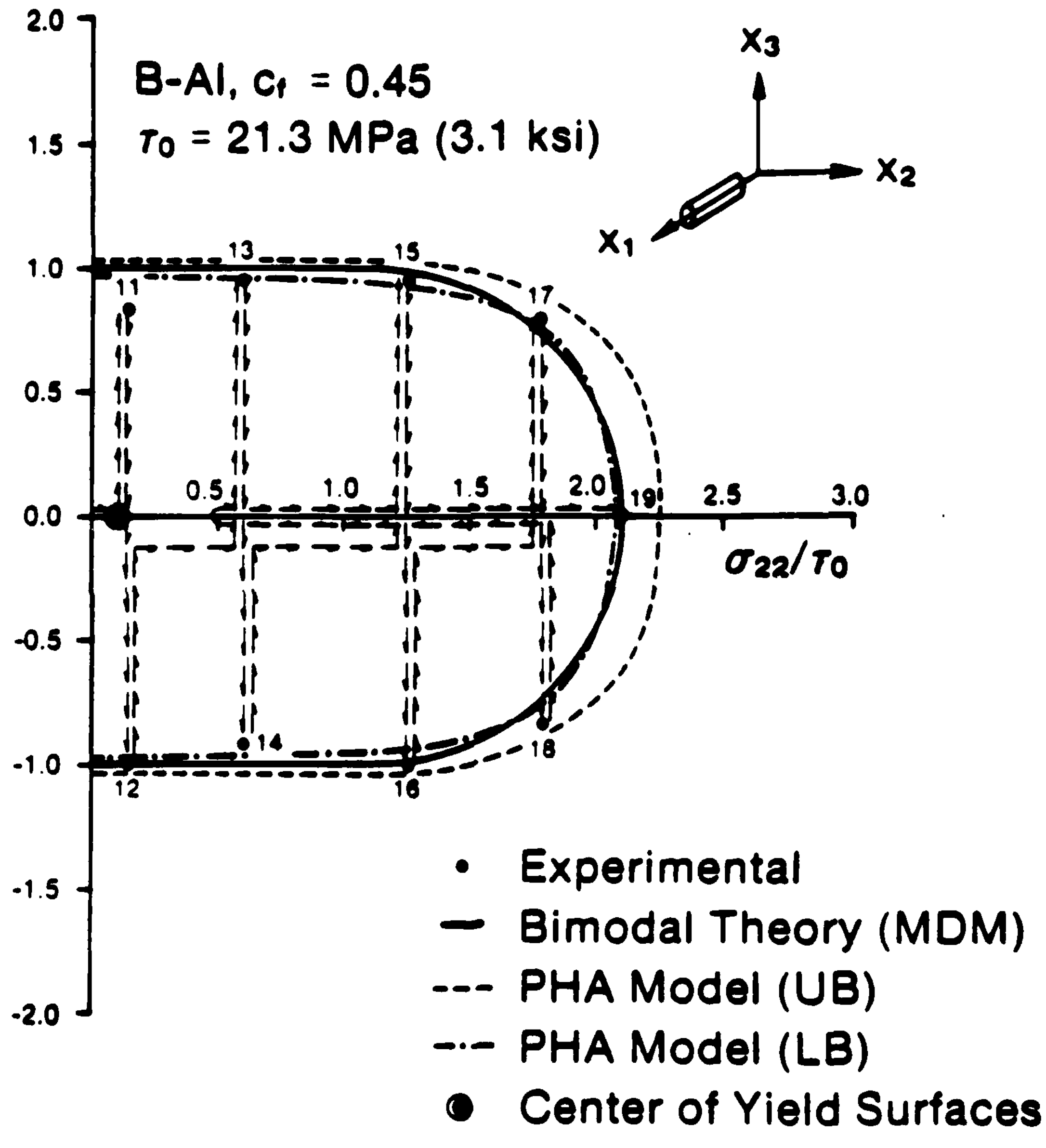


Figure 2. Initial yield surfaces of a B-Aℓ composite in the σ_{21} σ_{22}-plane. Comparison of experimental results with the yield surface of matrix-dominated mode, and with surfaces derived from the periodic hexagonal array (PHA) model.

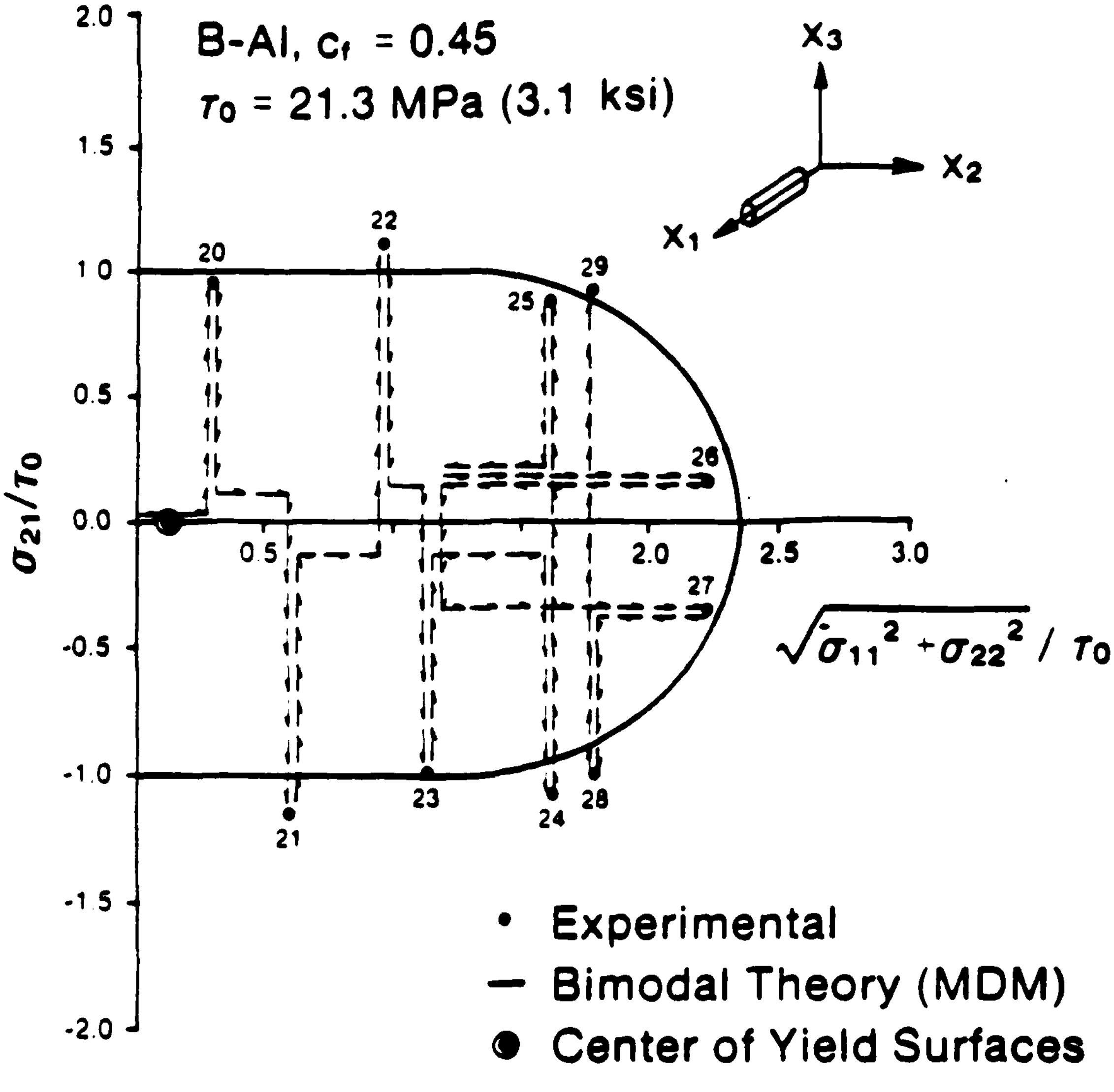


Figure 3. Initial yield surface of a B-Aℓ composite tube under internal pressure and torsion. Comparison of experimental results with the yield surface of the matrix-dominated mode.

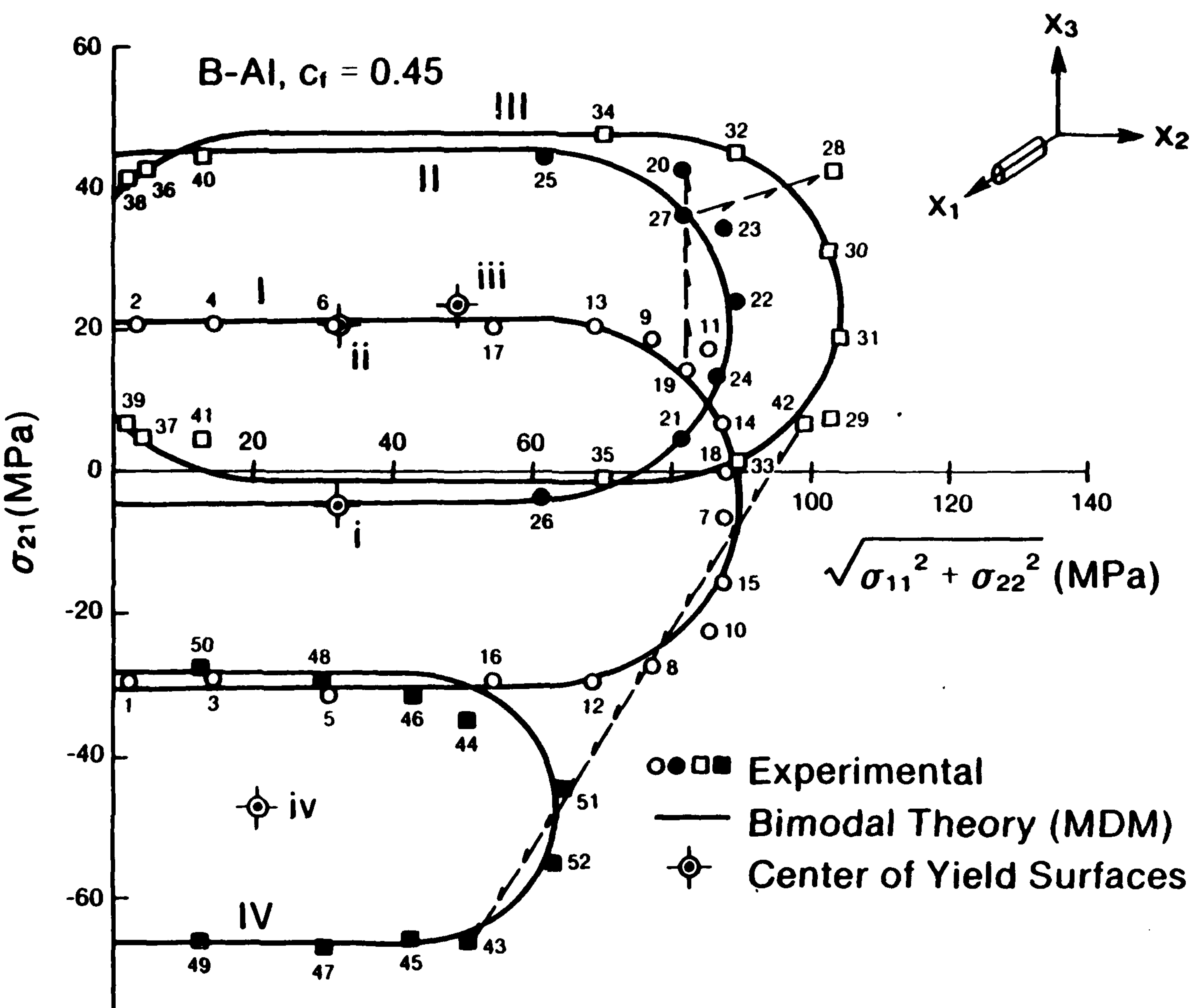


Figure 4. Subsequent yield surfaces of a B-Aℓ composite tube under internal pressure and torsion.

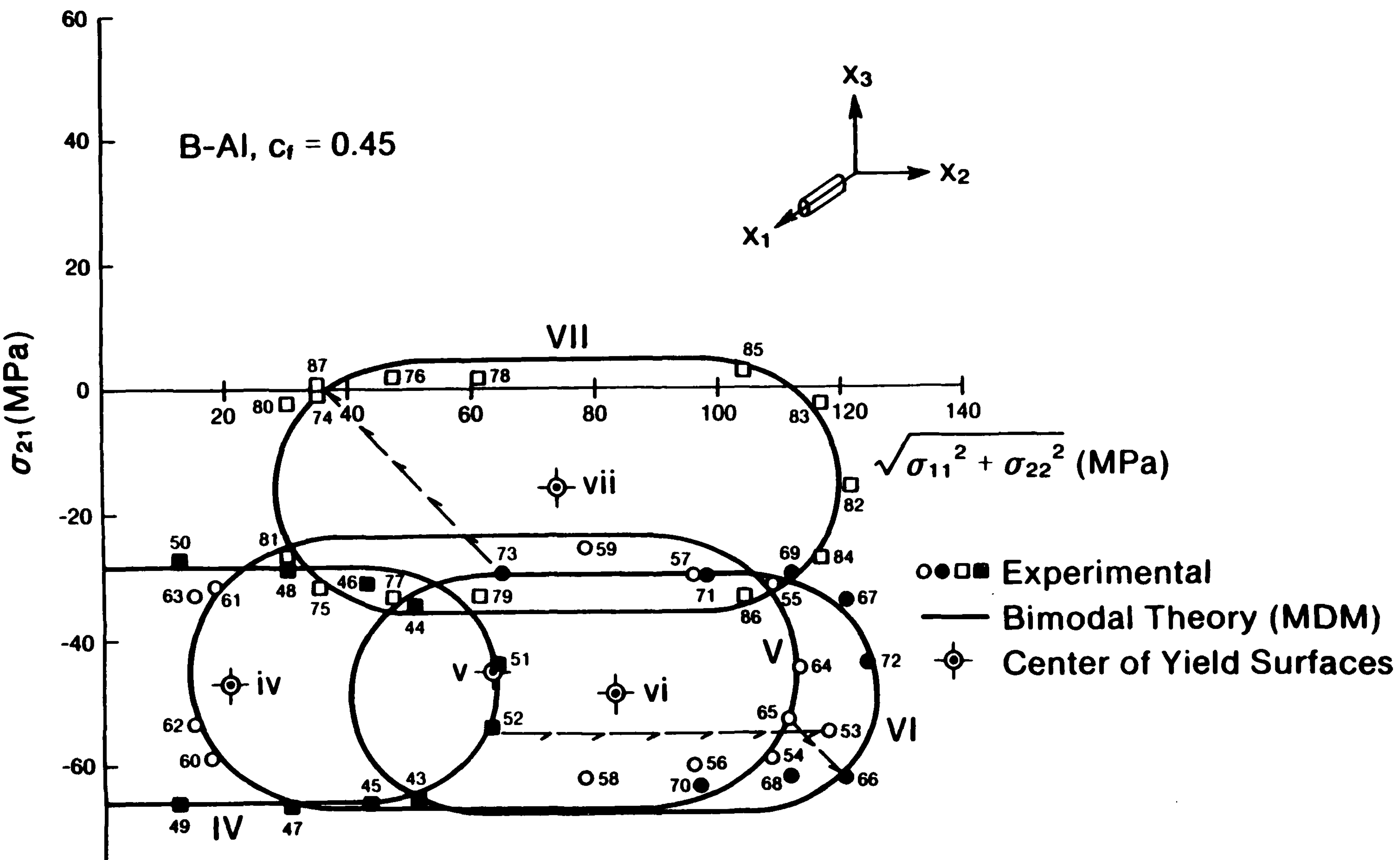


Figure 5. Subsequent yield surfaces of a B-Aℓ composite tube under internal pressure and torsion.

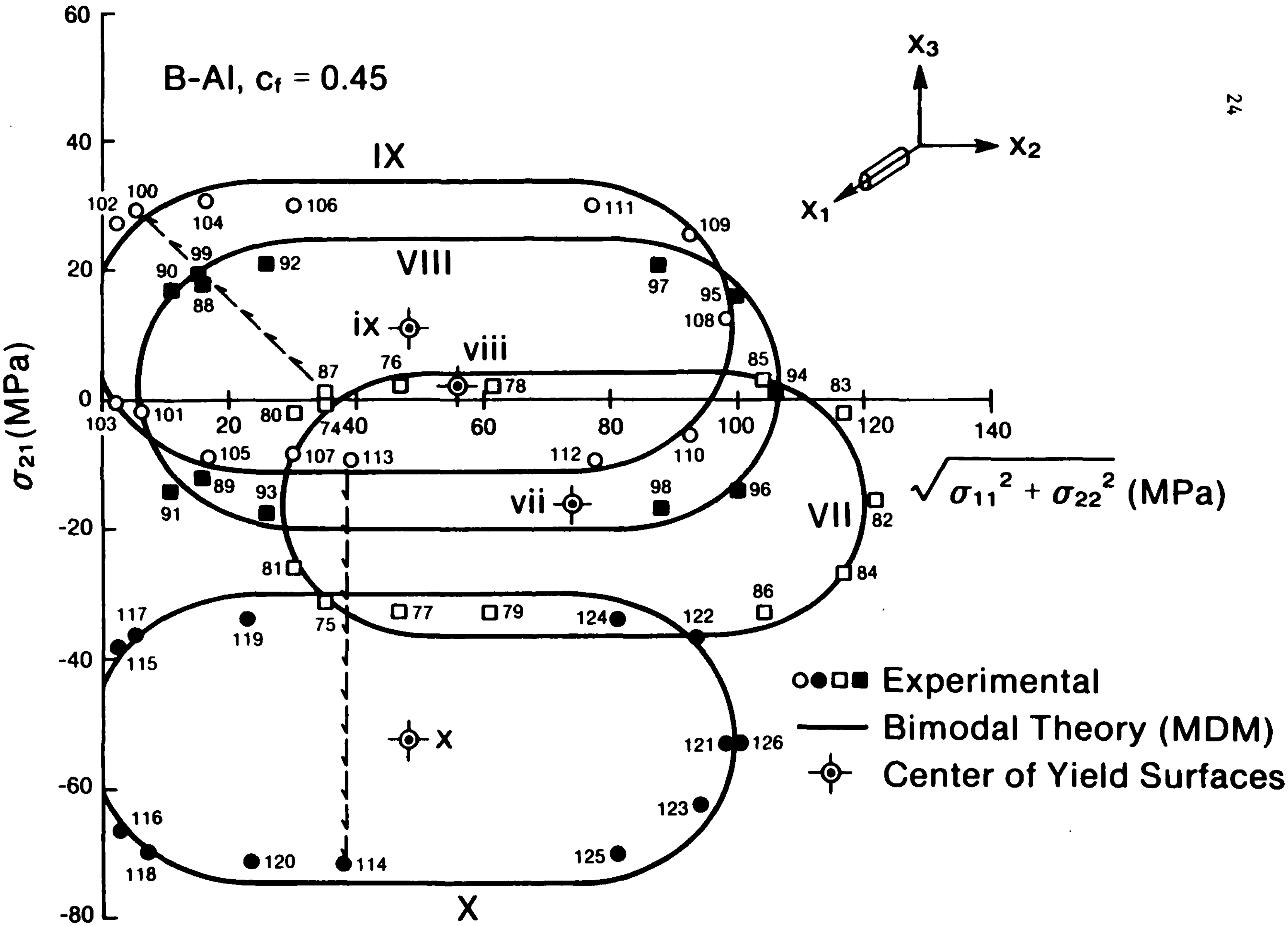


Figure 6. Subsequent yield surfaces of a B-Al composite tube under internal pressure and torsion.

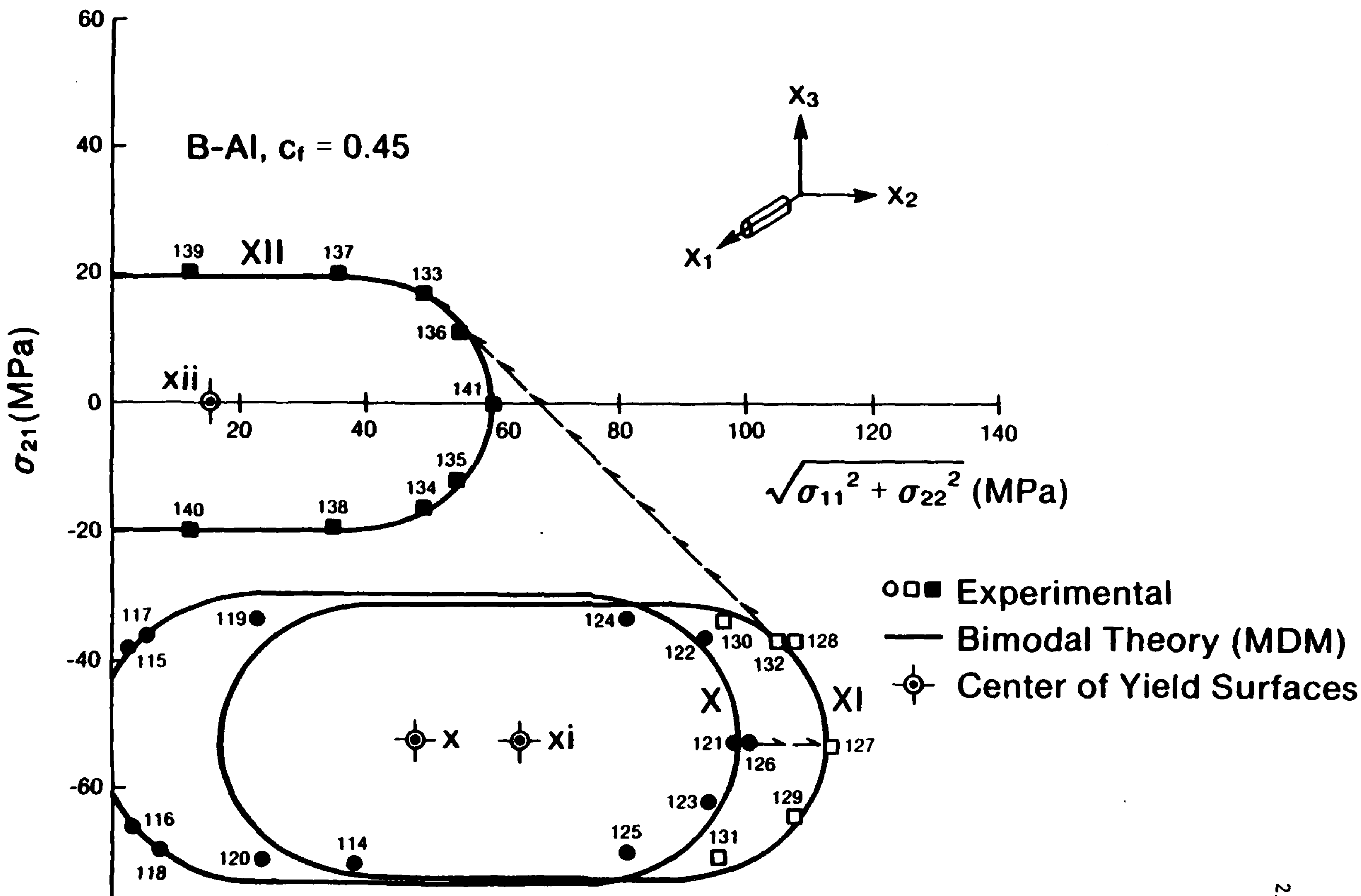


Figure 7. Subsequent yield surfaces of a B-Aℓ composite tube under internal pressure and torsion.

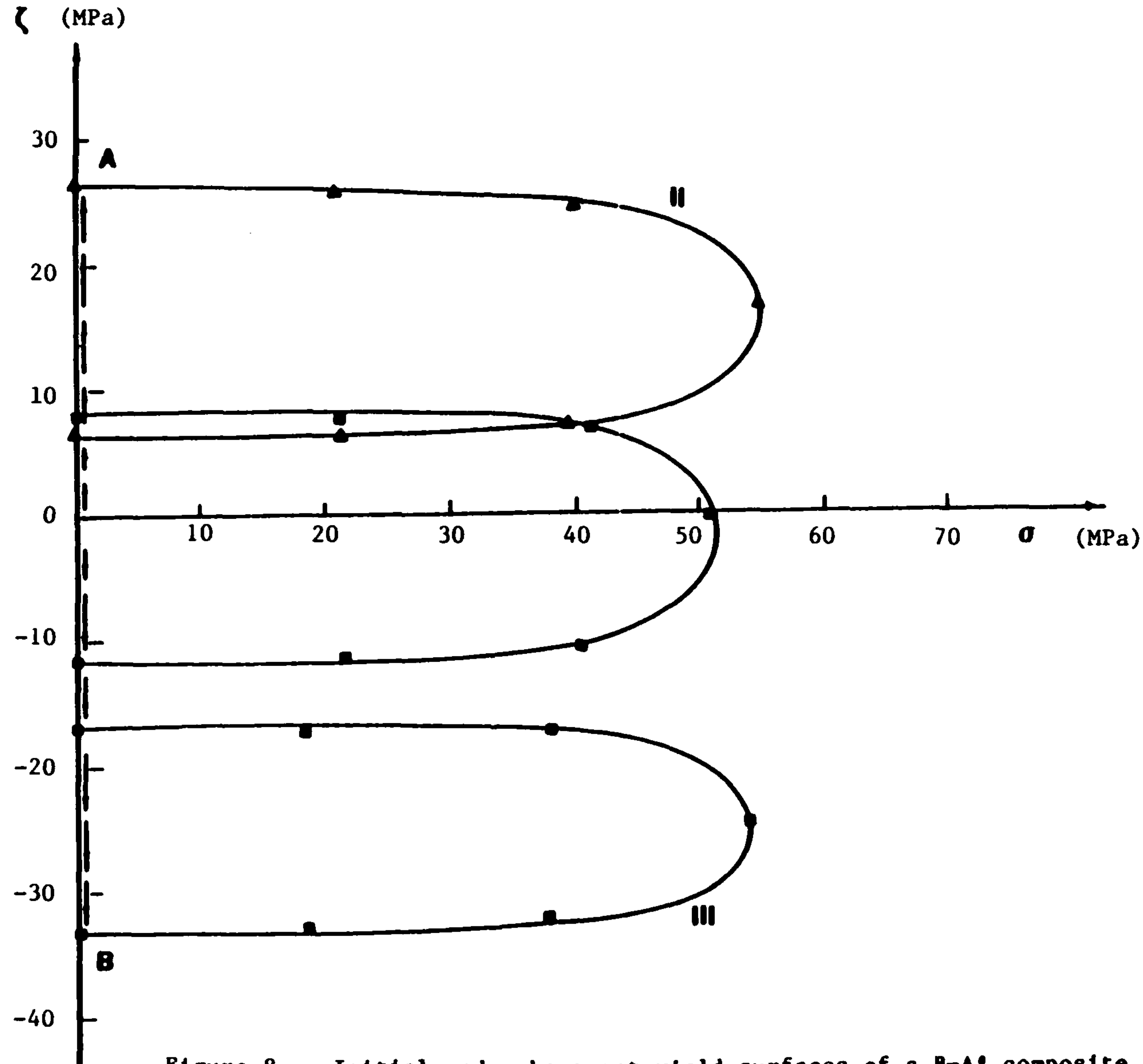


Figure 8. Initial and subsequent yield surfaces of a B-Aℓ composite.

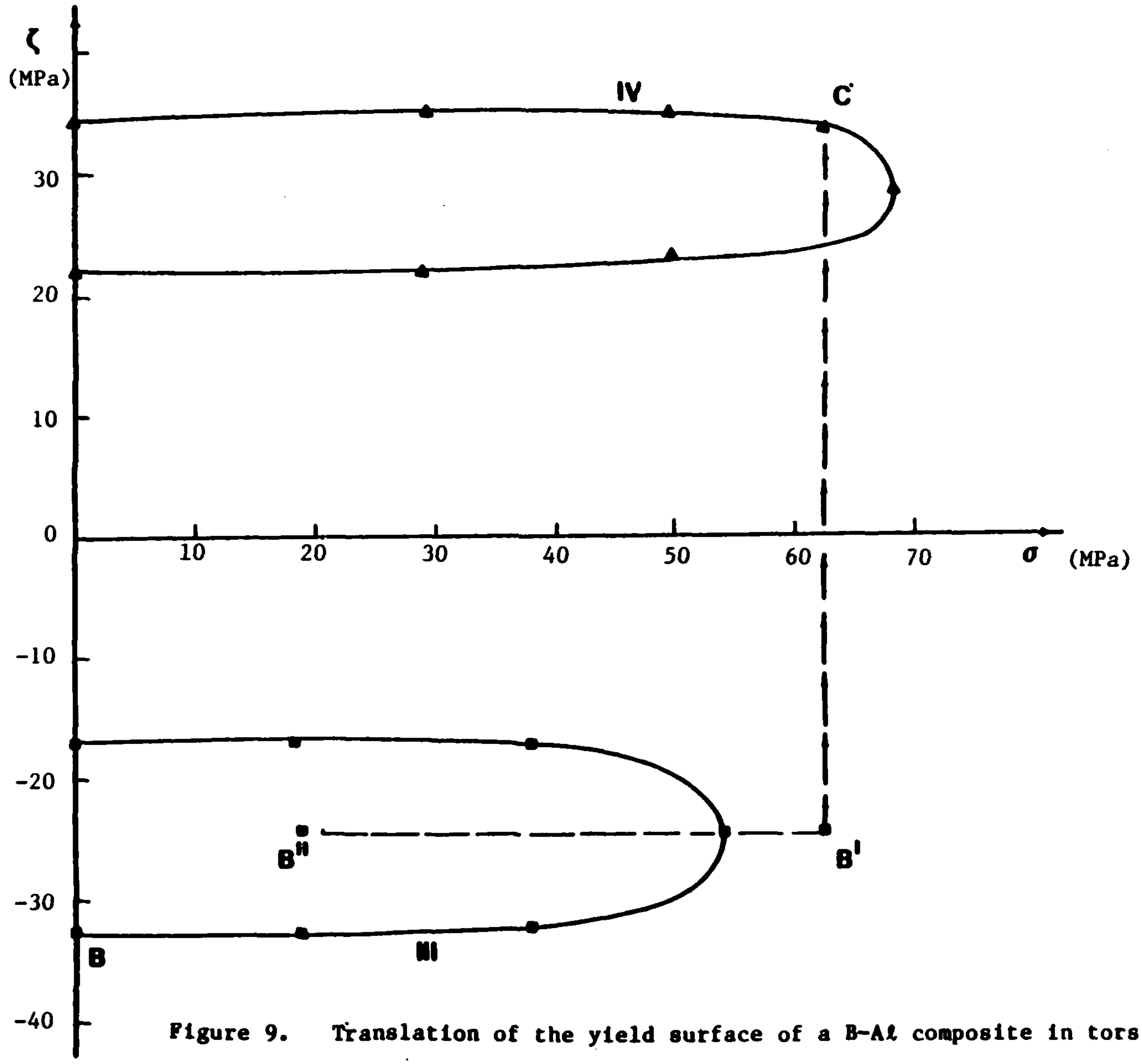


Figure 9. Translation of the yield surface of a B-Aℓ composite in torsion.

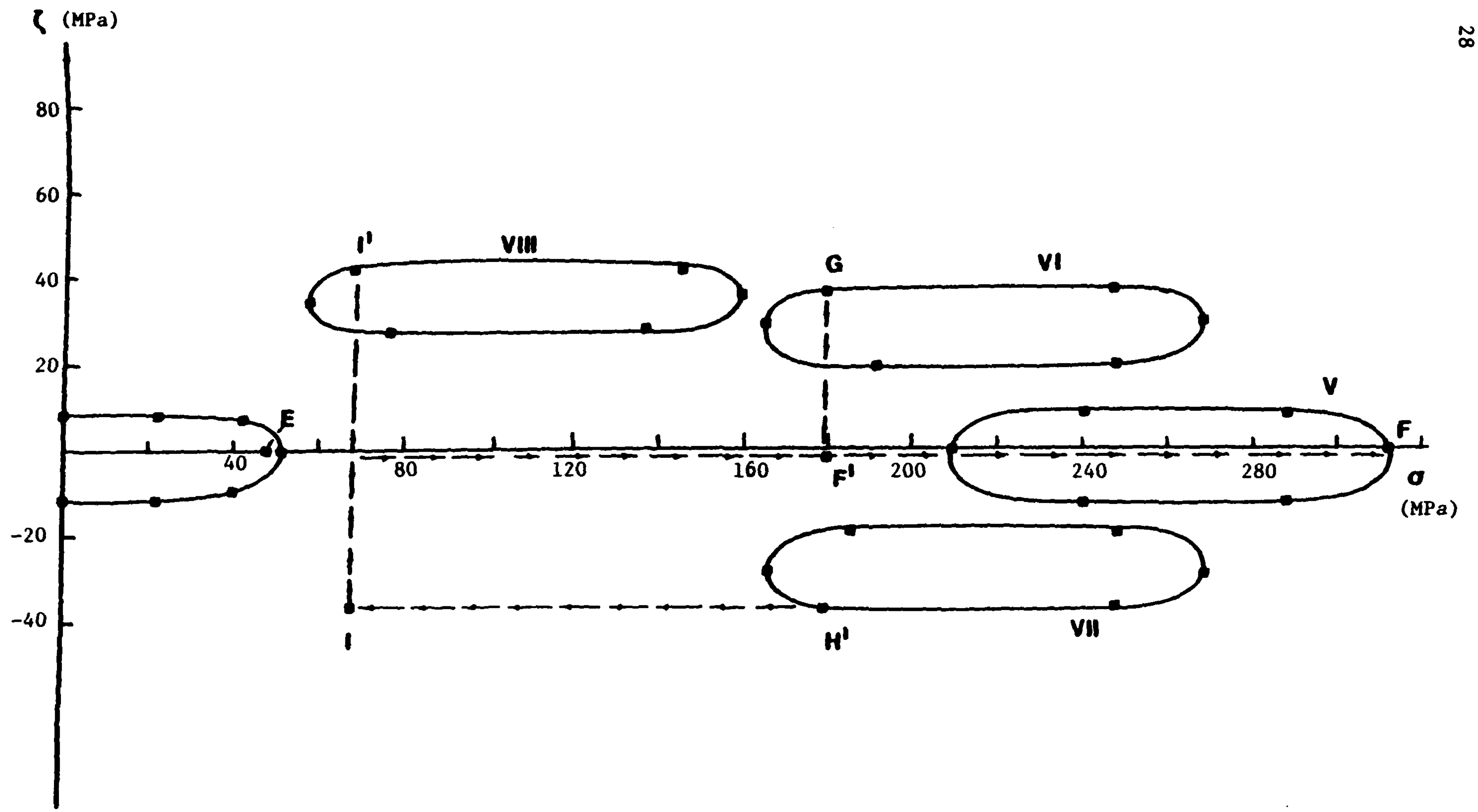


Figure 10. Rigid body translation of the yield surface of a B-Aℓ composite in stress space.

3. LIST OF PUBLICATIONS

1. G.J. Dvorak, and C.J. Wung, "Thermoplasticity of Unidirectional Metal Matrix Composites," Mechanics of Material Behavior, edited by G.J. Dvorak and R.T. Shield, Elsevier, Amsterdam, 1984, p. 87.

2. C.J. Wung, and G.J. Dvorak, "Strain-Space Plasticity Analysis of Fibrous Composites," International Journal of Plasticity, Vol. 1, 1985, p. 125.

3. G.J. Dvorak, and J.L. Teply, "Periodic Hexagonal Array Models for Plasticity Analysis of Composite Materials," Plasticity Today: Modeling, Methods and Applications, edited by A. Sawczuk and G. Bianchi, Elsevier, London, 1985, p. 625.

4. J.L. Teply, and G.J. Dvorak, "Dual Estimates of Overall Instantaneous Properties of Elastic-Plastic Composites," Continuum Models of Discrete Systems, edited by A.J.M. Spencer, Balkema Press, Rotterdam, 1987, p. 205.

5. J.L. Teply, and G.J. Dvorak, "Bounds on Overall Instantaneous Properties of Elastic-Plastic Composites," to appear in Journal of the Mechanics and Physics of Solids.

6. R.A. Chaudhuri, and K.R. Abu-Arja, "Plastic Deformation of a Boron/Aluminum Tube under Multi-Axial Loadings," Computers & Structures, Vol. 24, No. 6, 1986, p. 915.

7. G.J. Dvorak, and Y.A. Bahei-El-Din, "A Bimodal Plasticity Theory of Fibrous Composite Materials," to appear in Acta Mechanica.

4. LIST OF SCIENTIFIC PERSONNEL AND DEGREES GRANTED

Dr. George J. Dvorak, Principal Investigator
Dr. Aris Phillips, Co-principal Investigator
Dr. Reaz A. Chaudhuri

Mr. K.R. Abu-Arja, Graduate Student
Mr. Y. Macheret
Mr. A.T. Tehrani
Mr. C.J. Wung
Mr. J.L. Teply
Mr. B. Jenson
Mr. C.H. Liu

Degrees Granted:

J.L. Teply, Ph.D., 1984, University of Utah
Y. Macheret, Ph.D., 1985, Yale University
C.J. Wung, Ph.D., 1986, University of Utah
K.R. Abu-Arja, M.S., 1985, University of Utah
C.H. Liu, Ph.D. in progress at Yale University

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

MASTER COPY - FOR REPRODUCTION PURPOSES

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER	2. GOVT ACCESSION NO. N/A	3. RECIPIENT'S CATALOG NUMBER N/A
4. TITLE (and Subtitle) Plasticity of Fibrous Composites		5. TYPE OF REPORT & PERIOD COVERED Final 10/10/83 to 02/28/87
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) George J. Dvorak		8. CONTRACT OR GRANT NUMBER(s) DAAG29-83-K-0171 DAAG29-85-K-0011
9. PERFORMING ORGANIZATION NAME AND ADDRESS Rensselaer Polytechnic Institute Troy, New York 12180-3590		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS U. S. Army Research Office Post Office Box 12211 Research Triangle Park, NC 27709		12. REPORT DATE May 1987
		13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE NA

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

NA

18. SUPPLEMENTARY NOTES

The view, opinions, and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Composite Materials
Plasticity

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The purpose of this research program was to establish experimentally verified constitutive relations for isothermal elastic-plastic behavior of metal matrix fibrous composite materials. The theoretical part of the work was concerned with development of new constitutive models of elastic-plastic fibrous composite materials. Our goal was to identify modeling techniques which would permit derivation of overall instantaneous mechanical properties of the aggregate in terms of microstructural geometry and the properties of the phases. Since most fibers remain elastic until failure, the inelastic overall strains

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

are caused by plastic deformation of the matrix. Therefore, an important objective was to find connections between the elastic-plastic deformation of the neat matrix and the composite, and to develop models which would utilize such connections in predictions of the overall response. Also, among the possible approaches to the problem, it was necessary to identify those which would offer a guarantee of accuracy in applications involving incremental loading which could be verified experimentally. The experimental component of the research program consisted of measurements of initial and subsequent yield surfaces and total strains on matrix and composite specimens subjected to complex incremental loading sequences. The material selected for the experiments was the 6061Aℓ/B system. Tubular specimens (diameter 1.5 in.; wall thickness 0.050 in., length 8 in.) were manufactured by diffusion bonding of unidirectionally reinforced sheets by Amercom, Inc. of Chatsworth, CA. Three composite tubes and three matrix tubes were used. All specimens were annealed before testing. The experimental program emphasized verification of constitutive models. In particular, this part of the program served to confirm the validity of the bimodal plasticity theory of fibrous composites which is described in more detail in the sequel. It also provided experimental support for the periodic hexagonal array model which was developed in the theoretical part of the program.

END

10-87

DTIC