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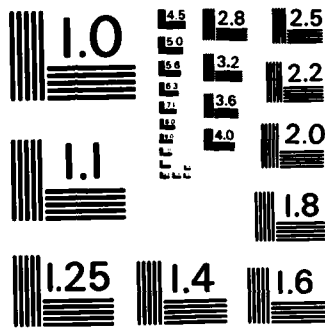


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**FINAL SCIENTIFIC REPORT**  
**TIME DEPENDENT INELASTIC BEHAVIOR OF MATERIALS**  
1 July 1980 - 30 September 1982

by

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Principal Investigator

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Technion - Israel Institute of Technology

### Objectives and Achievements

During the past two years of the research program, solutions have been obtained for a number of problems on the mechanical behavior of materials using the unified constitutive equations developed by Bodner and Partom. These problems are of both basic and applied importance and had previously been unsolvable using the standard material idealizations. They are the following:

1. Characterization of the time-dependent inelastic mechanical properties of metal matrix composites from the properties of the individual constituents.
2. Determination of the creep response of metals for variable loads and temperatures and for extreme variations in the applied stresses.
3. Prediction of plastic wave propagation in strain-rate dependent work-hardening materials.
4. Prediction of the formation of adiabatic shear bands in metals subjected to high rates of loading.

The work on laminated and fiber-reinforced elastic-viscoplastic composites was performed by J. Aboudi in a series of papers (numbers 1, 2, 3, 5, 8 and 10 of the following list of publications under the research grant). These papers have already received wide notice. At the present time, it seems that the methods developed by Aboudi are the only ones available for

predicting stress-strain curves for composites whose constituents are strain-rate dependent work-hardening materials.

Creep response of metals, in particular, copper and aluminum, was extensively studied by A. M. Merzer in publication 4 of the list. The same constitutive equations were used by a group at the AFWAL Materials Laboratory (MLLN) to develop a procedure for predicting creep crack growth in a high temperature alloy (IN-100) from overall displacement measurements. A paper on their work has recently been published:

"A Hybrid Experimental - Numerical Procedure for Determining Creep Crack Growth Rates," T. Hinnerich, T. Nicholas and A. Palazotto, Engineering Fracture Mechanics, vol. 16, pp.265-277, 1982.

Despite the large number of papers published on plastic wave propagation in rods, an analysis that could properly predict the various experimental observations has not been available. This has led to considerable controversy in the field on the relative importance of various material and mechanical effects. The results reported in publication number 9 by Bodner and Aboudi indicate good agreement with a wide range of experimental observations. Preliminary results from that paper have been published in a review article on the subject:

"Elastic-Plastic Stress Waves," T. Nicholas, "Impact Dynamics," J. Wiley and Sons, N.Y., pp.95-153, 1982.

An open problem that has received considerable attention is the mechanism of formation of adiabatic shear bands in metals

subjected to high loading rates. This problem is important in metal forming operations and in evaluating resistance to ballistic perforation. A predictive model for adiabatic shear bands has been developed by A. M. Merzer in publication 7. This work has already been cited in a review by Prof. G. Strang of MIT.

The problems discussed above were solved on the basis of constitutive equations that included both isotropic and anisotropic work-hardening and isotropic thermal recovery of hardening. Thermo-mechanical coupling was included in the treatment of adiabatic shear bands. The proper formulation of anisotropic work-hardening has been studied for some time and a preliminary theory was presented by Stouffer and Bodner (International Journal of Engineering Science, vol. 17, pp.757-764, 1979). A clarification and simplification of that theory has been presented in publication 6 by the same authors. It also includes a procedure for generalizing the theory to include pressure dependence of plastic flow. Even with this work, the anisotropic hardening theory requires further development in order that it could properly predict cyclic stress-strain curves. The present state of the anisotropic hardening theory with the modifications of publication 6 is considered to be applicable for loading histories that involve a limited number of changes in sign of the applied stress. It has been used in publications 9 and 10.

Other subjects of active research during the past two years for which results have not yet been published are: (1) inclusion of "damage" into the constitutive equations, and (2) the incorporation of the constitutive equations into finite element programs.

"Damage" is defined as the deterioration in the ability of the material to support stress and is introduced as a stress history dependent "softening" parameter into the equations. With this term, the equations are able to predict response characteristics leading to failure such as tertiary creep. A presentation of recent results on this topic was given at the Euromech Conference on "Damage Mechanics" in France in September 1981.

An essential requirement for the practical application of constitutive equations is their inclusion in finite element programs in an efficient manner. The elastic-viscoplastic equation of Bodner-Partom including anisotropic work-hardening have been adopted to the ADINA program and are being used to solve a number of fracture mechanics problems. These include calculation of the stress and strain fields in the vicinity of a crack tip for monotonic loadings at different rates and for cyclic loading including overloads. The results have a bearing on the questions of dynamic fracture toughness and on cyclic crack growth. It is expected that results of this part of the program will be available next year.

During the period of the research grant, presentations were made at international conferences of work performed under the auspices of the grant. These were as follows:

1. "Stress Wave Propagation in Rods of Elastic-Viscoplastic Materials,"  
S. R. Bodner and J. Aboudi,  
Annual Meeting of the Society of Engineering Science,  
Providence, R.I., 2-4 September, 1981.

2. "Evolution Equations for Isotropic and Anisotropic Damage Growth,"  
S. R. Bodner,  
Euromech Colloquim (147) on "Damage Mechanics,"  
Cachan, France, 22-25 September, 1981.
  
3. "Effective Constitutive Equations for Fiber-Reinforced Viscoplastic Composites,"  
J. Aboudi,  
IUTAM Symposium on the Mechanics of Composite Materials,  
Blacksburg, VA, 16-19 August, 1982.

In addition, Professor Bodner delivered lectures describing the research results at the AFWAL Materials Laboratory, Southwest Research Institute, the University of Illinois, Brown University, the University of Leicester (England), and the Swiss Federal Institute of Technology (Zurich).

In June 1982, Professor Bodner was awarded the Rothschild Prize in Israel in recognition of his research contributions to the fields of viscoelasticity, dynamic plasticity, and the constitutive behavior of materials. Most all this work was performed on projects sponsored in part by the United States Air Force Office of Scientific Research.

Personnel

In addition to the Principal Investigator, Professor S. R. Bodner, the following persons were engaged on the research program:

Professor Jacob Aboudi (Tel Aviv University)

Associate Professor Assa Rotem (Technion)

Dr. Anthony Merzer (Technion)

Mr. Zvi Zaphir (Graduate Student)

Professor Bodner was a Visiting Professor at the University of Illinois, Urbana, IL, during August 1980 (with Professor F. A. Leckie), and at the University of Cincinnati, Cincinnati, Ohio during September 1980 (with Professor D. C. Stouffer). During the summer of 1981, he was a Visiting Scientist at Southwest Research Institute, San Antonio, Texas (with Dr. U. S. Lindholm).

Publications of Research Program

1. "Effective Stiffness Theory for a Laminated Elastic-Viscoplastic Work-Hardening Composite," by J. Aboudi, International Journal of Solids and Structures, vol. 17, pp.421-431, 1981.

Abstract - Effective stiffness theory is derived for modelling the dynamic behavior of laminated composite material made of elastic-viscoplastic work-hardening constituents. The resulting theory represents the composite as a higher order continuum with microstructure, with the corresponding equations of motion and flow rules. The theory is illustrated and applied to obtain the dynamic response of a laminated slab subjected to time-dependent normal extended load in the direction of the layering.

2. "Generalized Effective Stiffness Theory for Nonelastic Laminated Composites," by J. Aboudi, International Journal of Engineering Science, vol. 19, pp.1269-1281, 1981.

Abstract - Effective stiffness theory of the N-th order is derived for the modelling of the three-dimensional dynamic motion of a laminated medium made of elastic-viscoplastic work-hardening constituents. The resulting theory represents the composite as a higher order homogeneous continuum with microstructure, whose motion is governed by higher order displacements and stresses. The derivation is systematic and can be applied to other types of nonelastic laminated media to the desired degree of accuracy.

3. "Generalized Effective Stiffness Theory for the Modeling of Fiber-Reinforced Composites," by J. Aboudi, International Journal of Solids and Structures, vol. 17, pp.1005-1018, 1981.

Abstract - Effective stiffness theory of the N-th order is derived for the modeling of the three-dimensional time-dependent motion of a fiber-reinforced composite. The fibers are assumed to be of a rectangular cross-section and are imbedded in the matrix in the form of a doubly periodic array. The resulting theory represents the composite as a higher order homogeneous continuum with microstructure whose motion is governed by higher order displacements. The derivation is systematic and can be applied to elastic as well as anelastic composites to the desired degree of accuracy.

4. "Steady and Transient Creep Behavior Based on Unified Constitutive Equations," A. M. Merzer, ASME Journal of Engineering Materials and Technology, vol. 104, pp.18-25, 1982.

Abstract - A set of constitutive equations, which has been used to describe a variety of quasi-static and dynamic viscoplastic phenomena, are applied to creep problems. Simulations of steady and transient creep at constant stress are obtained which compare well with experimental results both qualitatively and quantitatively. Simulations of creep resulting from rapid changes in the applied stress also compare well with observations. The constitutive equations can be used to describe logarithmic creep. These latter predictions are compatible with experimental results in considerable detail.

5. "A Continuum Theory for Fiber-Reinforced Elastic-Viscoplastic Composites," by J. Aboudi, International Journal of Engineering Science, vol. 20, pp.605-621, 1982.

Abstract - A higher order continuum theory with microstructure is derived for the modeling of the 3-dimensional motion of fiber-reinforced composites in which both the matrix and fiber constituents are assumed to be elastic-viscoplastic work-hardening materials. The fibers are unidirectional with rectangular cross-section and are imbedded in the matrix in the form of a doubly periodic array. The derivation of the theory is systematic and can be applied to various types of non-elastic composites to the desired degree of expansion. An appropriate reduction of the theory gives the average behavior of the viscoplastic composite in the form of effective rate-dependent stress-strain curves. In the special case of perfectly elastic constituents, the reduction gives the approximate effective moduli of the composite.

6. "Comments on Anisotropic Plastic Flow and Incompressibility," by S. R. Bodner and D. C. Stouffer, International Journal of Engineering Science (in press).

Abstract - The fully anisotropic plasticity theory of Stouffer and Bodner with stress history dependent internal state variables is modified to enforce plastic incompressibility which makes that theory consistent with stability and thermodynamic principles. Pressure dependence of plastic flow could be included through its influence on the hardening variables. An intermediate anisotropic

plasticity theory is described which is based on anisotropic work hardening and incremental isotropy of the flow law. A method is suggested for obtaining an effective scalar hardening parameter from the anisotropic components. The incremental isotropic formulation is simpler for numerical calculations and may be adequate for initially isotropic materials.

7. "Modelling of Adiabatic Shear Band Development from Small Imperfections," by A. M. Merzer, Journal of the Mechanics and Physics of Solids (in press).

Abstract - A model of shear banding is presented which shows how a wide shear band develops from a narrow imperfection in an elasto-viscoplastic material subjected to dynamic shear strain. The model predicts that the width of the shear band is (i) independent of the properties of the initial imperfection, and (ii) dependent upon thermal conductivity and strain rate. The dependence upon strain-rate is verified qualitatively and quantitatively from experimental results. Finally, the model predicts narrowing of the region of rapid straining with ongoing deformation as is observed in experiment.

8. "Effective Constitutive Equations for Fiber-Reinforced Viscoplastic Composites," by J. Aboudi, Proceedings of IUTAM Symposium on "The Mechanics of Composite Materials," Pergamon Press, 1982 (in press).

Abstract - Effective elastic-plastic stress-strain relations are derived for fiber-reinforced composites whose constituents are elastic-viscoplastic work-hardening materials. The composite is

made of unidirectional fibers which are imbedded in the matrix in the form of a square array. The derivation is based on a higher order continuum theory with microstructure which was developed recently by the author for the modeling of viscoplastic composites. A specific reduction of this theory gives the effective rate-dependent elastic-plastic behavior of the composite. In the special case of perfectly elastic constituents, the approximate effective moduli of the fiber-reinforced material are obtained. Average stress-average strain rate-dependent curves are constructed for numerous modes of loading from which the overall strength, rate-sensitivity and hardening of the composite can be studied.

9. "Stress Wave Propagation in Rods of Elastic-Viscoplastic Material," by S. R. Bodner and J. Aboudi, International Journal of Solids and Structures (submitted for publication).

Abstract - A number of uniaxial stress wave propagation problems are solved based on the unified, multi-dimensional, elastic-viscoplastic constitutive equations of Bodner-Partom and a finite difference numerical procedure. Solutions are obtained for cases of a velocity imposed for a time period or indefinitely at the end of semi-infinite and finite bars and for the condition of a high velocity superimposed on an applied low velocity after a time interval. Work-hardening is taken to be isotropic for stress of constant sign, while an isochoric, anisotropic work-hardening formulation is employed for problems involving stresses of reversed sign due to unloading or reflections. The numerical exercises are based on constants for a strongly strain-

rate sensitive material, titanium, and the results indicate very good qualitative agreement with a wide range of experimental observations.

10. "Effective Constitutive Equations for Fiber-Reinforced Viscoplastic Composites Exhibiting Anisotropic Hardening," by J. Aboudi, International Journal of Engineering Science (submitted for publication).

Abstract - Effective elastic-viscoplastic stress-strain relations are derived for fiber-reinforced composites whose constituents are elastic-viscoplastic materials displaying anisotropic hardening. The derivation is based on a recently developed high-order continuum theory with microstructure for the modeling of viscoplastic composites, and is generalized here to incorporate anisotropic hardening effects. A specific reduction of the theory gives the effective rate-dependent elastic-plastic behavior of the composite which exhibits plastic anisotropy. In the special case of perfectly elastic constituents, the approximate overall moduli of the fiber-reinforced composite are obtained. Rate-dependent average stress-strain curves are given for numerous modes of cyclic loading of the composite. The effective behavior of periodically bilaminated viscoplastic composites is determined as a special case.

### Directions of Further Research

Although the elastic-viscoplastic constitutive equations which were used as the basic reference in much of the current research work have reached an advanced state of development, there are certain generalizations and improvements to be made. Of specific interest are the following:

1. Extension of the equations to arbitrarily large deformations and strains using a Lagrangian description.
2. Formulation of appropriate evolutionary equations for the development of anisotropic damage; incorporation of anisotropic damage effects into the basic response equations.
3. Improvement of the anisotropic hardening theory for proper prediction of cyclic stress-strain curves when the number of cycles is large.

The elastic-viscoplastic constitutive equations have already been used as the basic material characterization in a number of important applications, some of which are described in this report. Other applications of interest that are presently being investigated are the following:

1. Application of the equations to fracture mechanics problems using the finite element method.
2. Generalization of Aboudi's theory of elastic-viscoplastic composites (based on a uniform array of fibers in a matrix) to the case of laminated composites in which the orientation of the fibers varies from layer to layer.