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Materials and Structures Program

Rensselaer Polytechnic Institute
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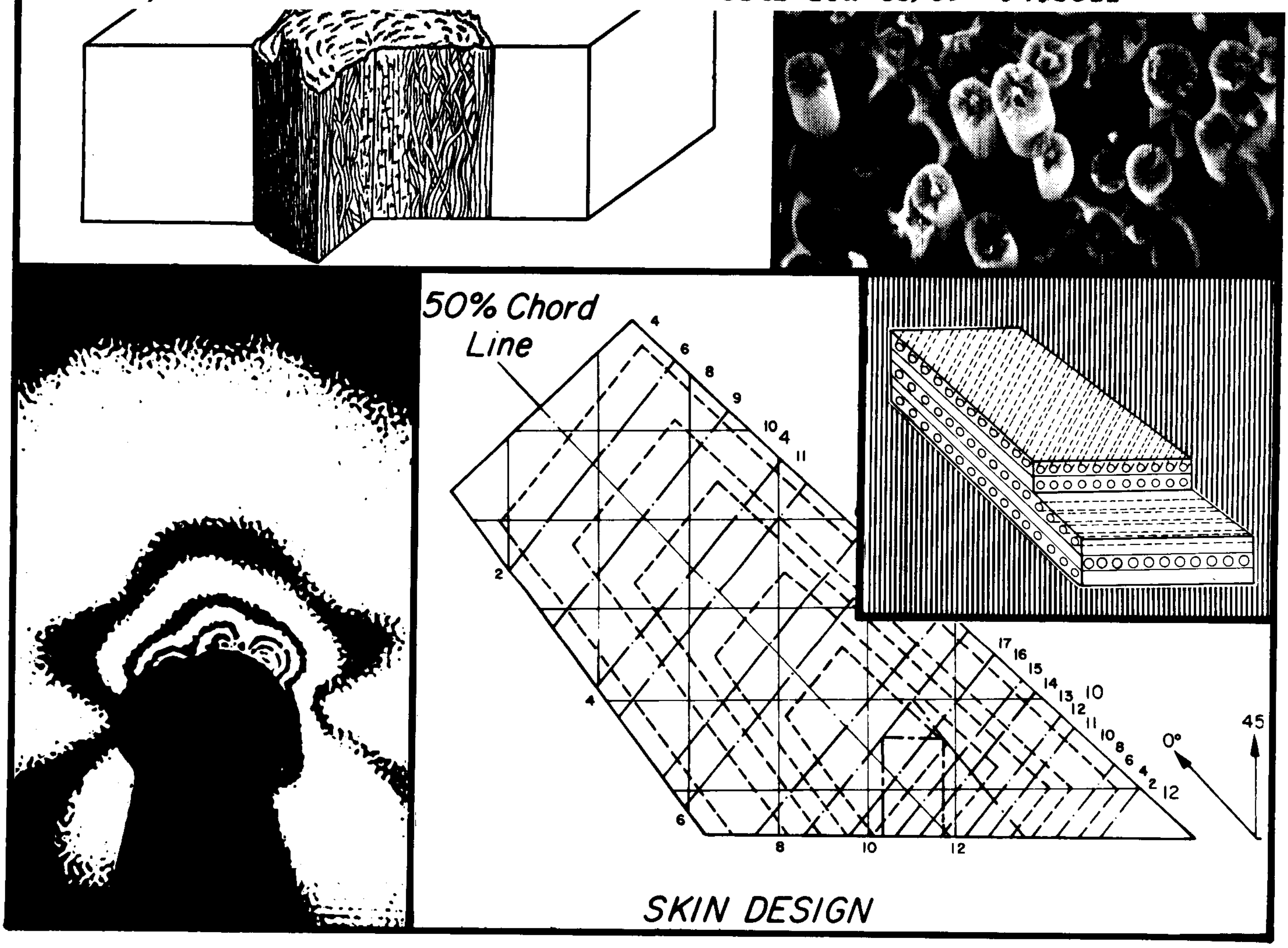

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Annual Progress Report
May 1, 1986 through April 30, 1987

COMPOSITE STRUCTURAL MATERIALS

Air Force Office of Scientific Research
and
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50th Report August 1987

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PART I

INTRODUCTION

INTRODUCTION

The development and application of composite materials to aerospace vehicle structures which began in the mid 1960's has now progressed to the point where what can be considered entire airframes are being designed and built using composites. At least two systems intended for production, the McDonnell-Douglas AV-8B and the Bell-Boeing V-22 aircraft are cases in point. Significantly, both are VTOL systems, in which empty-weight is an especially potent design variable. At the same time, certain aircraft and spacecraft components are being routinely designed and built using composites because either performance or economics require such use. At the low end of the temperature scale, tail surfaces provide one example of such applications (aircraft centers of gravity historically tend to fall too far aft); at the high end, reentry body lifting surface leading edges provide another example.

As such applications have become more wide-spread, the initial developments and use of composites based on thermoset resin matrices are increasingly making way for those incorporating thermoplastics - for a number of reasons. Probably foremost among these are higher damage tolerance and wider allowable operating temperature ranges. Still more advanced concepts for such projects as the "Orient Express", National AeroSpacePlane (NASP), and the so called Advanced Tactical Fighter and Attack aircraft call for higher temperature applications of composites than have ever been sought before for airframes. In fact, missions which call for hypersonic fighter aircraft and missles, ultra-manueverable and/or VTOL fighters which make use of thrust vectoring nozzles, and transatmospheric vehicles which routinely leave the atmosphere, orbit, reenter, land and are capable of rapid turn-around for repeated reuse, are blurring some of the traditional distinctions between <u>engine</u> materials and structures and <u>airframe</u> materials and structures. For many of these concepts, higher temperature capable composite structural materials - over ranges which are rather continuous from ~ 400^{o} to ~ 3000^{o}f - must be considered, not just desireable, but enabling technologies.

NASA and AFOSR continue to play leading roles in establishing the technology base required to realize the full promise of composites in sophisticated aerospace structures. This is being done through support of programs of fundamental research into composite materials and structures and the means by which they can be successfully applied in design and manufacture. RPI's program has been funded by NASA and AFOSR as part of an over-all university program in composites. Over the roughly ten years in which it has been underway, its purpose has been to develop critical advanced technology in the areas of physical properties, structural concepts and analysis, manufacturing, reliability and life prediction. Specific goals have changed as the state of composite materials and structures art has developed. In the early years strictly low temperature airframe applications were of interest, and major efforts were expended in establishing new structural design concepts and in exploring low cost, innovative fabrication techniques. More recently, such research has given way to the pressing need to deal with the problems of higher operating temperatures. Furthermore, in this era, only the most fundamental aspects seem appropriate.

The overall concept of RPI's program continues to be unusual for a university in several important aspects. First, the nature of the program has been comprehensive. We continue to probe to great depth in a relatively few, well chosen areas of investigation which, taken together, provide coverage of a wide spectrum of composite materials and structures issues. Although we have dropped many projects investigating the behavior of generic structural elements, fabrication science and technology and applicable, generally useful computer methodology developments, the expansion of temperature ranges has added a new dimension to the spectrum of composite issues. It is clear that as new directions are added to RPI's program, particularly with limited funds and personnel, older ones must be dropped. In this period, renewed emphasis was placed on the more fundamental issues associated with relatively little-explored areas of resin matrix composites and with the newer constituent materials: those fibers and matrices capable of higher temperatures. A number of studies involving the older resin matrix manufacturing processes, directionally solidified eutectics, and edge-initiated delamination failures have all been phased out over the past two years.

Second, interactions among faculty contributing to program objectives is on a day to day basis without regard to organizational lines. These contributors are a group wider than that supported under the project. Program management is largely at the working level, and administrative, scientific and technical decisions are made, for the most part, independent of considerations normally associated with academic departments. This kind of involvement includes faculty, staff and students from chemistry, civil engineering, materials engineering, aeronautical engineering, mechanical engineering, and mechanics, depending on the flow of the research.

Both of these characteristics of the NASA/AFOSR program of research in composite materials and structures foster the kinds of fundamental advances whch are triggered by insights into aspects beyond the narrow confines of an individual discipline. This is often sought in many fields at a university, but seldom achieved.

A third aspect is increasing the interaction between appropriate members of NASA's staff of Research Center scientists and engineers and those active in the program at RPI. This has required identification of individual researchers within NASA centers whose areas of interest, specialization and active investigation are in some way related to those of RPI faculty supported under the subject grant. A program of active interchange is then encouraged and the means by which such interaction can be fostered is sought. Benefits which result from this increased communication include a clearer window to directions in academia for NASA researchers; opportunities to profit from NASA experience, expertise and facilities for the faculty and students so involved; and an additional channel for cross-fertilization across NASA Research Center missions through the campus program. Finally, collaboration among RPI investigators is encouraged through management mechanisms; for example, asking faculty whose research promises to be synergistic to propose to the program's Budget Advisory Committee jointly.

In short, the NASA/AFOSR Composites Aircraft Program is a multi-faceted program planned and managed so that scientists and engineers in a number of pertinent disciplines at RPI will interact, both among themselves and with counterpart NASA Center researchers, to achieve its goals. Research in basic composition, characteristics and processing science of composite materials and their constituents has been planned each year, with the guidance of NASA and AFOSR technical monitors and Research Center engineers and scientists, to address the most pressing and promising aspects of composites in that particular era. In the current period, for example, issues related to the fabrication of non-resin matrix composites and the micro, mezzo and macromechanics of thermoplastic and metal matrix composites have been emphasized.

In the following sections, more detailed descriptions of the progress achieved in the various component parts of this comprehensive program are presented.

PART II

RESEARCH

RESEARCH

A. THE EFFECTS OF CHEMICAL VAPOR DEPOSITION AND THERMAL TREATMENTS ON THE PROPERTIES OF PITCH-BASED CARBON FIBER

Sr. Investigator: R. J. Diefendorf

INTRODUCTION

Chemical vapor deposition is one of the earliest means of processing composite materials and their constituents. It is of interest for carbon because of its potential for both increasing fiber properties and as a means of forming carbon/carbon composites. The purpose of this research is to determine the effects of carbon layers, established by chemical vapor deposition (CVD), on the mechanical properties of pitch-based carbon fiber. One specific question is the extent to which a carbon coating can fill or "heal" those surface flaws which contribute to low stress failures.

STATUS

Work performed in the last reporting period indicated that moduli and possibly strength, as well as interfacial bonding could be altered with the application of a carbon coating. Another area of study was the effect on coating structure of different precursor gases. Initial work was also begun to determine if, by varying deposition parameters, fiber structure could be altered to improve its overall performance. The intent, of course, is to incorporate these findings, if successful, into carbon/carbon production techniques to produce a much higher performance material than is presently possible.

PROGRESS DURING THE REPORTING PERIOD

Furnace parameters were varied in deposition experiments in attempts to achieve the desired penetrative ability of the deposition species. Lower temperatures and pressures and shorter gas contact times yielded the best penetration results. The ranges of parameters used are listed in Table I-A-1, below:

Table II-A-1

Furnace Parameters

Temperature	800-1600C
Pressure	0.2-200 Torr
Flow	50-6500 ccm/s
Time	0.16-10 hours

Gases: Methane, Hydrogen, Naphthalene, and Dicyclopentadiene

Pitch-based carbon fiber, in the form of a single filament or as a tow, was held in a graphite jig and used as a substrate for deposition. Tensile testing was performed to determine the mechanical properties SEM, X-Ray, and optical microscopy were used to analyze fracture surfaces, fiber surface topology, and deposition microstructure.

A "sheath" effect occurred for the treatments in which a substantial coating was achieved. Fibers with apparently brittle and adherent coatings had reduced strength values. Coatings with little adherence and those that did not behave in a bittle manner either caused no adverse effects on properties or improved fiber strength. Although coating thicknesses obtained during experimentation ranged from 0 to 2μm, in many cases they were not discernible under SEM. In general, the fiber properties are not dependent upon the thickness of the deposited layer, but rather the parameters used to obtain the layer, i.e., the structure of the layer. Lower carbon to hydrogen ratios and short gas contact times and/or high gas flow rates yielded in most cases, reduced strength and modulus values.

Microstructural changes resulting in improved fiber modulus were achieved when using dicyclopentadiene as a source gas at elevated temperatures of 1600C and in a 3-hour methane treatment at 1000C. More uniform preferred orientation properties appear to be a reason for the increased modulus values; however, the mechanisms for this improvement are still being studied.

In other experiments to determine if the increased mobility of carbon atoms in the presence of hydrogen could lead to improved preferred orientation of the fiber structure, it was determined that a hydrogen environment, with or without the addition of an applied stress, has little effect on the fiber's structure or its mechanical properties at the temperatures investigated.

PLANS FOR THE UPCOMING PERIOD

Studies to determine the actual mechanism responsible for the increased modulus values observed in certain treatments will be continued. Modulus can be altered by improving preferred orientation, by decreasing the interlayer compliance of the fiber, or by the addition of a highly oriented, adherent coating. The experiments will center on these effects. More work at the higher temperatures will be performed to observe the reproducibility of the "sheath" effect and its effect on strength of the fiber. The possibility of increased strengths with higher temperature CVD seems to be indicated.

Finally, the effect of CVD coatings from different precursor gases also will be investigated to determine their effect on interfacial bond strength. By controlling the interface with a CVD coating, vast improvements in the properties of epoxy matrix and ceramic matrix composites could be achieved.

PRESENTATIONS AND PUBLICATIONS BY PROF. R. J. DIEFENDORF ON THIS SUBJECT.

"The Relationship of Structure to Properties in Carbon Fibers", presented at the Third Japan-U.S. Conference on Composite Materials, Tokyo, Japan, June 23-25, 1986.

"The Chemical Vapor Deposition of Carbon Capillary Tubes II", presented at the 4th International Carbon Conference, Baden-Baden, Deutschen Keramischen Gesellschaft, West Germany, June 30-July 4, 1986.

"Carbon Fibers From Mesophase Pitch", presented at the Rockwell Science Center, Thousand Oaks, Ca. July 11, 1986.

"Carbon Fibers", presented at SUNY-Buffalo, N.Y., April 2, 1987.

"Chemical Vapor Deposition", presented at Sohio, Niagara Falls, N.Y., April 6, 1987.

"Composite Processing", presented as the Sach's Memorial Lecture, Syracuse University, Syracuse, N.Y., April 21, 1987.

B. INELASTIC DEFORMATION OF METAL MATRIX LAMINATES

Sr. Investigator: E. Krempl

INTRODUCTION

Classical laminate theory, assuming uniformly or linearly distributed strains (for in-plane loading and bending, respectively), has served as a useful tool in the design of composites [1,2]. This theory is presently limited to linear elastic behavior and cannot be employed when significant time dependence or plasticity occurs. Both such effects can be encountered in metal matrix composite applications, especially when elevated temperature service is contemplated.

STATUS

During the past decade, the principal investigator and his students have examined the room temperature and elevated temperature behavior of engineering alloys using servocontrolled testing machines. The behavior of the alloys was found to be viscoplastic, even at ambient temperatures [3 through 7]. Consequently, the theory of viscoplasticity based on overstress (VBO) was developed in uniaxial [8] and in isotropic form [9]. A full invariant, orthotropic version of this theory has been established using tensor function representation theorems [10]. A simplified version of this theory was derived in [11]. This simplified version retains the essential features of the original theory including the absence of a yield surface associated with loading and unloading conditions and the existence of asymptotic solutions for constant strain (stress) rate loading. In the theory, the number of material functions is reduced as much as possible to facilitate applications.

PROGRESS DURING REPORTING PERIOD

Lamina Behavior

The simplified theory of [11] was specialized for the plane stress case so as to represent the state of stress in a single ply. Details can be found in a forthcoming report [12].

To demonstrate the usefulness of the theory, it was applied to test data reported by Kreider and Prewo [13] and reproduced here as Figure II-B-1. In this figure, uniaxial stress-strain diagrams in various directions are shown for a single ply of BORSIC(100-μm)/AL-6061-T6 metal matrix composite. Since no test results for the viscous properties of this metal matrix composite were provided in [13], the viscous

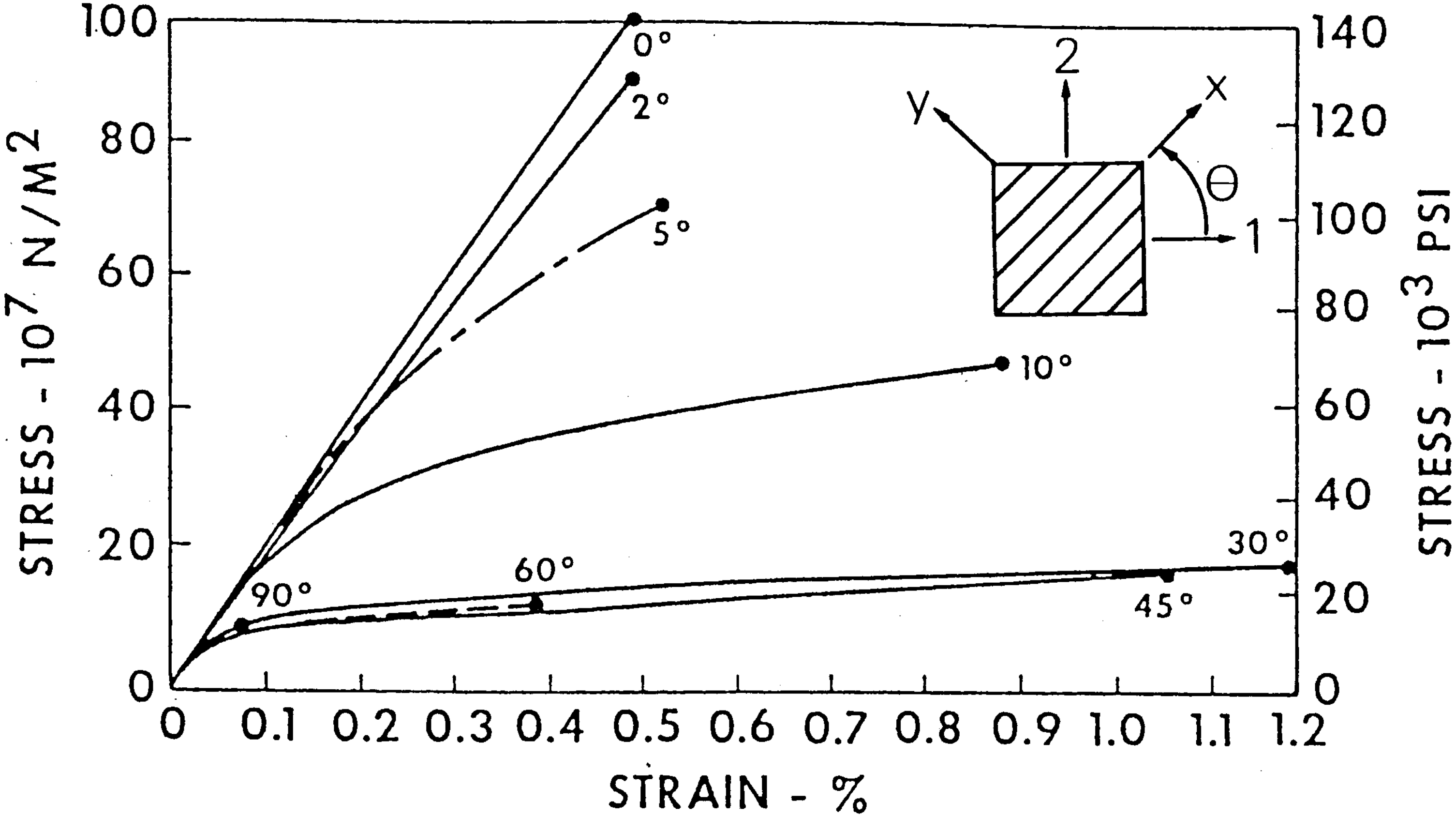

Figure II-B-1
Stress-Strain Curves for 6061 Aluminum Reinforced with 100-μm Borsic Fibers Tensile Tested at Indicated Angles to Fiber Axis, From Kreider and Prewo [13].

properties of AL-6061-T6 alloy given in [9] were used. The matrix in [13] and the alloy in [9] have the same designation and heat treatment, but it is recognized that in situ and neat metal properties can be different.

Figure II-B-2 shows the correlation provided by the orthotropic VBO theory using a particular set of material constants. The curves represent the numerical integration of the system of differential equations under constant strain rate.

All integrations were performed on an IBM AT personal computer using the routine DGEAR for the solution of stiff nonlinear differential equations.

Once the material functions and constants are determined, the set of differential equations can be used for other deformation histories. As an example, the lamina behaviors predicted by the theory under cyclic loading are shown in Figures II-B-3 and 4. The loops shown here are closed after one cycle, demonstrating the consequences of a theory incorporating cyclic neutral behavior. Figures II-B-3a and 3b show hysteresis loops with short time relaxation periods in directions relative to the fiber axis of 5° (Fig. II-B-3a) and 45° (Fig. II-B-3b), respectively. It can be seen that relaxation behavior is much more pronounced on loading than on unloading, and that it is more pronounced in Figure II-B-3b than 3a, due to the increased influence of the matrix (which is viscoplastic). Predictions of short-term creep and hysteresis are shown in Figures II-B-4a and 4b. Creep is also more pronounced during loading than unloading. No creep is observed during unloading where the material behavior is nearly elastic.

No cyclic experiments were reported in [13], so that no cyclic comparisons are possible. The predicted hysteresis loops show the essential features of cyclic neutral behavior, however, and the time dependence is also as expected based on isotropic material behavior at room temperatures [5]. Until cyclic experiments with metal matrix composites become available, the features shown in Figures II-B-3 and 4 will remain uncorroborated theoretical predictions.

Laminate Behavior

A laminate theory for metal matrix composites was then developed following the assumptions and methods of the classical laminate theory [1,2], and incorporating the orthotropic VBO theory. This will also be reported in [12]. The equations were programmed for routine DGEAR integration of the stiff differential equations of the viscoplasticity theory based on overstress which result for cases representing the in-plane loading of symmetric but otherwise arbitrary lay-ups.

Examples of the cyclic behavior predicted by this theory are given in Figures II-B-5 and 6. In each case, one cycle is computed with relaxation periods as in the

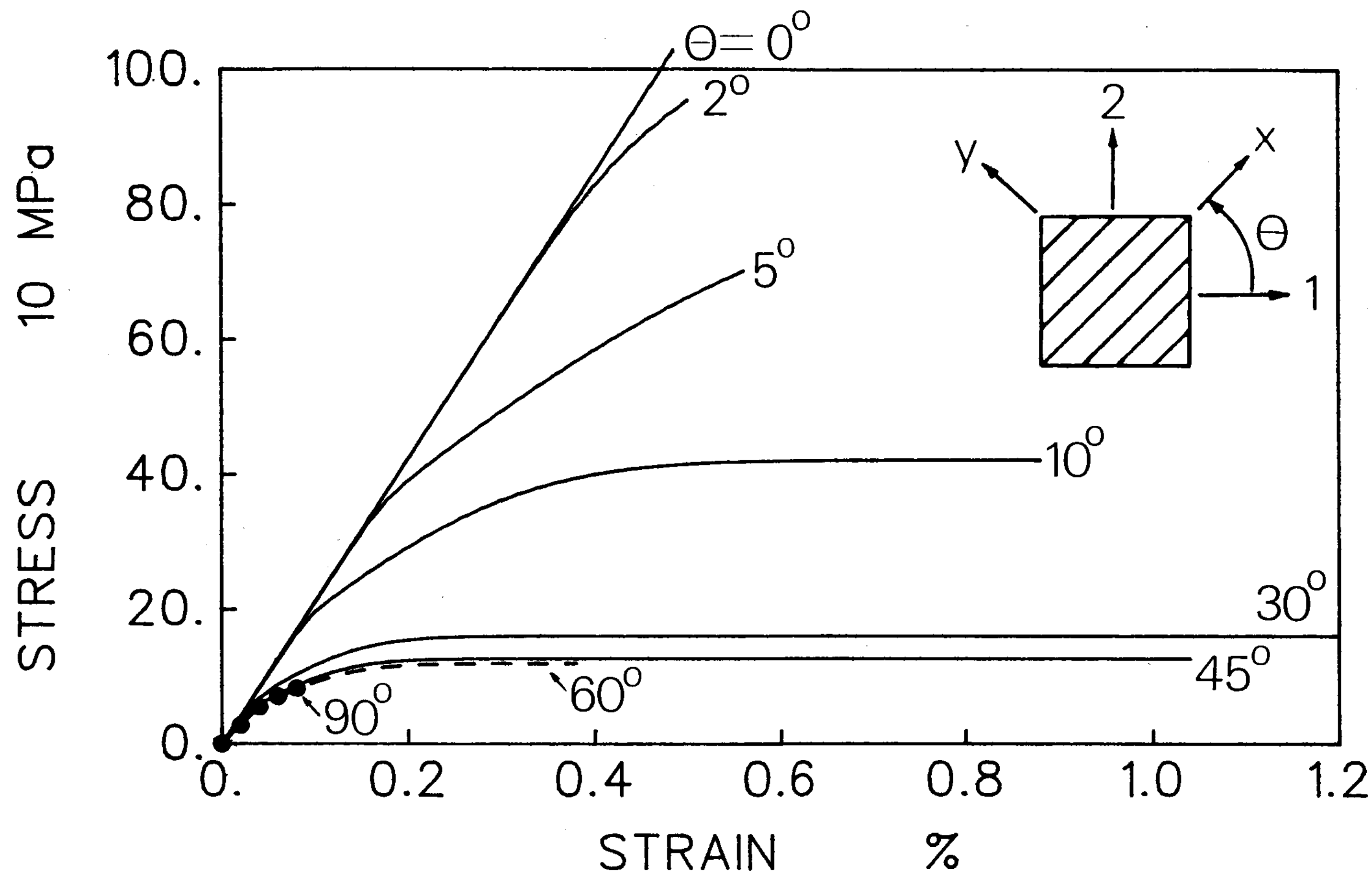

Figure II-B-2

Simulation of the Results Shown in Fig. II-B-1 Using the Viscoplasticity Theory Based on Overstress (VBO). Strain Rate 10^{-s} $1/_{s}$.

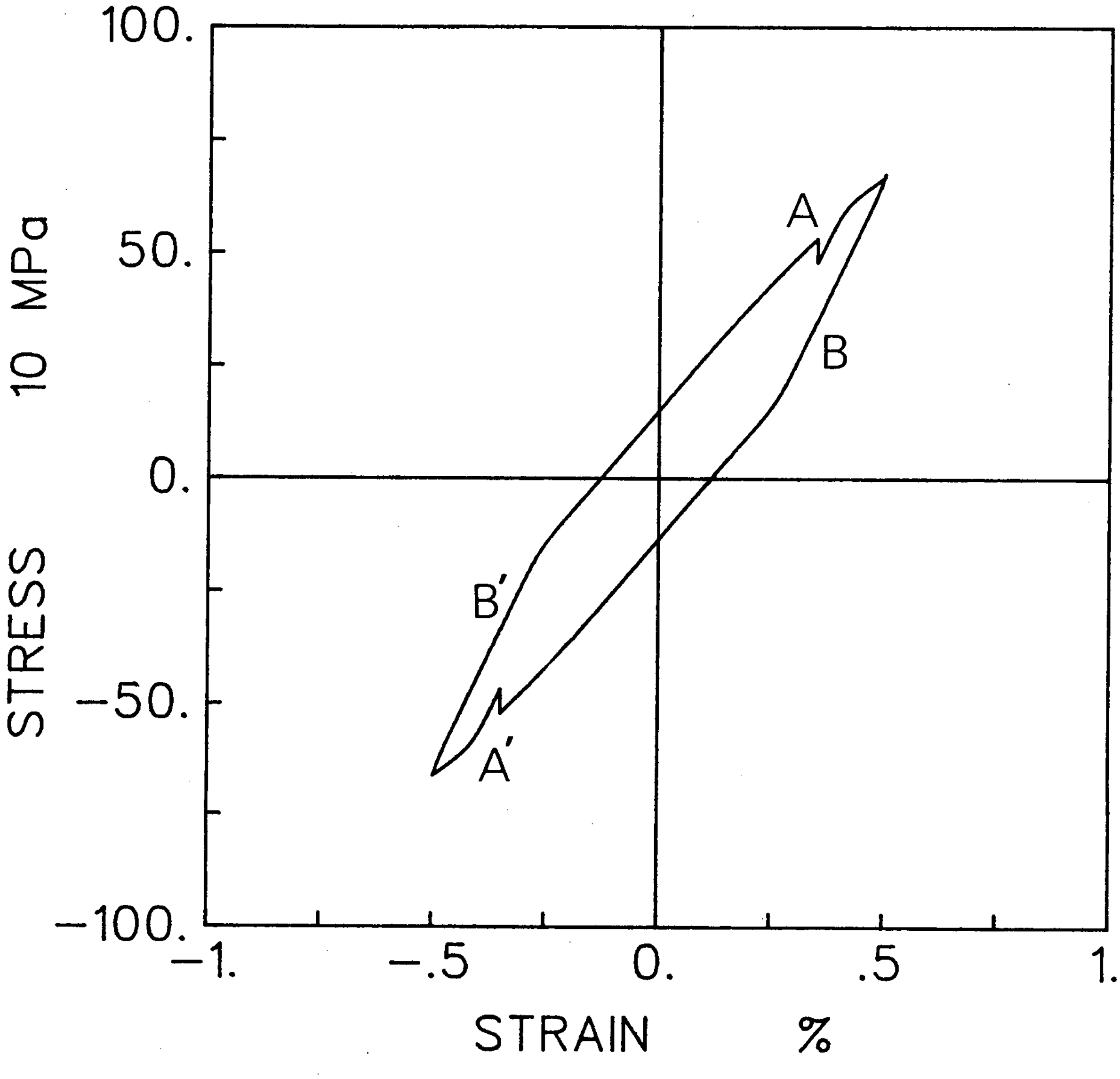

Figure II-B-3a
Cyclic Loading of a 5° Ply at a Strain Range of 1%. Predicted by the VBO at a Strain Rate of 10^{-5} 1/s. At Points A, A', B, B' a 1000 s Relaxation Hold-Time is Introduced. Note that the Stress Relaxes Only at Points A and A' During Loading but no Relaxation is Observed at the Same Strain During Unloading, Points B and B'.

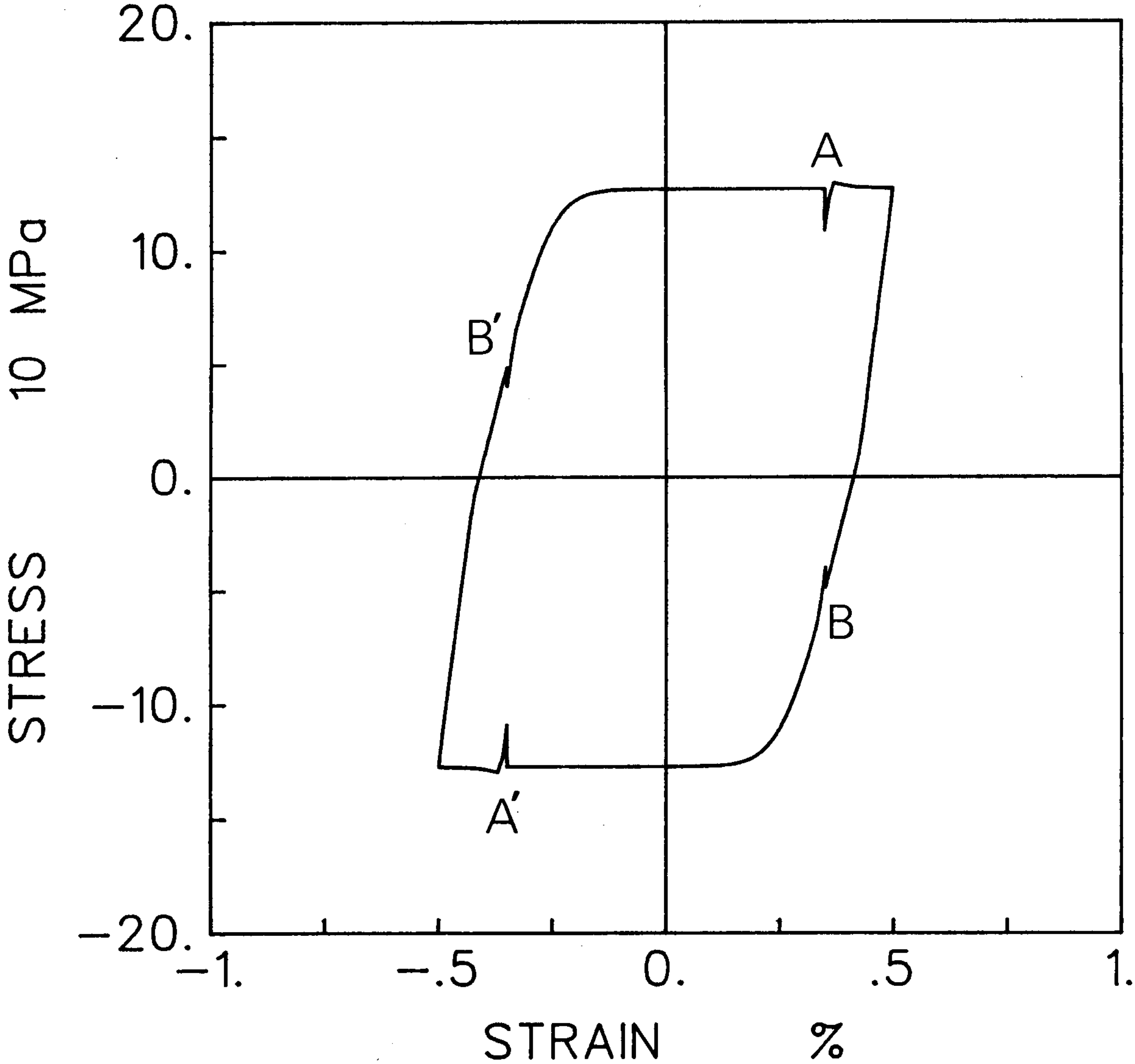

Figure II-B-3b
Cyclic Loading of a 5^{o} Ply at a Strain Range of 1% in the 45^{o} Direction. Due to Matrix Dominance, the Hyseresis Loop in the Same Strain Range is Much More Pronounced than in Fig. II-B-3a. Again the Relaxation Drop is Much More Pronounced at Points A, A' than at Points B, B'.

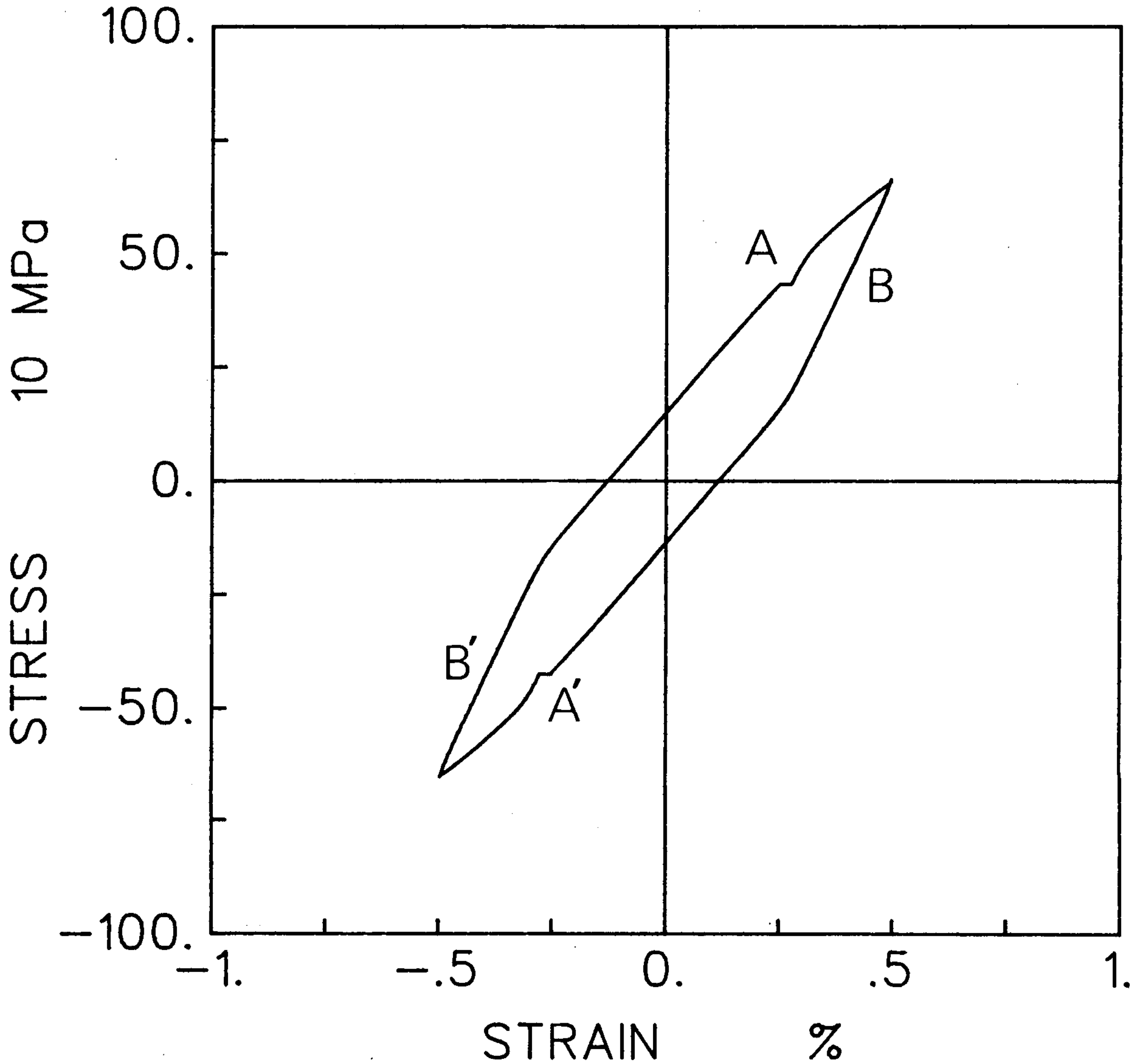

Figure II-B-4a
Same as Fig. II-B-1 Except that a 200 s Creep Hold-Time is Introduced at Points A, A', B, and B'. Although the Magnitude of the Stress is Equal at Points A, A' and B, B', no Creep is Noticeable on this Graph at Points B, B'.

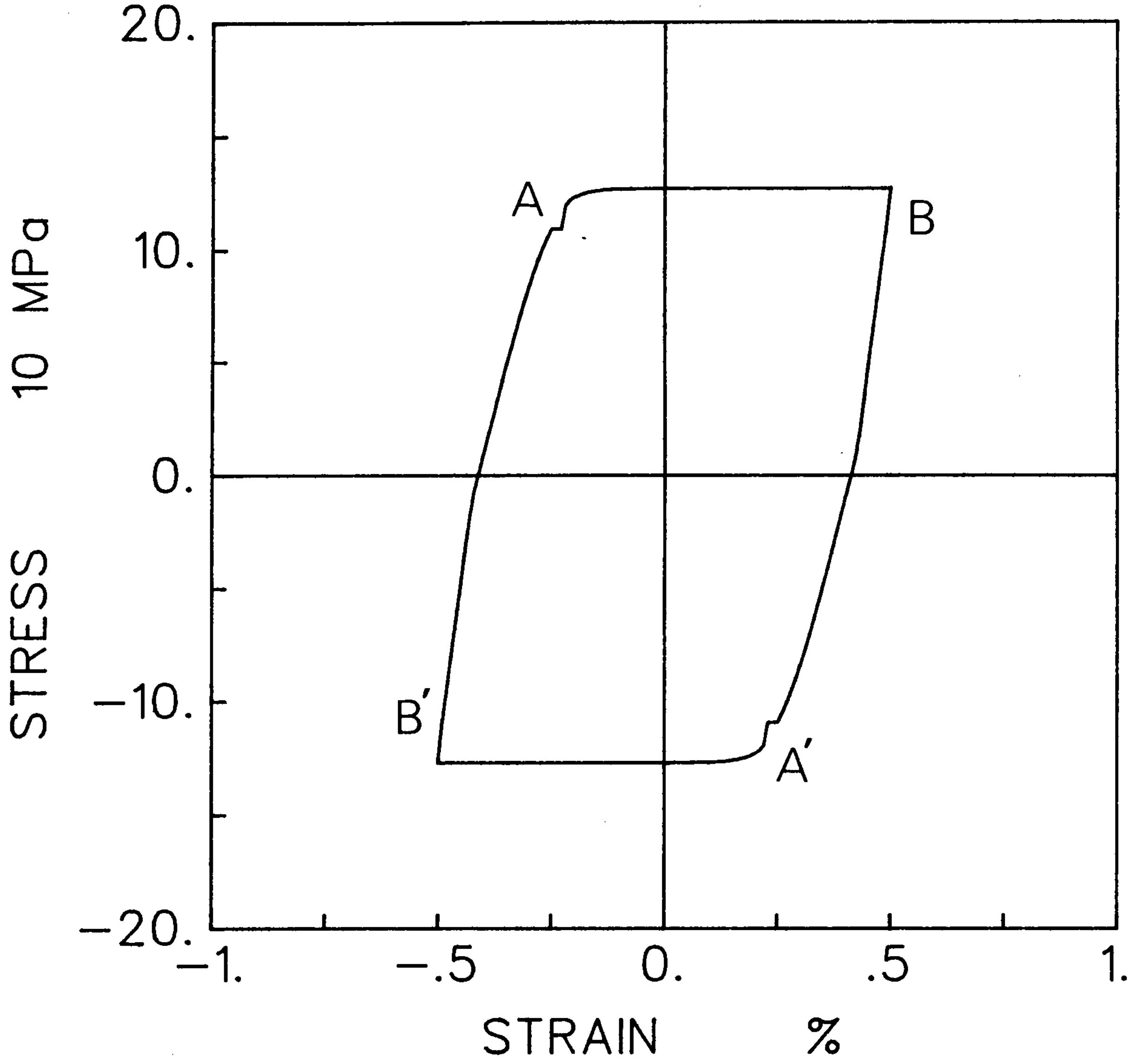

Figure II-B-4b
Same as Fig. II-B-4a Except that the Direction of Straining is 45°.

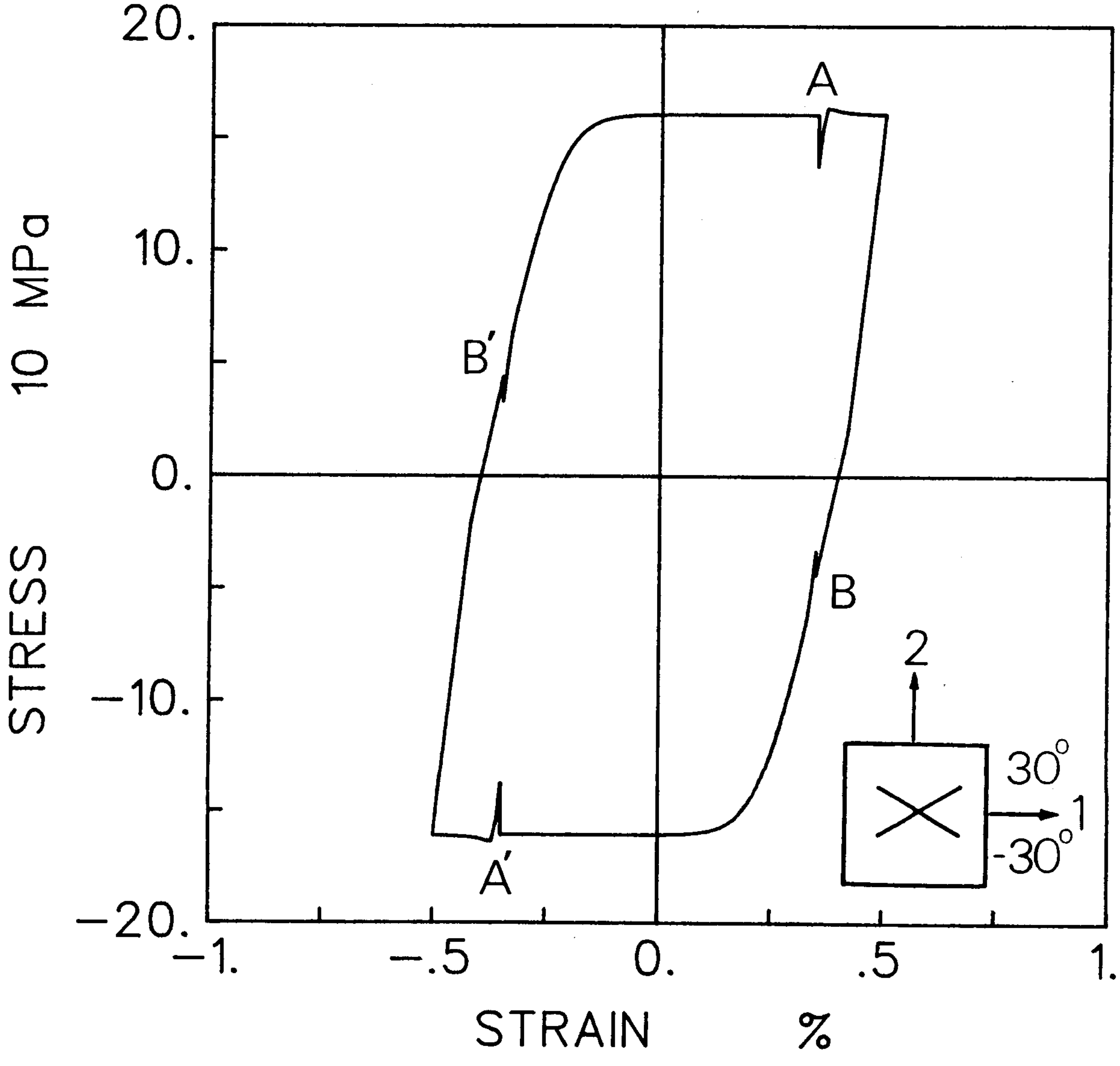

Figure II-B-5

Behavior of a [±30]s Laminate Predicted Using VBO. A 1000 s Relaxation Hold-Time is Introduced at Points A, A', B, and B'. The Difference of the Relaxation Behavior at Points A, A', B, and B' is Preserved. Strain Rate 10^{-5} 1/s.

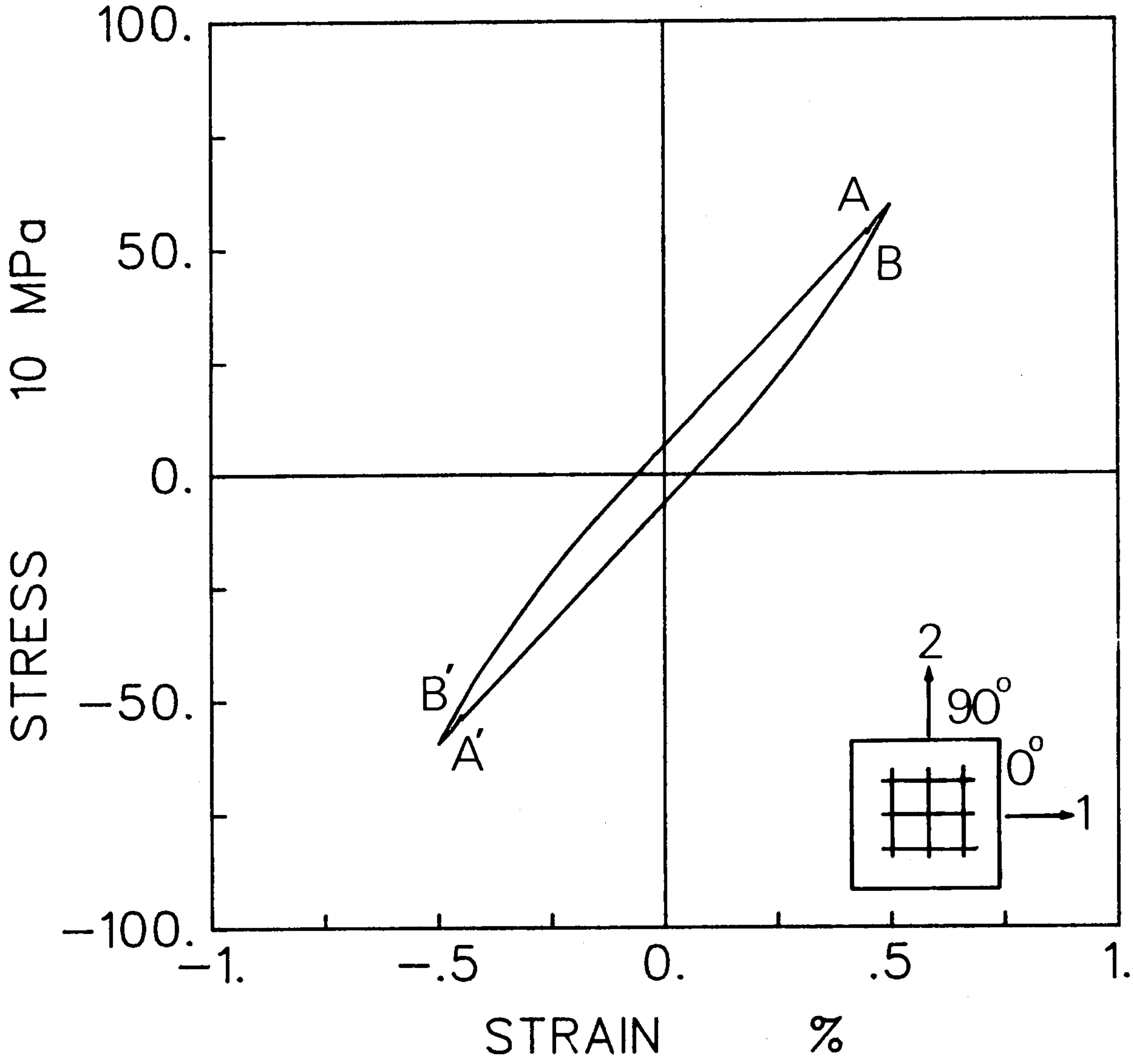

Figure II-B-6

Same as Fig. II-B-5 Except that the Laminate is a [0/90]s Lay-Up. The Fiber Dominance in the Deformation is Evident by the Small Hysteresis Loop and the Insignificant Stress Drop During Relaxation.

lamina case. It is evident that the behavior of the $[0/90]_s$ laminate in Figure II-B-6, is quite different from the matrix dominated behavior of the $[\pm 30]_s$ laminate shown in Figure II-B-5.

As in the case of the cyclic ply computation, no experimental data are available for correlation with these laminates. These figures are, therefore, mostly intended to demonstrate the versatility of the proposed approach. Details will be reported in [12].

PLANS FOR THE UPCOMING PERIOD

The theory will be correlated with the results of other experiments available in the literature. A simple laminate theory for bending will be formulated and numerical experiments performed.

PRESENTATIONS AND PUBLICATIONS BY PROF. E. KREMPL ON THIS SUBJECT

"The Viscoplasticity Theory Based on Overstress Applied to the Modeling of a Nickel Base Super Alloy at 815°C", with Lu, H. & Yao, D., presented at the 3rd Symposium on Nonlinear Constitutive Relations for High Temperature Applications, Akron, Ohio, June 11-13, 1986. To appear in the Proceedings.

"Cyclic Uniaxial and Biaxaial Hardening of Type 304 Stainless Steel Modeled by the Viscoplasticity Theory Based on Overstress", with Yao, D., presented at the 3rd Symposium on Nonlinear Constitutive Relations for High Temperature Applications. Akron, Ohio. June 11-13, 1986. To appear in the Proceedings.

"A Simplified Orthotropic Formulation of the Viscoplasticity Theory Based on Overstress", with Sutcu, M, presented at the 3rd Symposium on Nonlinear Constitutive Relations for High Temperature Applications, Akron, Ohio, June 11-13, 1986. To appear in the Proceedings.

"Biaxial Fatigue and Deformation Behavior of Graphite/Epoxy Composites", presented seminar, Department of Mechanical Engineering, University of Delaware, Newark, Delaware, September 19, 1986.

"Biaxial Fatigue and Deformation Behavior of Graphite/Epoxy Composites", presented at Southwest Mechanics Lecture Series, The University of Oklahoma, Norman, Oklahoma, November 10, 1986.

"Isotropic and Orthotropic Formulations of the Viscoplastic Theory Based on Overstress", presented at International Conference on Constitutive Laws for Engineering Materials: Theory and Applications, Tucson, Arizona, January 7, 1987.

C. ANALYSIS OF FATIGUE DAMAGE IN FIBROUS MMC LAMINATES

Sr. Investigator: G. Dvorak

INTRODUCTION

The mechanism of fatigue damage in Metal Matrix Composite (MMC) laminates can be described as follows: cracks nucleate and grow in individual plies of the laminate as a result of cyclic plastic straining of the matrix. If the plastic straining is terminated, e.g., by ply cracking which allows a crack accommodation strain to replace the cyclic plastic strain, then the matrix, or more precisely, each matrix segment between cracks, returns to an elastic state. If this happens in all plies, the composite "shakes down", damage accumulation stops, a saturation damage state is reached. Our objective is to find the crack density in each ply which corresponds to the shake-down state of a laminate under applied cyclic load.

STATUS

This work is part of a continuing investigation of the mechanisms of fatigue damage in metal matrix fibrous laminates. Earlier experimental work [14] showed that B-Al laminates under cyclic loading may experience extensive matrix cracking that, in a saturation state, may cause a substantial reduction (~-50%) of overall stiffness and strength. The same effect was later observed with SiC-Aℓ laminates. We had also found that the extent of fatigue damage depends on applied load amplitude and that no damage occurs in laminates cycled within the shake-down range, in which there is no cyclic plastic straining in the matrix. Results obtained in the present work suggest that the extent of fatigue damage at a given load amplitude is determined by the requirement that the composite laminate must reach a shake-down state through damage accumulation.

Progress During the Reporting Period

The analysis conducted during the reporting period is based on a combination of techniques derived from plasticity analysis of MMC plates and from damage analysis of elastic composite laminates [15], [16], [17]. For each given increment of load amplitude, one finds an increment in ply crack density that assures that the average stresses in the ligaments that remain between the cracks do not violate the yield condition for the ply in question.

The analysis was performed in strain space, because all plies of the laminated plate experience identical strain magnitudes under in-plane loads. Plastic response of the plies can then be described, in part, with the help of relaxation surfaces. The ply remains elastic if strained within its relaxation surface. If cracks are added to the ply, the overall stiffness of the ply is reduced and, therefore, the relaxation surface expands for strains which cause the cracks to open. An example is shown in Figure II-C-1. In a cyclically loaded laminate, cracks are incrementally added to all plies in which the yield condition would be violated under current overall load. Figure II-C-2 shows an example of relaxation surfaces of a $(0/90)_{2S}$ laminate which has reached a certain damage state.

The modeling procedure was applied to several B-Al laminates which were tested in an earlier experimental program. Stiffness changes caused in saturation damage state at various load amplitude levels were calculated and compared with experiments. The theoretical results were found to be in good agreement with experimental data. This is shown in Figure II-C-3.

PLANS FOR THE UPCOMING PERIOD

In the 1987-88 research program we hope to develop new models of time-dependent deformation of fibrous metal matrix composites at elevated temperatures. The approach will be based on our previous work in plasticity of MMC, and it will incorporate the creep properties of the fiber and matrix. In particular, we expect that the fibrous composite may deform in several distinct modes, depending on the applied state of stress, and on the elastic properties of the phases. Micromechanical analysis of these modes will be performed, and predictions of overall instantaneous response will be made in terms of phase properties, microstructural geometry, and previous deformation history.

PRESENTATIONS AND PUBLICATIONS BY PROF. G. DVORAK ON THIS SUBJECT

"Damage Mechanics of Composite Materials", colloquium, Northwestern University, May 2, 1986.

"Fracture Mechanics of Metal Matrix Composites", presented at ONR Workshop on Failure Mechanics, University of Maryland, May 12-13, 1986.

"Analysis of Fatigue Cracking of Fibrous Metal Matrix Laminates", Symposium on Advanced Composite Materials, General Electric Co., May 14, 1986.

"Damage in Metal Matrix Composites", presented at SDIO/ONR Composites Consortium Program Review, Woods Hole, MA., June 2-3, 1986.

"Thermal Expansion of Elastic-Plastic Composite Materials", presented at 10th U.S. National Congress of Applied Mechanics, ASME, Austin, Texas, June 16-20, 1986.

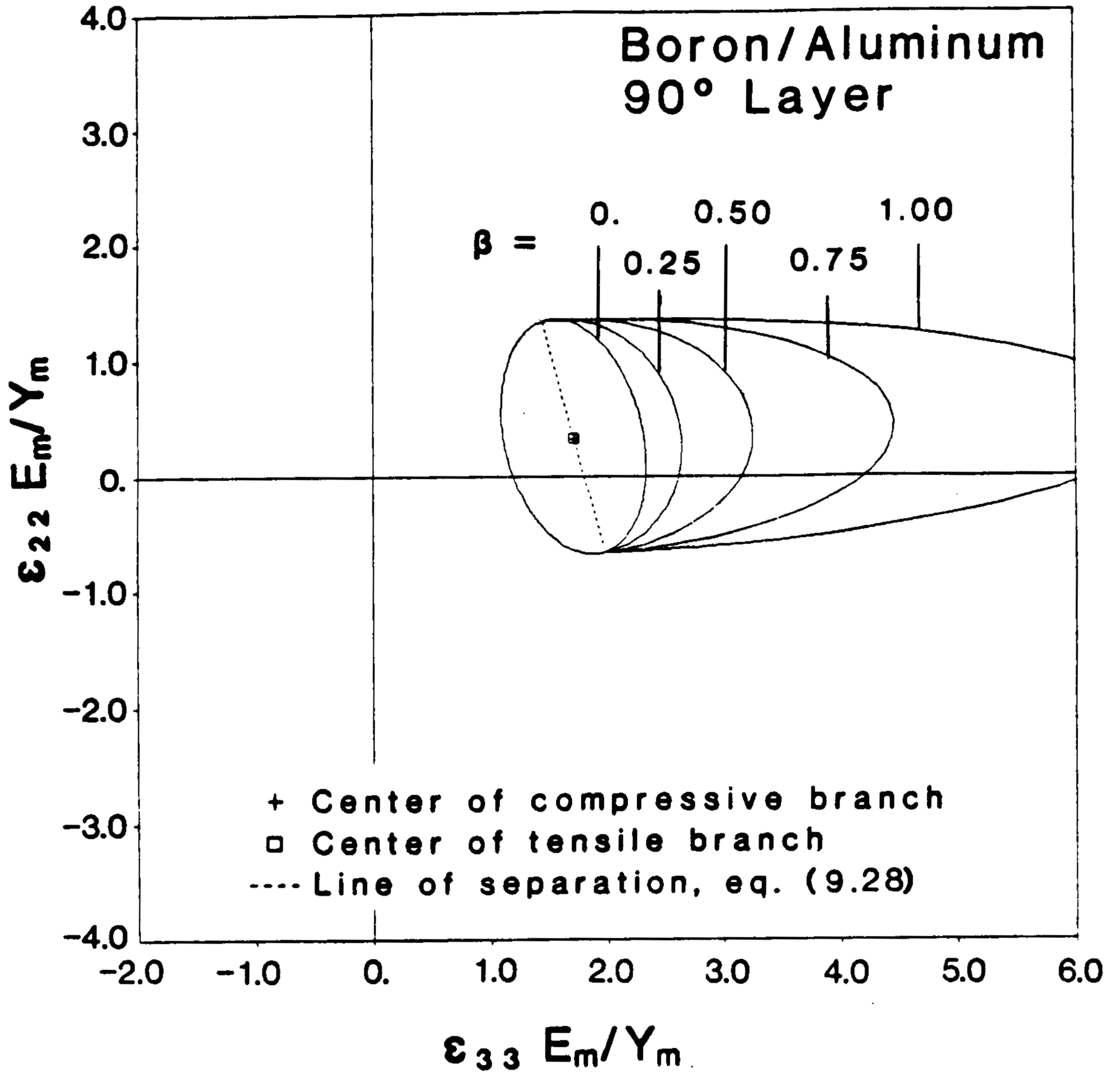

Figure II-C-1

Relaxation Surfaces of the 90^{o} Layer at Different Crack Densities.

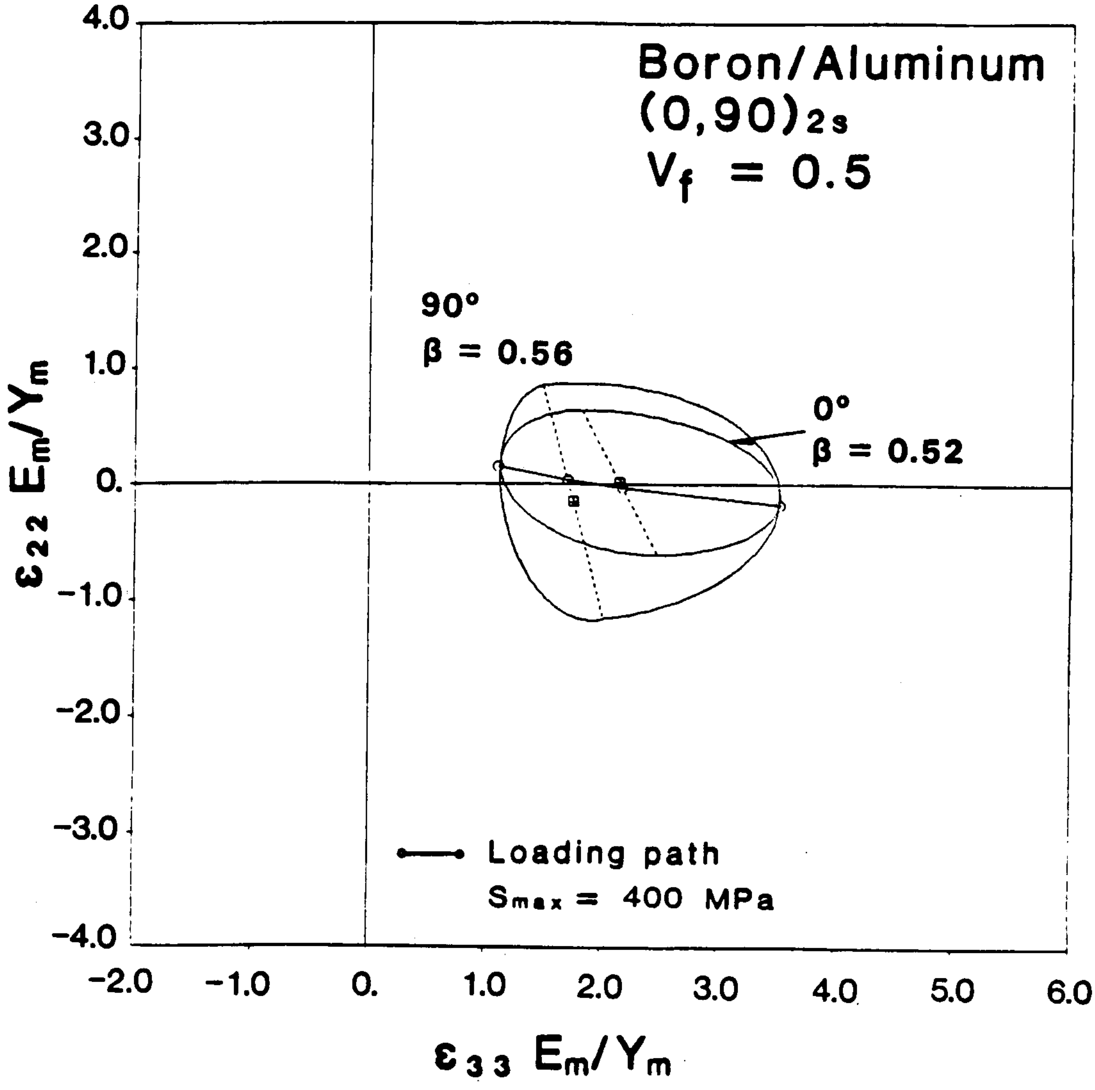

Figure II-C-2

Final Relaxation Surface at S_{max} = 400 MPa.

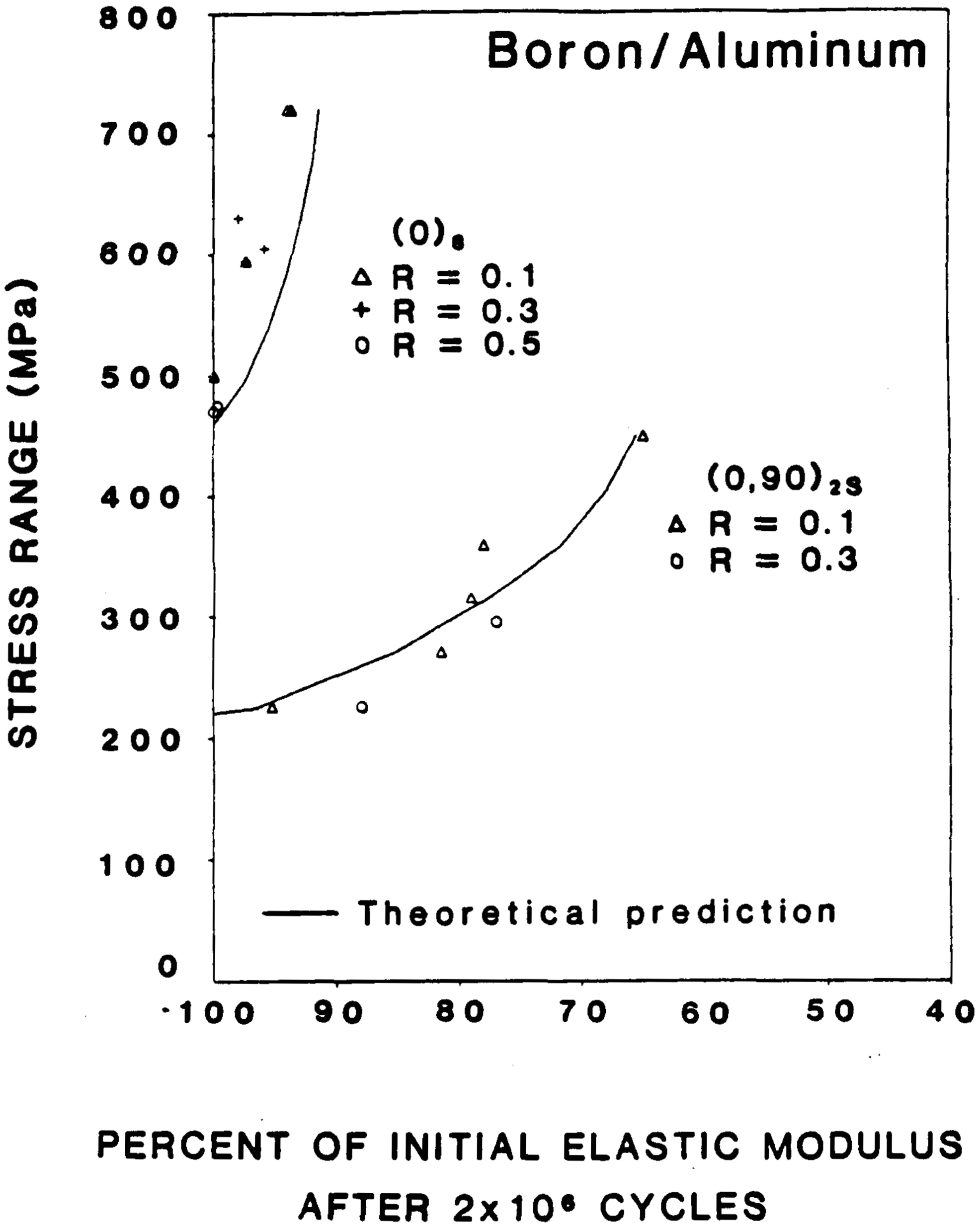

Figure II-C-3

Change in Elastic Modulus of a B-Al Plate Related to Applied Stress Range. Comparison of Theoretical Predictions with Experimental Data reported by Dvorak and Johnson (1980) and Johnson (1979).

"Thermomechanical Couplings in Solids" and "Thermomechanical Deformation and Coupling in Elastic-Plastic Composite Materials", invited lecturer, IUTAM Symposium, Paris, France, September 1-5, 1986.

"Plasticity of Composite Materials", colloquium, Texas A&M University, November 11, 1986.

"Plasticity of Composite Materials", colloquium, Rice University, November 12, 1986.

"Fatigue Damage Analysis in Metal Matrix Laminates", invited lecturer, ASME Winter Annual Meeting, Anaheim, CA, December 7-12, 1986.

"Recent Developments in Plasticity of Fiber Metal Matrix Composites", Mechanics Colloquium, Yale University, January 21, 1987.

"Bimodal Plasticity Theory of Composite Materials", Symposium in Memory of Aris Phillips, Gainesville, Florida, January 28-30, 1987.

"Recent Developments in Plasticiity of Composite Materials", seminar, University of California at Berkeley, February 23, 1987.

"Cracks Approaching Interfaces: The Image Crack Method", ONR Workshop on Composite Materials - Interface Science, Leesburg, Virginia, March 11, 1987.

"Analysis of Metal Matrix Composites for Spacecraft Applications", presented at ONR SDI Review, University of Maryland, March 30, 1987.

"A Bimodal Plasticity Theory of Composite Materials", seminar, Brown University, April 6, 1987.

"Recent Developments in Composites Plasticity", seminar, Lawrence Livermore Laboratories, Livermore, CA, April 23, 1987.

D. DELAMINATION FRACTURE TOUGHNESS IN THERMOPLASTIC MATRIX COMPOSITES

Sr. Investigator: S. S. Sternstein

INTRODUCTION

The delamination fracture toughness of high performance composite laminates is of considerable importance in applications where some degree of out-of-plane loading will be experienced or in cases where in-plane compression loads must be supported. In the latter case, delamination severely limits the compression loads which can be safely carried. Many investigators also believe that delamination toughness plays a major role in damage tolerance with respect to planar impacts.

Thermoplastic matrix composites have the potential for significant improvement in delamination fracture toughness. However, the relationship between neat matrix and in situ matrix behavior is not understood well, owing in large measure to the finite strain, nonlinear viscoplastic behavior which thermoplastic matrices are known to exhibit. The objective of this research is to investigate the parameters which influence such behavior.

STATUS

Several studies of the micromechanics of delamination failure as related to matrix properties have been initiated which are aimed at elucidating the matrix-related failure modes of thermoplastic matrix composites. Specifically, the following studies are in progress:

1) Delamination fracture toughness tests aimed at relating the Double Cantilever Beam (DCB) delamination compression buckling fracture toughness to ply microstructure and local deformation (crack path) patterns.

2) A companion series of numerical analyses, to examine the DCB test itself using finite element analysis (FEA) and a nonlinear, rate and stress state dependent constitutive equation specifically developed for the polycarbonate matrix material used in Part 1. This study is joint with Professor M. Shephard who is responsible for the FEA computations. (See Part II-E of this report.)

3) New experiments, initiated to examine delamination fatigue crack initiation mechanisms in several thermoplastic and thermoset matrix composites.

4) Companion numerical analyses, again using advanced constitutive relationships and FEA for the Mode II delamination fatigue problem of Part 3.

5) A related study, currently in progress, on the compression strength of

thermoplastic matrix composites.

PROGRESS DURING THE REPORTING PERIOD

This progress report will cover only Part 1 of the program, as listed above. Our intent here is to develop a self-consistent data set applicable to the delamination fracture toughness of polycarbonate matrix composites, with and without fiber sizing, and the resultant fracture path as examined by reflected light microscopy. In addition, electron microscopy studies were performed on the sized and unsized samples to determine the extent of fiber-matrix adhesion.

Experimental Results

Unidirectional, 12 ply laminates were prepared using high quality polycarbonate matrix prepreg prepared by NASA-Langley. Both unsized and epoxy sized AS4 carbon fibers were used. In some, but not all, samples an additional film of polycarbonate of either 50μm or 250μm thickness was inserted at the midplane. In all cases a starter crack was introduced by using a Kapton film at one edge between the central plies of the laminate. Double cantilever beams were cut from the master sheet using standard techniques. Each sample was fitted with aluminum end-blocks containing holes for pivot pins through which the loading was applied. The end-blocks were epoxied to the samples. Samples were deformed in the DCB mode using a crosshead rate of 1 cm/min. An LVDT (linear variable differential transformer) was used to measure overall displacement at each of the two ends of the double cantilever beam.

Microscopy samples were obtained from the broken DCB samples and either potted for reflected light microscopy or gold-plated for scanning electron microscopy.

A typical load vs. deflection curve which exhibits permanent deflection is shown in Figure II-D-1. Permanent deflection is accounted for in the data reduction scheme. Most samples demonstrated at least seven crack jumps (non-planar crack propagation). The inset graph shows the sample compliance vs. the edge-measured, crack jump length. Correction for the plastic deformation offset of the load-unload curves was made. The compiance vs. crack jump curve was fit using a second order Chebyshev polynomial which was differentiated to give dc/da. The standard DCB formula was then used to compute $G_{Ic} = \frac{P^2}{2w}(dc/da)$ where P is the breaking load, w is the sample width and dc/da is the change in sample compliance with crack jump length. The results are given in tabular form in Table II-D-1 and 2 for the various samples. The values of G_{Ic} reported are the averages for each sample excluding the first crack jump. The standard deviation for the values of G_{Ic} from all the crack jumps obtained in a given sample are also shown (as Δ). For the 51μm

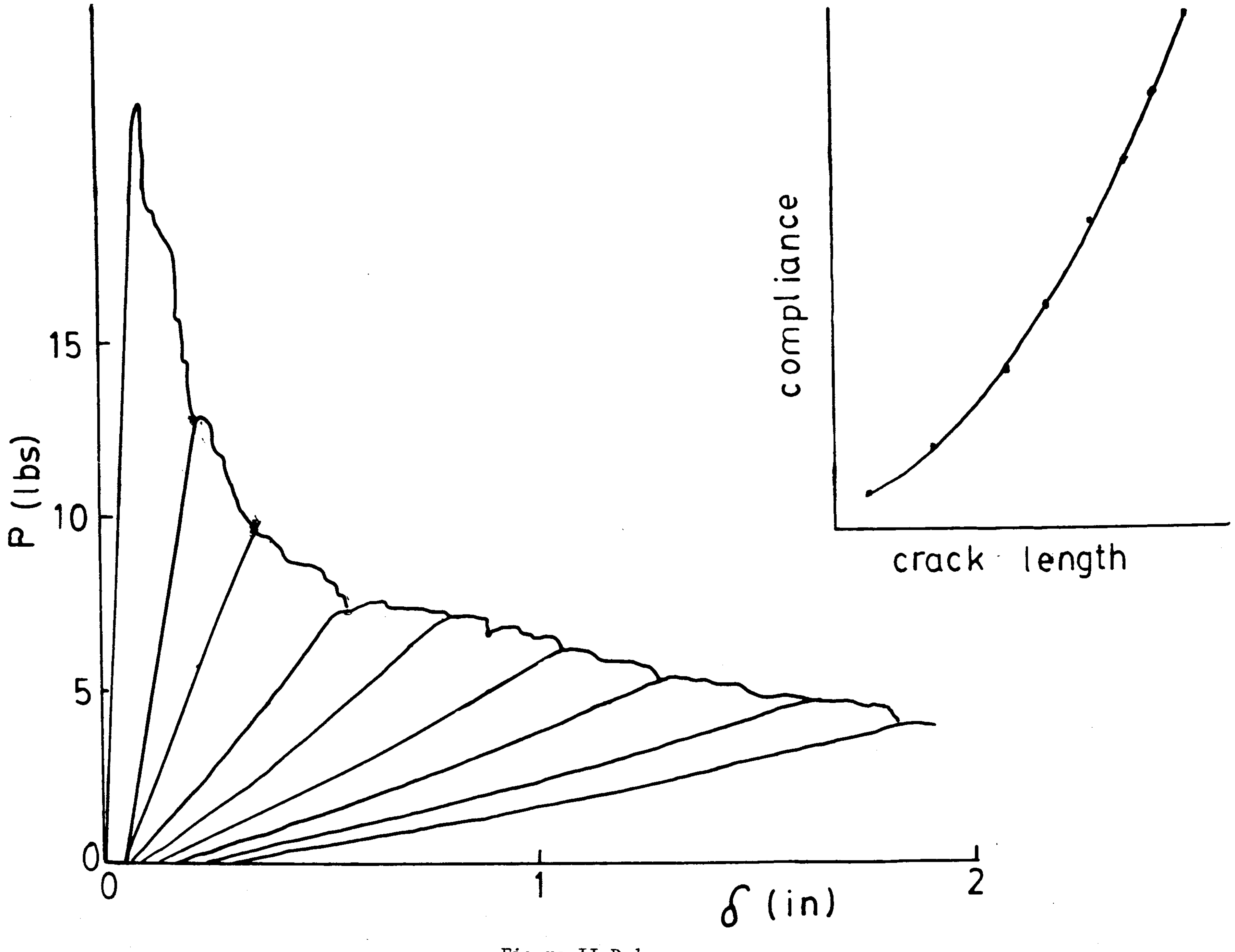

Figure II-D-1

Table II-D-1

Polycarbonate - AS4 Unsized
DCB Fracture Toughness

	No Central Film		51μm Film		254μm Film	
	G_{Ic} (J/m²)	Δ	G_{Ic} (J/m²)	Δ	G_{Ic} (J/m²)	Δ
	859	95	1179	120	1564	238
	914	234	1319	136	1495	168
	1105	268	1549	270	1234	86
	1235	194	990	198	1352	77
	825	142	1482	208	952	100
	1090	138	1298	222	1470	216
	886	159	1124	165	1516	158
			856	268	1516	117
			1026	210	1650	184
			1047	92	1729	152
			920	129		
			1283	926		
avg. among samples	987	162	1173	218	1447	222

Table II-D-2

Polycarbonate - AS4 Epoxy Size
DCB Fracture Toughness

	No Central Film		51μm Central Film		254μm Film	
	G_{Ic} (J/m²)	Δ	G_{Ic} (J/m²)	Δ	G_{Ic} (J/m²)	Δ
	2217	236	2129	60	1814	144
	2197	289	2565	96	1916	205
	2415	278	2000	190	1753	332
	2273	183	2081	184	2131	598
	2338	248	2362	203	2160	363
	2209	250	2114	287	1920	233
	2151	231	2331	171	*1733	167
	1875	298	2023	176	1769	146
	2470	302	2065	173	*2162	119
	1910	128	2131	151	2236	213
	2170	202	1949	222		
	2139	425				
	2135	222				
avg. among samples	2188	163	2159	185	1959	195

*See Figure II-D-6 and Figure 7 for optical micrographs of these samples.

film, unsized sample which showed a standard deviation of 926 J/m^2 (See Table II-D-1), removal of the second and third crack jumps reduces the standard deviation to 48 J/m^2. Similarly, the standard deviation of 598 J/m^2 for the 254μm film, epoxy-sized sample (See Table II-D-2), was reduced to 147 J/m^2 by removal of the second crack jump.

It is particularly noteworthy that there was not a regular pattern of increasing or decreasing G_{IC} vs. crack jump number in any given sample. Also, the standard deviation of G_{IC} samples is not substantially different from that calculated from the results obtained within a sample. Other investigators have observed a regular increase of G_{IC} with each crack jump in a given sample and have attributed this to fiber bridging. We see no evidence of such an effect and speculate that fiber wavyness and/or fiber wash during lamination may have resulted in trends not supported by our data. In any event, this again illustrates the lack of agreement among laboratories on specific properties of composites.

The epoxy-sized samples (Table II-D-2) show no effect of film thickness on measured G_{IC}. However, the 254μm film in the unsized samples (Table II-D-1) appears to have given a statistically significant higher G_{IC} than the other unsized samples. The fracture toughness of the epoxy-sized samples is about double that of the unsized samples. This suggests that there is a favorable influence of increased interfacial adhesion between matrix and fibers. Such a conclusion is borne out by the SEM photomicrographs in Figures II-D-2 and 3. The presence of ribbons of debonded polycarbonate matrix are clearly evident in Figure II-D-3 (unsized) whereas the adhesion of matrix (grey) to the fibers is evident in Figure II-D-2 (sized). Higher magnifications of the same failure surfaces are shown in Figures II-D-4 and 5.

Optical micrographs are shown in Figures II-D-6 and 7 for two samples cut from the same master sheet, containing a central film of 254μm thickness and with epoxy-sized fibers. One sample tested at the low end of the G_{IC} values for this sample batch, whereas the other tested high for G_{IC}. In Table II-D-2, these samples are indicated with an asterisk. It is apparent that the sample with a low G_{IC} (Figure II-D-6) contains a delamination crack which very infrequently crossed the central tough film. Conversely, the tough sample (Figure II-D-7) shows a crack path which has jumped across the tough film resulting in a greater area production rate per unit crack jump.

We offer no explanation for the determining factor whcih controls the crack jumping (or the lack of such jumping), but conjecture that residual stresses (thermal, etc.) and local variations in microstructure resulting in variations of stiffness and

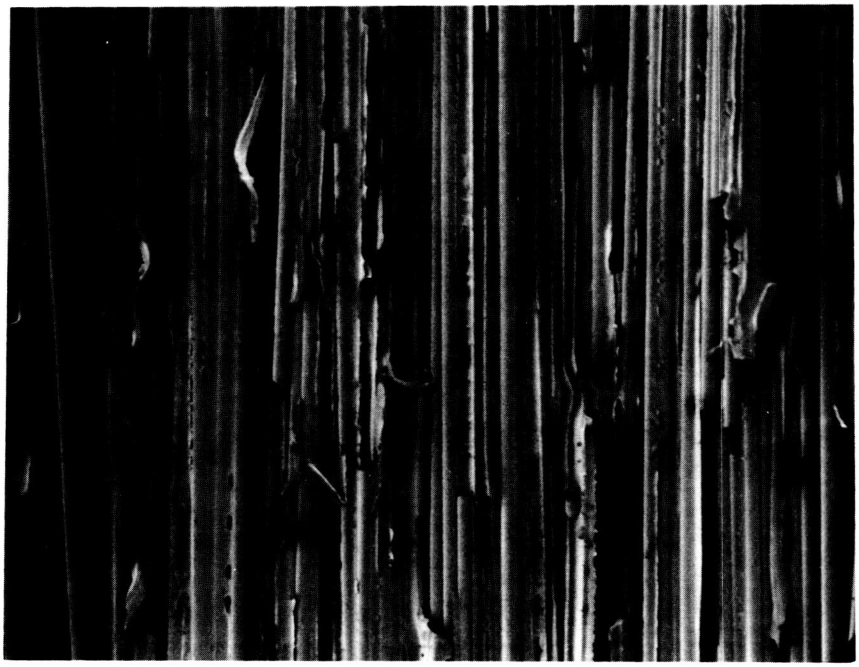

Figure II-D-2

Epoxy Sized Sample, 254μm Film. Failure Occurs Within Ply, Matrix Failure.
G_{Ic} = 2235 J/m^2

Figure II-D-3

Unsized Sample, No Film. Failure Occurs Within Ply, Interface Failure.
G_{Ic} = 1235 J/m^2.

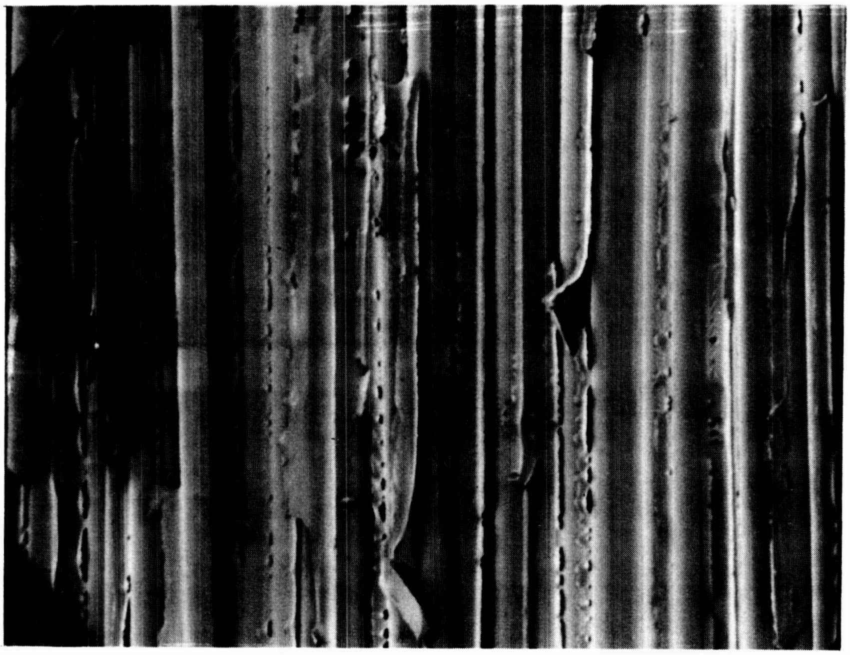

Figure II-D-4

Epoxy Sized Sample, 254μm Film. Matrix Failure, Limited Debonding. $G_{Ic} = 2235\ J/m^2$.

Figure II-D-5

Unsized Sample, No Films. Fibers Debonding. $G_{Ic} = 1235\ J/m^2$.

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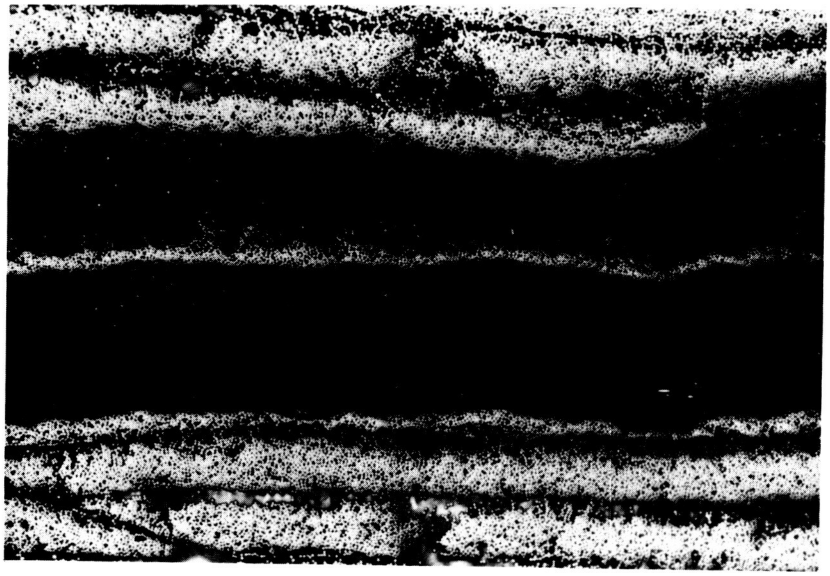

Figure II-D-6

Epoxy Sized Sample, 254μm Film. Failure Occurs Within Ply. $G_{Ic} = 1733\ J/m^2$.

Figure II-D-7

Epoxy Sized Sample, 254μm Film. Failure Path Crosses Film. $G_{Ic} = 2161\ J/m^2$.

strength play a role. We are attempting to model such effects using FEA. In any event, it is clear that crack jumping (nonplanar crack propagation) may play a significant role in the statistical spread of fracture toughness values among ostensibly identical samples.

PLANS FOR THE UPCOMING PERIOD

In the next reporting period we plan to place major emphasis on the constitutive-microstructural modeling of failure properties in thermoplastic matrix composites and to investigate both Mode 1 and Mode 2 delamination problems using FEA methods.

PRESENTATIONS AND PUBLICATIONS BY PROF. S. STERNSTEIN ON THIS SUBJECT

"Thermoplastic Matrix Composites", seminar, University of Connecticut, Storrs, CT, March 8, 1987.

"Matrix Dominated Mechanical Properties of Composites", seminar, TRW Research Center, Los Angeles, CA., April 10, 1987.

"Mechanical Properties of Composites", lecture, Alcoa Conference on Micromechanics, Hilton Head, SC, June 8, 1987.

"Thermoplastic Matrix Composites", lecture, Gordon Conference on Composites, Santa Barbara, CA., January 1987.

"A Micrographic Study of Bending Failure in Five Thermoplastic/Carbon Fiber Composite Laminates", with S. W. Yurgartis, accepted for publication by Journal of Materials Science, April 1987.

E. NUMERICAL INVESTIGATION OF THE MICROMECHANICS OF COMPOSITE FRACTURE

Sr. Investigator: M. S. Shephard

INTRODUCTION

The behavior of and failure mechanisms in composite materials can usually be better understood if analytic/numerical analyses are used appropriately in support of an experimental program. The goal of this work is to provide nonlinear finite element analysis capabilities which, coupled with an experimental program, will provide increased understanding of composite behavior. Initial efforts consist of two phases: first, modeling thermoplastic composites, concentrating on the development of nonlinear time-dependent constitutive relations; and second, incorporating them into an existing nonlinear finite element program that has the capability of adding new material models. Professor S. Sternstein is providing the technical expertise required to develop constitutive equations that can realistically model the measured material behavior. (See Section II-D, of this report.)

STATUS

The currently available finite element analysis codes which could provide a framework on which to build analyses for the nonlinear analysis of composite materials, do not contain the forms of constitutive relations and mixing models necessary to properly analyze these materials in the nonlinear range. Therefore, our efforts have been concentrated on the development and implementation of such models in a nonlinear finite element code; namely, ABAQUS. As indicated below, the development and implementation of these procedures is nearing completion. In addition, numerical studies of specific experimental configurations were initiated.

PROGRESS DURING REPORTING PERIOD

Efforts during the reporting period concentrated on developing a time-dependent constitutive relationship for the matrix material and combining this mathematical model with the periodic hexagonal array model of fibers in this matrix.

Matrix Constitutive Relation

A nonlinear viscoelastic material model has now been developed. Emphasis was placed on capturing the essential mechanical characteristics of thermoplastics, including rate dependence, stress component interactions and transient behavior. The

Eyring stress-biased barrier model is generalized to three dimensions such that the hydrostatic pressure correctly modifies the deviatoric response.

The rheological model chosen to represent the viscoelastic response of thermoplastic matrix material is based on the following two assumptions:

1) The linear-elastic hydrostatic component of the hydrostatic stress produces an elastic dilatational response represented by

$$\sigma_{kk} = 3B\epsilon_{kk}$$

Where B = Bulk modulus
σ = stress (total)
ϵ = strain (total)

2) The non-linear rate-dependent deviatoric component of strain, ϵ, can be related to stress by assuming that the material is represented by a Maxwell element in series with a Voigt element, as follows

(in which $(\dot{\ }) \triangleq \frac{d}{dt}$):

$$\dot{e} = \frac{\dot{S}}{2G_1} + \frac{S}{n_1} + \frac{2G_2}{n_2}\left(e - \frac{S}{2G_1} - \int_0^t \frac{S}{n_1}\,dt\right) \qquad \text{[Eq.1]}$$

Where n = solid state viscosity
S = deviatoric stress
G = shear modulus
Subscripts 1 and 2 define properties before and after onset of nonlinearity, respectively.
$e = \epsilon - {}^1/_3 \mathrm{tr}e \cdot I$
$S = \sigma - {}^1/_3 \mathrm{tr}e . I$
tre indicates the trace of the matrix
and I = unit matrix

For the dashpot in the Voigt element, an activated non-Newtonian viscosity term is used (I. M. Ward [19]), which obeys the Eyring hyperbolic-sine flow law. Eyring's model assumes that applied stress shifts the potential energy barriers decreasing the material's resistance towards deformation.

In the Eyring model: $\dot{e} = \dfrac{S_{dashpot}}{n_2}$; $\dot{e} = K \sinh(\alpha\, S_{dashpot})$

Where: $K = e_o e^{\frac{-\Delta H}{RT}}$

$\alpha = \frac{\upsilon}{RT}$

and e_o = a constant pre-expontial factor

υ = activation volume for the molecular event

ΔH = the activation energy (assumed constant by Eyring)

R = ideal gas constant

T = absolute temperature

Sherby and Dorn (I.M.Ward [19]) had found that increasing stress decreases the activation energy; $\Delta H \rightarrow \Delta H - \mu \cdot \sigma_m$ where μ = parameter which controls the decrease of the activation energy with increasing hydrostatic stress and

$\sigma_m = \frac{1}{3} \sigma_{kk}$

Sternstein and Ho (I.M. Ward [19]) found that hydrostatic stress causes the onset of nonlinearity. These two ideas were combined to yield

$$\dot{e} = K \cdot e^{\beta \sigma_m} \sinh(\alpha S_{dashpot}) \qquad \text{[Eq. 2]}$$

where $\beta = \frac{\mu}{RT}$

Substituting [Eq. 2] into [Eq. 1] led to the relation

$$\dot{e}_{ij} = \frac{\dot{S}_{ij}}{2G_1} + \frac{S_{ij}}{n} + Ke^{\beta \sigma_m} \cdot \sinh \left[\alpha \left\{ S_{ij} - 2G_2 \left(e_{ij} - \frac{S_{ij}}{2G_1} - \int_o^t \frac{S_{ij}}{n} dt \right) \right\} \right] \qquad \text{[Eq. 3]}$$

The resulting equation was successfully used by Cessna and Sternstein [20] to characterize polymer deformation at the leading edge of a crack tip.

Since a displacement-based Finite Element Method was anticipated, this equation was inverted to the form:

$S = f(e)$

Then, using deviatoric components instead of total stresses, the final form of the general, 3-D nonlinear viscoelastic constitutive equation was obtained; namely:

$$\dot{S}_{ij} = 2G_1 \dot{e}_{ij} - \frac{2G_1}{n} S_{ij}$$

$$-2G_1 K e^{\frac{\beta}{3}\sigma_{kk}} \sinh\left[\alpha\left\{S_{ij} - 2G_2\left(e_{ij} \frac{-S_{ij}}{2G_1} - \int_0^t \frac{S_{ij}}{n}\,dt\right)\right\}\right] \qquad \text{[Eq. 4]}$$

This expression is intended to be used to predict the behavior of thermoplastic matrices in composites. The physical interpretation of the various parameters can be recapitulated as follows for the Eyring stress activated dashpot:

K is the parameter which accounts for the activation energy; energy needed to overcome potential energy barrier.

α is the parameter which accounts for the activation volume; the volume of the polymer segment which has to move as a whole in order for flow to take place.

β is the parameter which describes the pressure effect on shear 'yield' stress and determines the difference between tension and compression.

B is the elastic bulk modulus

G_1 is the shear modulus before 'yield'

G_2 is the shear modulus after 'yield'

n is the solid state viscosity

Combining the hydrostatic and deviatoric components of the model, after a certain amount of algebra, an expression for the total strain rate in terms of total stresses was obtained.

This is

$$\dot{\epsilon}_{ij} = \frac{\dot{\sigma}_{ij}}{2G_1} + \left(\frac{1}{9B} - \frac{1}{6G_1}\right)\dot{\sigma}_{kk}\delta_{ij} + \frac{\sigma_{ij}}{n} - \frac{\sigma_{kk}}{3n}\delta_{ij} +$$

$$K e^{\frac{\beta}{3}\sigma_{kk}} \sinh\left[\alpha\left\{\left(1 + \frac{G_2}{G_1}\right)\sigma_{ij} + \left(\frac{2G_2}{9B} - \frac{G_2}{3G_1} - \frac{1}{3}\right)\sigma_{kk}\delta_{ij} -\right.\right.$$

$$\left.\left. 2G_2\epsilon_{ij} + 2G_2\int_0^t \left(\frac{\sigma_{ij}}{n} - \frac{\sigma_{kk}}{3n}\delta_{ij}\right)dt\right\}\right] \qquad \text{[Eq. 5]}$$

<u>Implementation in a Finite Element Code.</u>

The ABAQUS finite element code [21] which includes the option of a "User Defined Subroutine - UMAT", was selected as the platform for implementing the constitutive equation. The basic problem is to find the state of equilibrium corresponding to applied loads in which the resultant forces must vanish: ie,

$\{R(t)\}-\{F(t)\} = 0$

Where $\{R(t)\}$ represents the forces due to externally applied loads

$\{F(t)\}$ represents the forces due to internal stresses

The actual analysis process requires iteration, and in the general case, increments taken in terms of load or time steps.

For a given increment, the main program assembles the global system of equations, solves for the unknown increment in displacements, evaluates the corresponding increment in strains and calls UMAT for each material point examined, to first calculate the increment in stresses according to the user's law, and then evaluate the material stiffness matrix. At this point, the program passes into UMAT the variables that need to be defined and/or updated and those needed for the calculations.

The user must update the stress vector at the material point in accordance with the constitutive law. Another set of variables that must be defined for use in the next iteration is the material Jacobian relation between the increment in stresses and strains. This is used by ABAQUS to evaluate the element stiffness matrices in the mesh.

The coding of UMAT is based on the following logic:

In a given time step, $dt=t(n)-t(n-1)$:

(1) From ABAQUS we know:

the stresses $\{\sigma\}$ and $\{S\}$

the strains $\{\epsilon\}$ and $\{e\}$ at $t=t(n-1)$

and an estimate of the increment in strains $\{\Delta\epsilon\}$ corresponding to dt.

(2) The constitutive equation is expressed in terms of $\{S\}$ and $\{\epsilon\}$.

(3) The trapezoidal finite difference approximation is used for time integration to obtain a new relation between $\{\Delta S\}$ and $\{\Delta\epsilon\}$.

(4) The six nonlinear equations for $\{\Delta S\}$ are solved using Newton-Raphson iteration. (The resulting algebraic equations are solved separately and not as a system, for reasons to be mentioned later).

(5) The stress vectors $\{S\}$ and $\{\sigma\}$ are updated.

(6) The Jacobian matrix $[\frac{\partial\Delta\sigma}{\partial\Delta\epsilon}]$ is then defined.

The details of the manipulations required for this process are extensive [22] and are not presented here.

<u>Results Using Examples.</u>

The implementation of the time-dependent constitutive law requires careful handling. To begin a set, preliminary tests were made for a simple 1-D linear viscoelastic model, to check the behavior of the subroutine as the applied loading rate changes and parameters become nonlinear. The manner in which variables pass into and out of UMAT under these circumstances was of particular interest. Specific results are not presented here; the experience gained during these tests, however, they did indicate the possibility of instabilities in the time integration procedure if the time steps are not carefully monitored.

Predictions using a uniaxial version of the model and a simple numerical analysis program were then obtained. Two different sets of material properties were used to illustrate the sensitivity of the model to some of them. (See Table II-E-1)

Table II-E-1

MATERIAL PROPERTIES

	SET 1	SET 2
K	5.0E-18	1.0E-20
α	9.0E-08	9.0E-08
β	1.0E-14	2.0E-08
G1	.88E+10	.88E+10
G2	.88E+09	.88E+09
B	4.1E+10	4.1E+10
n	1.0E+16	1.0E+16

UNITS: dynes - cm - sec
1dyne/cm^2 = 0.1Pa

Theory and experiments were devised to show the influence of

(1) Proper rate-dependence on 'yielding'

(2) 'Yield' stress in compression > 'yield' stress in tension (by 'yielding', here, we mean the onset of nonlinearity.)

The first set of results shows that for three different strain rates, one obtains three different response-curves with common elastic branch, different 'yield'-stress level and almost parallel post-'yield' behavior; i.e. for higher strain-rate we get higher response. The comparison of these curves with experimental data is reasonably good (Fig. II-E-1). Similar results are obtained for uniaxial tension vs. compression (Fig. II-E-2). The behavior is also altered by adding constraints (Fig. II-E-3). The last two cases illustrate the effect of the hydrostatic component on the overall behavior.

The remaining examples are from the ABAQUS implementation of the constitutive

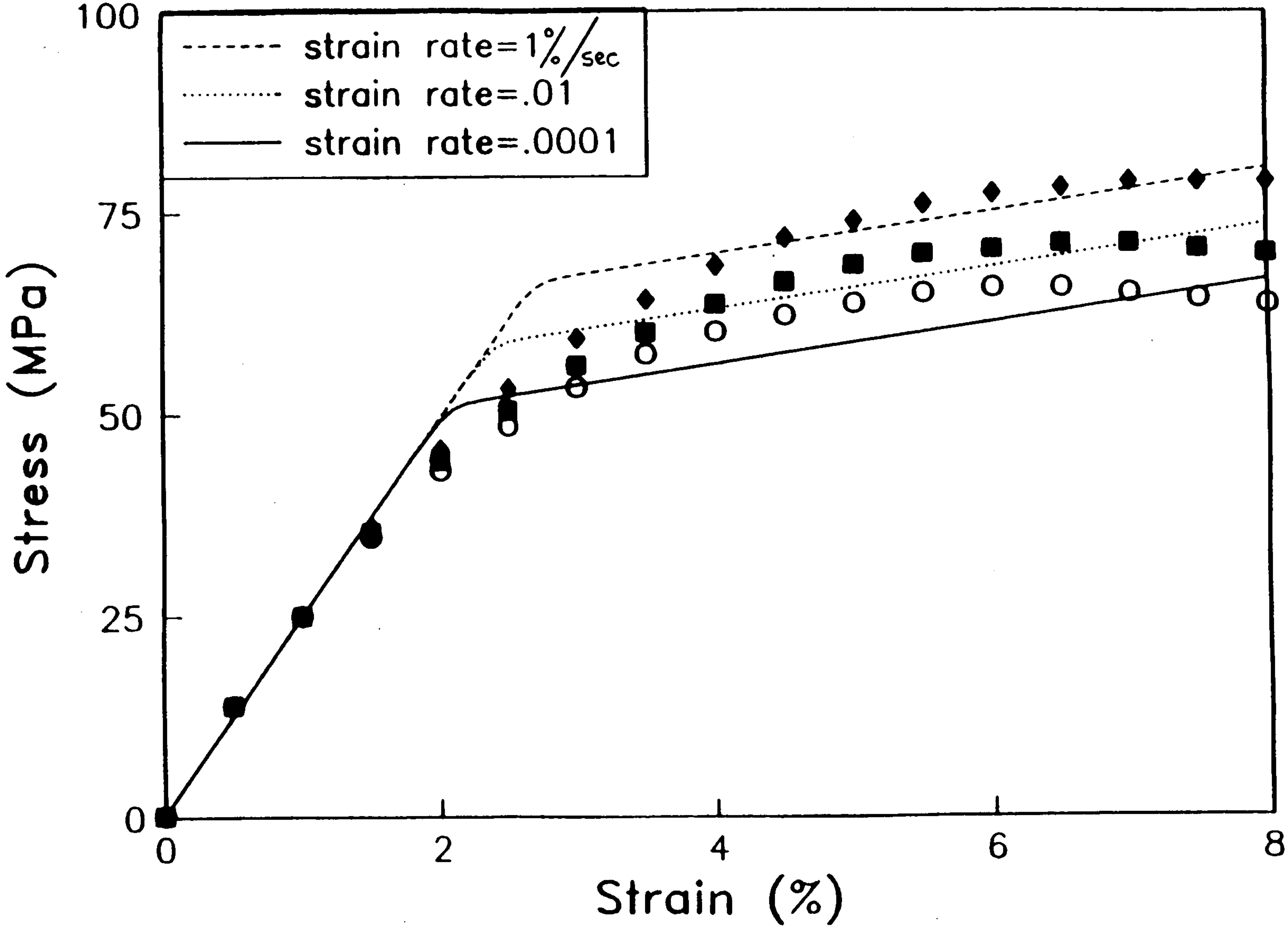

Figure II-E-1

Stress vs. Strain, Uniaxial Tension.

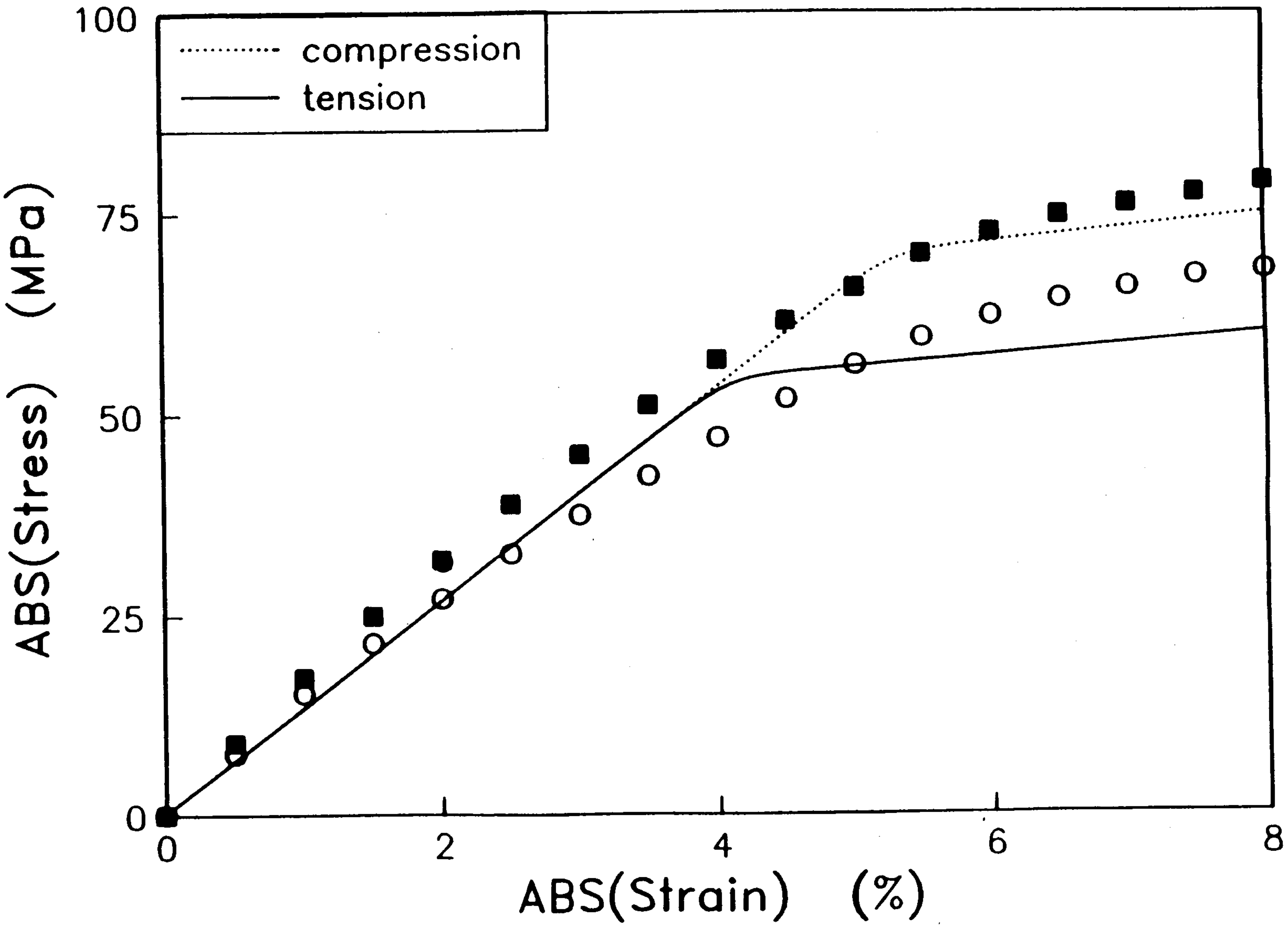
100
75
50
25
0
ABS(Stress) (MPa)
compression
tension
0
2
4
6
8
ABS(Strain) (%)

Figure II-E-2

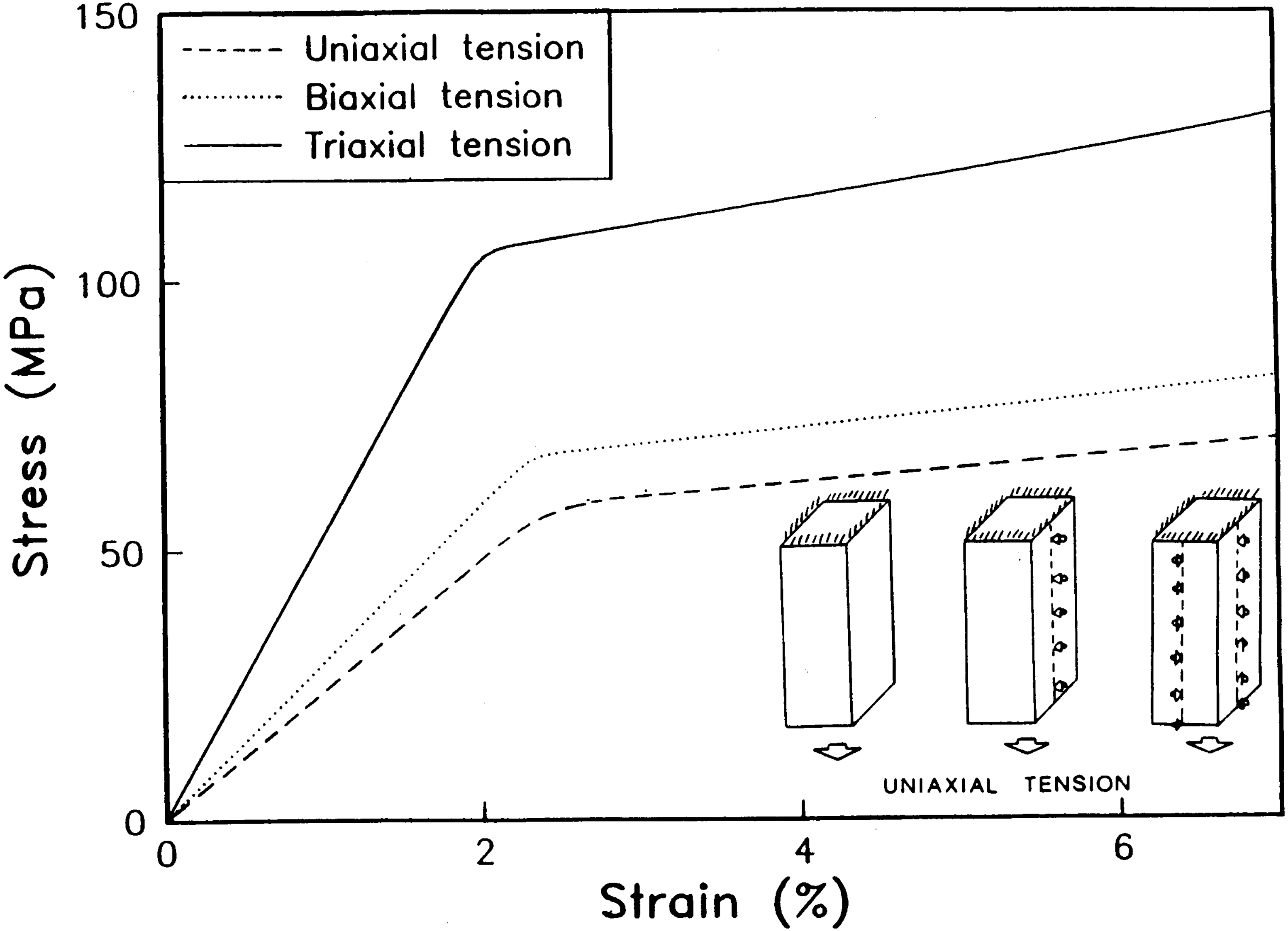

Figure II-E-3

Stress vs. Strain Summary, Strain rate = .01
Uniaxial Tension - 3 Levels of Constraints

equation. The first example problem is a sample of a homogeneous, isotropic thermoplastic matrix (Polycarbonate-Lexan) subject to plane-strain uniaxial tension and compression via applied prescribed displacements at the one edge and proper boundary conditions at the other (shown below). The fibers are not included yet in the analysis, for reasons mentioned previously. A finite element mesh of 8-noded quadrilaterals with a 3x3/2x2 integration scheme was chosen from the ABAQUS element library to model the sample.

Examining the behavior of the model in cycling loading (Fig. II-E-4), one can see the so-called 'ratcheting effect', i.e. the progressive compression of the hysteresis loops resulting from unloading in the post-'yield' area. The unloading curve becomes almost immediately elastic, ie parallel to the original ascending branch. The new loading curve then follows the same path, until it reaches the onset of nonlinearity which is located at almost the original 'yield' stress level.

When performing a couple of full cycles (tension and compression) under strain-control (Fig. II-E-5), no 'ratcheting' was allowed and despite the different stress level in opposite sign loadings, no "Baushinger effect" was noticed. After the first cycle was totally reversed, it followed exactly the same path as it did originally.

Several load-and-hold tests were performed for uniaxial tension. We loaded very quickly up to a specific stress level which was on the elastic branch of the response or a little bit above the onset of 'yielding', and then kept this stress constant through a certain time period. The plots of strain vs. time (Fig. II-E-6), show the expected creep behavior when the stress level is beyond the onset of nonlinearity.

The final example problem was a beam bending test under pure moment. The stress distribution at the center cross-section of the beam was monitored as the value of the applied moment increased. When the tensile stress reached the onset of nonlinearity, the original linear stress distribution became curvilinear in the part of the beam which was under tension. This caused the over-shifting of the neutral axis towards the compression part, because now, more of the beam depth must be under tension, to satisfy the cross-sectional force and moment equilibrium equations:

$$\int_{-\frac{h}{2}}^{\frac{h}{2}} \sigma_x dy = 0 \quad \text{and}$$

$$\int_{-\frac{h}{2}}^{\frac{h}{2}} \sigma_x y \, dy = 0$$

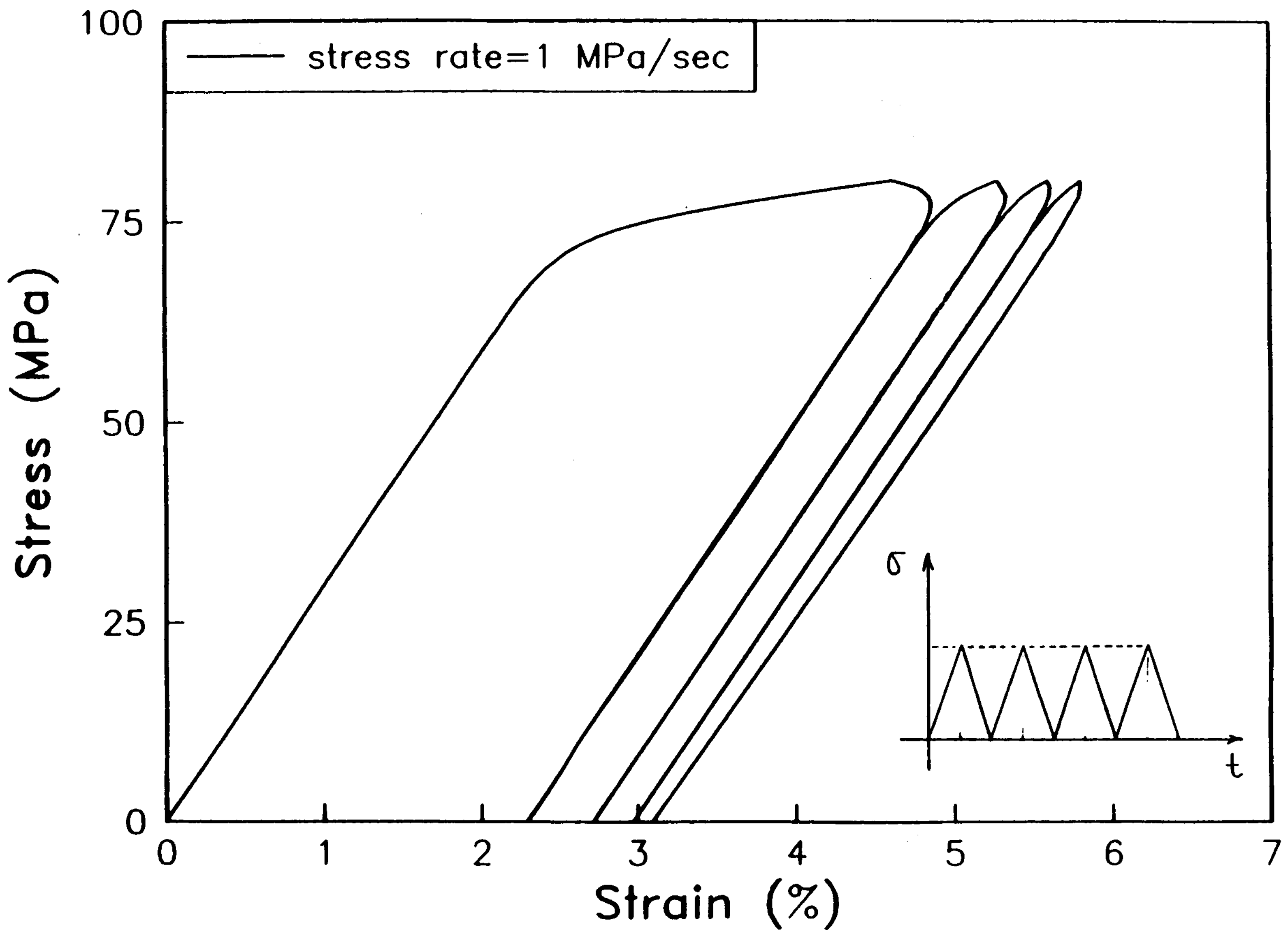

Figure II-E-4

Load & Unload, Plane Strain Tension Cycling Loading

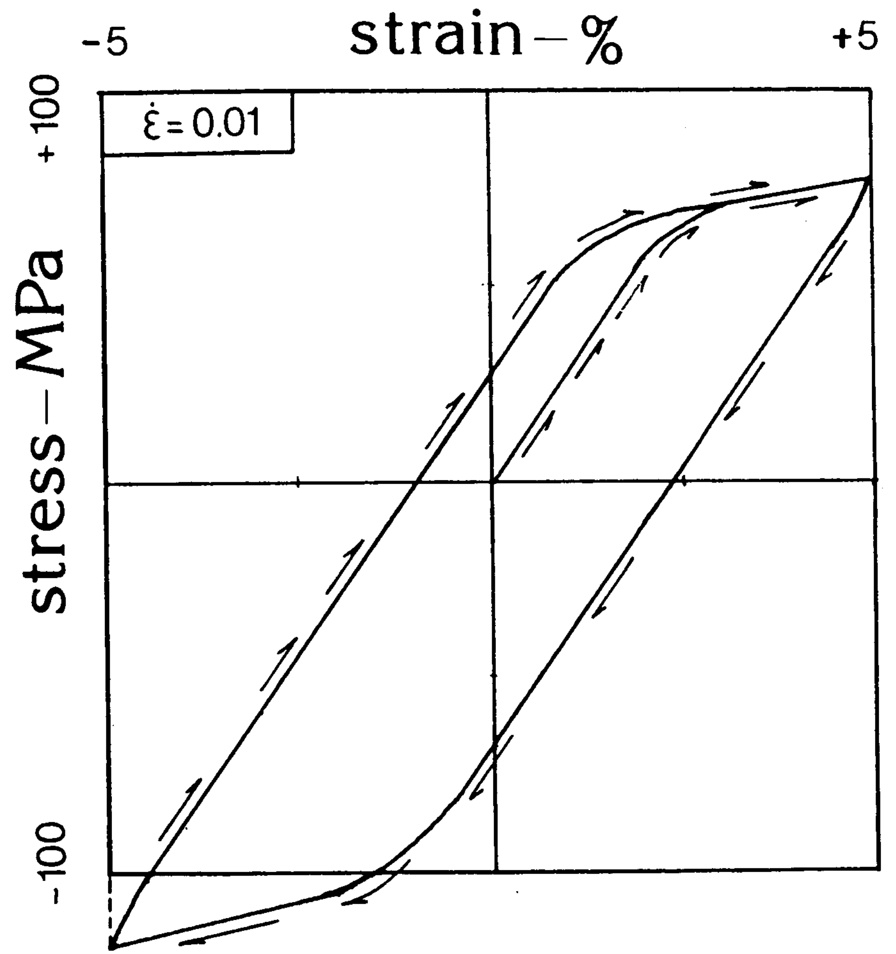

Figure II-E-5

Stress-Strain Relations in Two Full Cycles Under Strain Control.

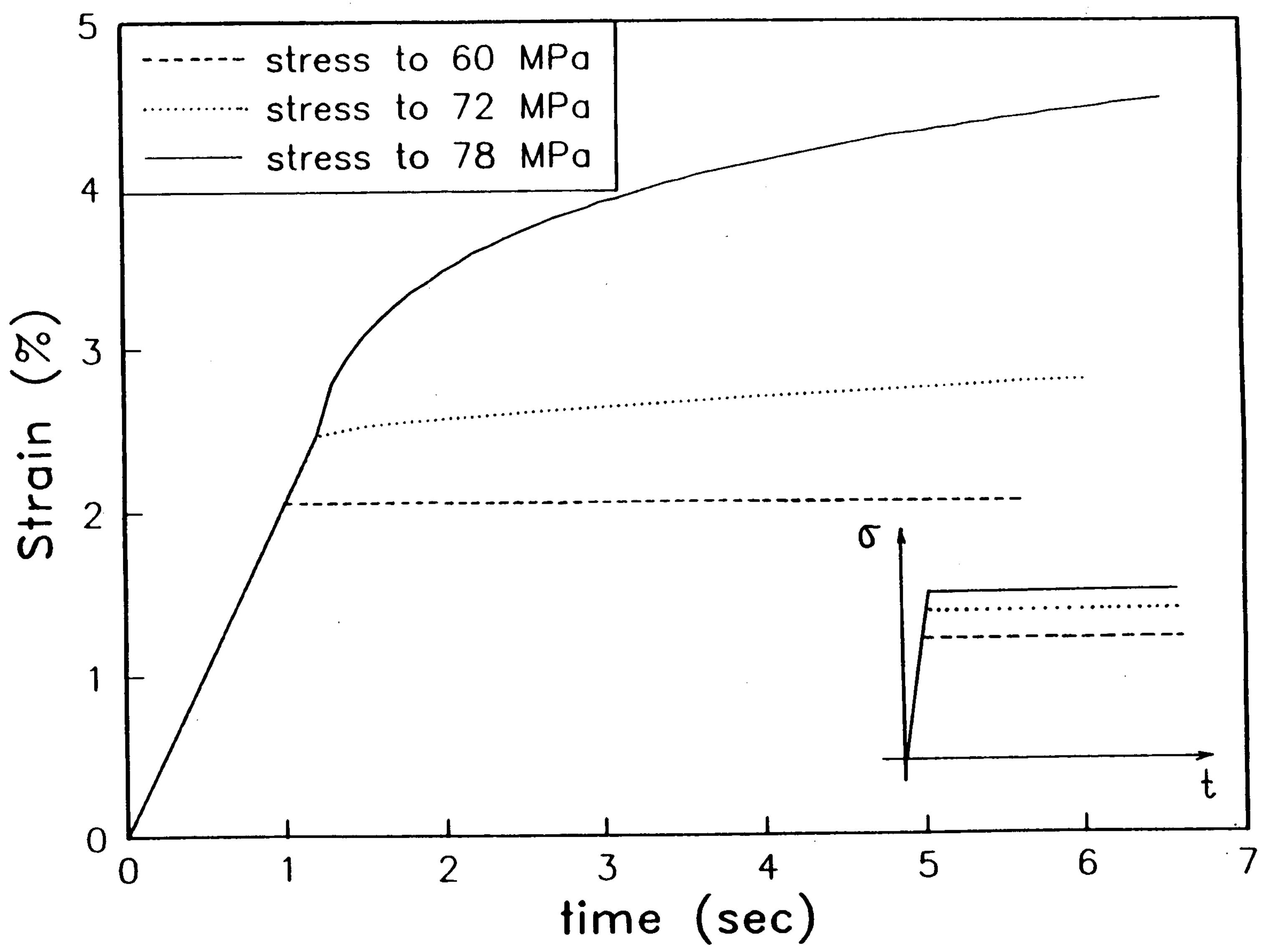

Figure II-E-6

Strain vs Time: Ramp & Hold, Stress Rate = 60 MPa/sec.

When the stress overpasses the compressive 'yielding' point, its distribution over the beam depth becomes non-linear in both the outer tensile and compressive areas. The progressive overshifting of the neutral axis plotted versus the applied moment and some characteristic stress diagrams are shown in Fig. II-E-7.

The Periodic Hexagonal Array (PHA) Mixing Model for Thermoplastics

Several sophisticated mixing models have been developed recently in order to model, in a realistic way, the inelastic behavior of fibrous composites. The basic argument for using mixing models in composites is the level of scale that the user wants to look at. For small scale systems, where fiber-matrix interaction, local plastic deformations, debonding, delamination or even random fiber distribution cannot be ignored, use of the smoothed properties of a mixing model is inappropriate. On the other hand, when the macroscopic behavior of a composite system is under consideration, a good mixing model is appropriate. The combination of both scale levels in the same analysis is a difficult task, which requires special attention in the effort to capture those phenomena which affect the overall behavior. We belive, however, that the use of our constitutive relation for the matrix, within a reliable mixing model, will provide a useful tool in those areas where only macroscopic response is needed.

The Periodic Hexagonal Array (PHA) model developed by G. J. Dvorak and J. L. Teply [23] for the elastoplastic behavior of metal matrix composites was selected for this work. The nonlinear matrix behavior is to be predicted by the constitutive relation presented in the preceeding subsections.

The structure of the PHA is suitable for Finite Element Analysis, because it can be very easily used as a User Defined Subroutine to provide the characteristics of the material behavior in a general purpose F.E. program. Figure II-E-8 illustrates the interface between the F.E. program (ABAQUS), the subroutine which defines the material behavior (UMAT), the mixing model (PHA) and the matrix constitutive relation (VISCOUS).

Our efforts are focused on the evaluation of the instantaneous material Jacobian matrix using the VISCOUS matrix constitutive relationship. Once this is determined we can estimate the increment in stresses by a simple multiplication with the given increment in strains. This material matrix, corresponding to smoothed properties, is obtained from an analysis of the representative volume element (RVE), which requires a local finite element analysis of the mesh (fiber and matrix subelements) in the (RVE), subjected to boundary conditions which exclude rigid body motion [24].

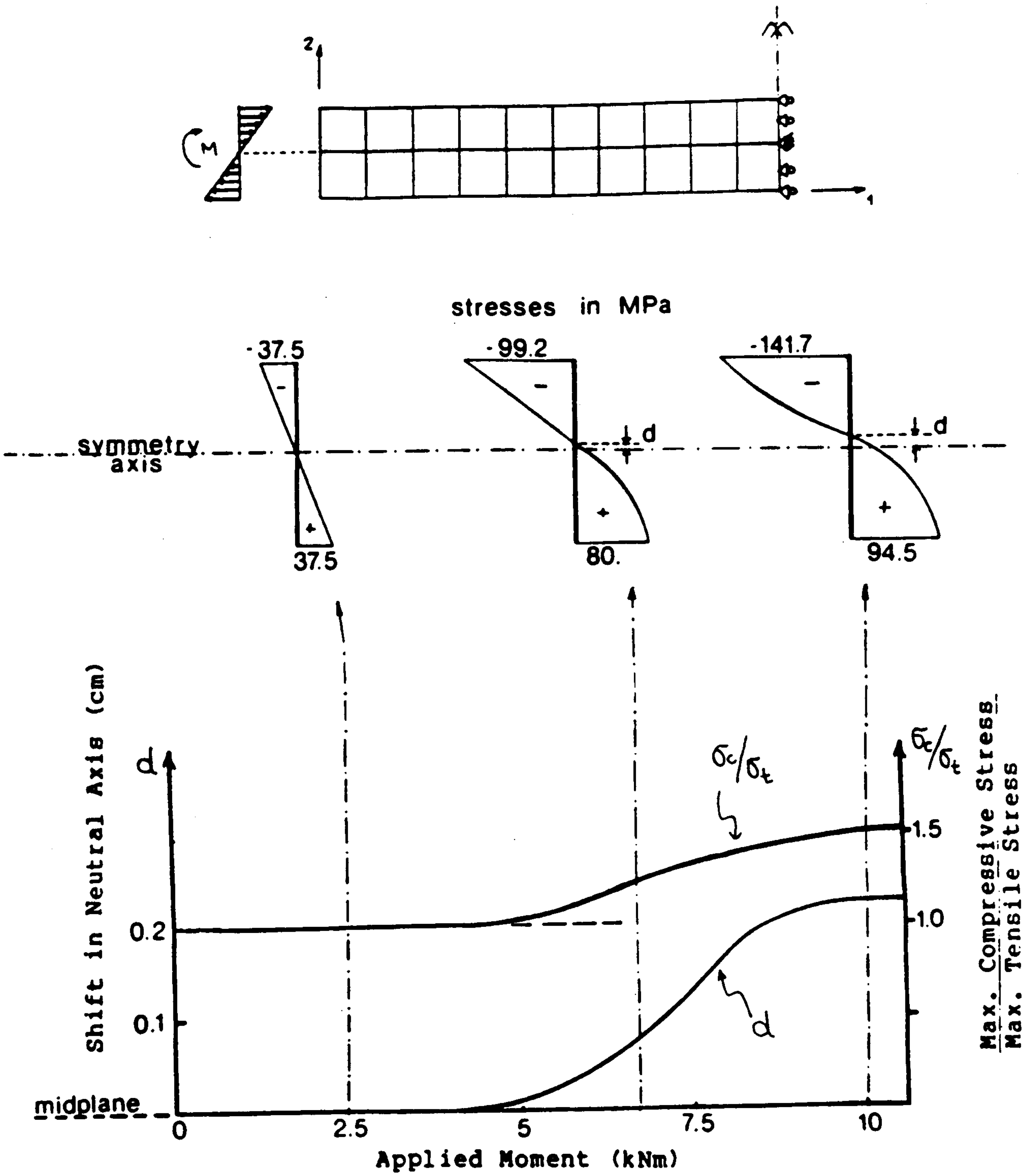

Figure II-E-7

Nonlinear Effects in a Beam Under Pure Bending.

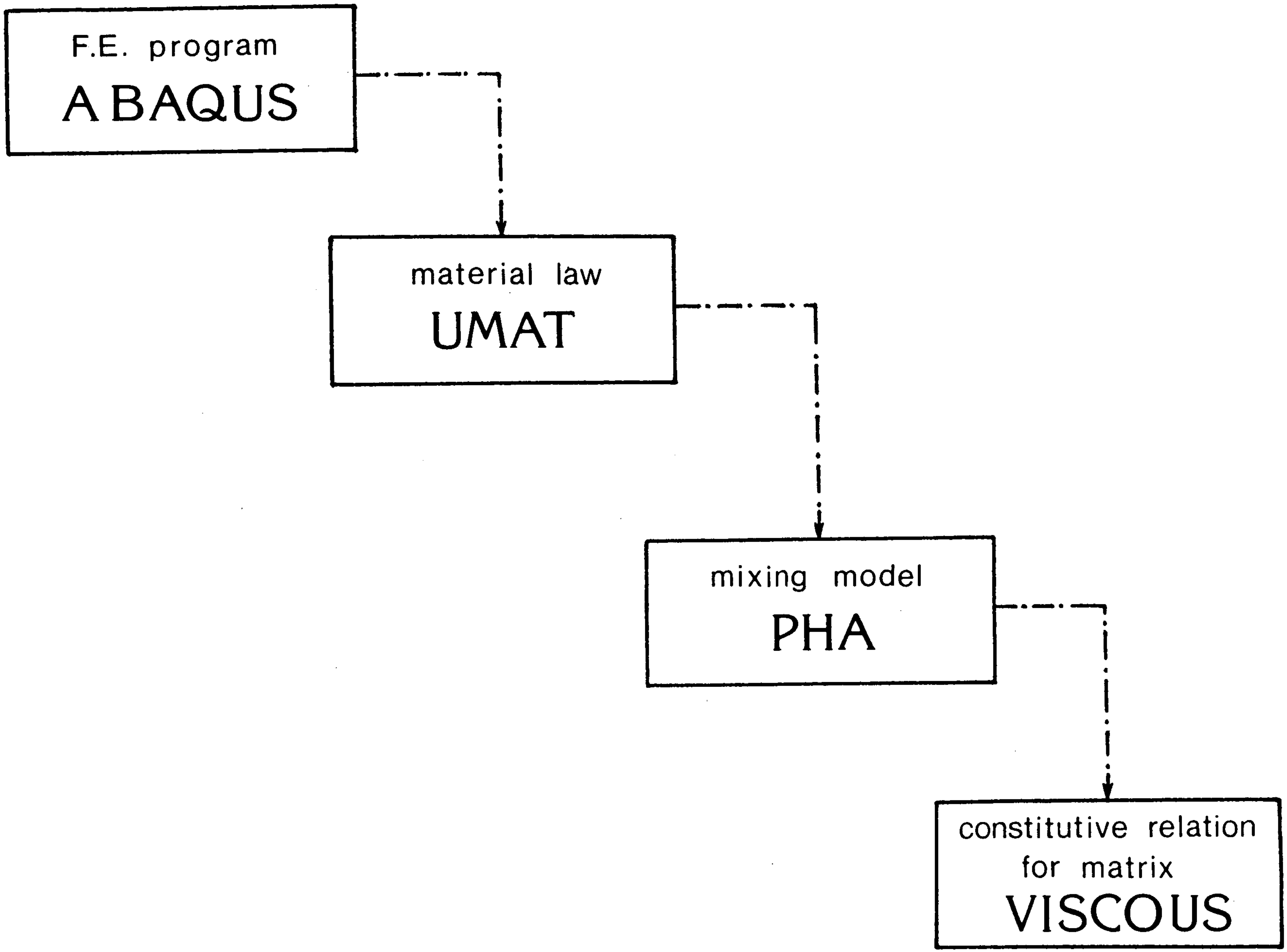

Figure II-E-8

Four Different Levels

The detailed steps required are as follows:

(1) Given the overall stress, strain and strain increment, calculate local stress, strain and strain increment for each of the fiber and matrix subelements in the RVE. This is accomplished by use of stress and strain concentration factors. Their evaluation is presented, in detail, in [24]. In fact, this step is performed only for matrix subelements, since the fiber behavior is assumed to be linear elastic and its material matrix does not depend on the stress-strain state.

(2) Evaluate the fiber contribution to stiffness, using the elastic material matrix and the shape functions for the fiber subelements. This step is performed only once, since the above contribution remains constant.

(3) Evaluate the matrix contribution to stiffness, using subroutine VISCOUS* for the material matrix and the shape functions for the matrix subelements in the RVE. This step has to be performed at every time step and global iteration, since the matrix behavior depends on the current stress-strain state.

(4) Add the contribution to both fiber and matrix and come up with an expression of the overall instantaneous stiffness in terms of local moduli and volume fraction.

(5) Multiply the overall instantaneous stiffness by the given increment in strains to get the corresponding increment in stresses. Return those values back to ABAQUS main.

The fact that the proposed constitutive relation is defined in strain-space (given strain - return stress) makes it easy to incorporate into the PHA, since it is totally compatible with the displacement-based finite element method.

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* The subroutine VISCOUS is called at each integration point of the structure, for each one of the matrix subelements in RVE. It returns the material matrix (stress-strain relation), given the local stress-strain state and the current strain increment. The algorithms included in VISCOUS are exactly those described earlier in this section, representing the nonlinear time-dependent constitutive relation for thermoplastics.

PLANS FOR UPCOMING PERIOD

Efforts during the upcoming period will be devoted to continuing the development of numerical analysis capabilities and applying them to specific experimental configurations. This work will be focused on the following areas:

1) Completing the PHA model for thermoplastic composites.

2) Investigating the effect of each parameter and stress/strain component and its significance on overall composite material behavior.

3) Using a more sophisticated time integration operator in the model formulation, to insure efficiency, accuracy and rapid convergence.

4) Developing a 2-D version of the PHA mixing model, in order to avoid performing 3-D analyses. This task may involve considerable work if we reformulate the model, rather than just enforcing the constraints of the plane cases to the more general 3-D formulation.

We have just begun investigating the problem of fracture toughness of thermoplastic composites by modeling Mode I and Mode II fracture specimens and determining the local stress fields around the crack tip. The interaction between fibers and thin matrix films close to the crack tip is expected to be significant, in particular when using a realistic time-dependent model for the matrix. Of course, the effort to combine a macroscopic analysis (say the Double Cantilever Beam (DCB) test) and a close look at the crack tip, will not be easy. Comparisons between the classical fracture mechanics approach based on an infinitely sharp crack, and the kind of blunt cracks which appear to be encountered with thermoplastics, will also be made. Energy considerations will be included to determine the amount of energy that is dissipated versus that which is stored. Consideration will also be given to the bulk (hydrostatic) energy component versus the shear (deviatoric). The final goal is to understand why thermoplastic composites are structurally tougher than those with conventional thermoset matrix materials.

These analyses are being closely coordinated with experiments being carried out by Professor Sternstein.

PUBLICATIONS AND PRESENTATIONS BY PROFESSOR M. SHEPHARD ON THIS SUBJECT

"The N-Criterion for Predicting Crack Growth Increment", with N.A.B. Yehia, Engng. Fracture Mech., Vol. 26, No. 3, 1987.

"Progress on Automated Finite Element Modeling", presentation at Pratt and Whitney Aircraft, Hartford, CT, September 18, 1986.

"Automated Finite Element Modeling", Grumman Aircraft, Bethpage, NY, February 6, 1987.

"Nonlinear Finite Element Modeling of Composites", ONR review of SDI related composites work, U. of Maryland, College Park, Maryland, March 31, 1987.

"Finite Element Modeling of Thermoplastic Composites - Constitutive Relations for Matrix Materials", with R.J. Bankert, S.S. Sternstein and N.D. Lambropoulos, abstract accepted for ASTM Symposium on Advances in Thermo-plastic Matrix Composite Materials", October 1987.

F. GENERAL BEAM THEORY FOR COMPOSITE STRUCTURES

Sr. Investigator: O. Bauchau

INTRODUCTION

This work has concentrated on the development of a general beam theory for thin walled structures, including cross-sectional deformations. Both numerical and experimental aspects have been investigated. Since no assumption is made in this work about the cross-sectional deformation, the resulting analysis should yield results equivalent to a full three-dimensional model of the structure. The cost of the analysis, on the other hand, should be orders of magnitude lower than a conventional three dimensional finite element analysis.

STATUS

The proposed generalized beam theory has important applications in light weight aeronautical structures. Wing boxes and fuselages are often composed of flat or curved panels, reinforced by members with fairly deep stiffness. A major problem in the design of such built-up shell structures subjected to in-plane compressive and/or shearing loads is the existence of many different failure modes, and the possible interaction between these modes. The buckling and post-buckling analysis of these structures using the finite element method has become popular, but the non-linear analysis of complex shell structures requires very large amounts of computing time and is too expensive to be used systematically in the predesign process. The increasingly widespread use of composites for thin-walled structures adds impetus to the effort to develop efficient methodologies which make no a priori assumptions regarding failure modes; particularly because of the relatively limited experience with such applications.

PROGRESS DURING REPORTING PERIOD

During this research period, the generalized beam model was developed. The governing equations are as follows:

$$-\bar{K}\underline{u}'' + \tilde{K}\underline{u}' + K\underline{u} = \underline{Q} \qquad \text{Eq. (1)}$$

Where:

$\bar{K}$, $\tilde{K}$, and K are stiffness matrices resulting from the discretization of the cross-section of the structure,

$\underline{u}(z)$ is the vector of modal displacements,

$(\ )'$ denotes a derivative with respect to the axial variable, z, Q is the load vector.

Equation (1) represents a set of coupled differential equations that can be solved by first finding the eigen deformation modes from the following quadratic eigenproblem.

$$(-P_i^2\bar{K} + P_i\tilde{K} + K)\,\underline{\bar{u}}_i = 0 \qquad \text{Eq. (2)}$$

Where:

$\underline{\bar{u}}_i$ are the eigen deformation modes which characterize the in-plane deformation modes of the section, and

P_i are the associated eigenvalues.

The task of solving Eq. (2) proved to be extremely difficult: a special procedure based on the Generalized Lanczos Algorithm was developed, and the eigen deformation modes for various sections were successfully obtained. The convergence of the eigenvalue extraction routine, however, was fairly slow, not because of an inherent deficiency of the algorithm, but because of the existance of closely-spaced eigenvalues. This means that the solution of the overall problem, based on the superposition of these modes, would be very slow in converging as well, since the contribution of each mode is inversely proportional to the values of the eigennumbers.

Another approach to the solution of Eq. (1) has now been taken. The displacement function vector $\underline{u}$ is expanded in a series of Tchebychev polynomials along the axis of the beam. This numerical procedure is showing great efficiency.

PLANS FOR THE UPCOMING PERIOD

Following guidance from NASA/AFOSR monitors, on the occasion of the program site visit on December 18 and 19, 1986, support for this project under the subject grant was terminated as of the end of the reporting period. In view of the promise of the Tchebychev polynominal approach, however, the methodology development for the efficient analysis of composite structures with thin cross-sections is expected to be completed under other funding.

PART III

TECHNICAL INTERCHANGE

TECHNICAL INTERCHANGE

Technical meetings, both on- and off-campus, provide for the interchange of technical information. In order to assure that Rensselaer faculty/staff members can participate, a central listing of upcoming meetings is compiled, maintained and distributed on a periodioc basis. The calendar for this reporting period is shown in Table III-1. Table III-2 shows the meetings attended by RPI composites program faculty/staff/students during the reporting period. Some on-campus meetings, with special speakers particularly relevant to composites, are listed in Table III-3. A list of composites-related visits to relevant organizations, attended by RPI faculty/staff/students, along with the purpose of each visit is presented in Table III-4.

The diversity of the research conducted within this program has increased over the last several years. To insure information transfer, once-a-week luncheon programs have been held among the faculty and graduate students involved (listed in Part IV. Personnel - of this report). These meetings are held during the academic year and are known as "Brown Bag Lunches" (BBL's), since attendees bring their own. Each BBL allows an opportunity for graduate students and faculty to briefly present plans for, problems encountered in and recent results from their individual projects. These seminars also are occasions for short reports on the content of off-campus meetings attended by any of the faculty/staff participants (see Tables III-2 and III-4) and for brief administrative reports, usually on the part of one of the Co-Principal Investigators. Off-campus visitors, at RPI during a BBL day, are often invited to "sit in". Table III-5 lists a calendar of internal, oral progress reports as they were given at BBL's during this reporting period.

As an important part of the steps taken to increase communication between NASA researchers and their RPI counterparts in areas of interest under this grant, a series of Research Coordination Meetings have been held with members of NASA Langley and Lewis Research Center's Materials and Structures scientist/engineers. These meetings are summarized in Table III-6.

Table III-1

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Calendar of Composites-Related Events

May 1, 1986 through April 30, 1987

DATES	MEETING	SPONSOR	PLACE
12-19 May 86	Workshop on Failure Mechanics	ONR	College Park, MD
14 May 86	Symposium on Advanced Composite Materials	GE	Schenectady, NY
19-21 May 86	27th Structures, Structural Dynamics & Materials Conf.	AIAA/ASME/ ASCE/AHS	San Antonio, TX
19-23 May 86	Intl. Conf. on Advanced Composite Materials	Chinese Soc. for Matl. Sc.	Taipei, Taiwan
21 May 86	An Introduction to Advanced Composites - Materials Processes, Equipment & Applications	CoGSME	Philadelphia, PA
22 May 86	Advanced RTM for Advanced Composite Production	CoGSME	Philadelphia, PA
2-3 Jun 86	Composites Consortium Program Review	SDIO/ONR	Woods Hole, MA
2-6 Jun 86	Intl. Conf. on Role of Fracture Mechanics in Modern Technology	Kyushu Univ.	Fukuoka, Japan
4-5 Jun 86	Technology in 1990's: Advanced Materials	SME	London, England
8-13 Jun 86	Spring Conference on Experimental Mechanics	SEM(SESA)	New Orleans, LA
9-12 Jun 86	AUTOCOM '86 - Advanced Applications of Composites for Automotive	SME	Dearborn, MI
11-13 Jun 86	3rd Symposium on Nonlinear Constitutive Relations for High Temperature Applications		Akron, OH
16-20 Jun 86	10th U.S. National Congress on Applied Mechanics	ASME	Austin, TX

Table III-1 (continued)

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Calendar of Composites-Related Events

May 1, 1986 through April 30, 1987

DATES	MEETING	SPONSOR	PLACE
23-25 Jun 86	3rd Japan-U.S. Conference on Composite Materials	NSF	Tokyo, Japan
30 Jun - 2 Jul 86	19th National Symposium on Fracture Mechanics	ASTM	San Antonio, TX
30 Jun - 4 Jul 86	4th Inter. Carbon Conf.	D.K.G.	Baden-Baden, West Germany
21-23 Jul 86	2nd Intl. Symposium on the Nondestructive Characterization of Materials	Industrial Matls. Res. Inst. (NRCC)	Montreal, Canada
19-21 Aug 86	Conf. on Nondestructive Testing & Evaluation of Advanced Matls & Composites	DoD	Colorado Springs, CO
25-29 Aug 86	Intl. Conf. & Exposition on Engineering Ceramics	Am. Soc. for Metals	Buffalo, NY
25-29 Aug 86	COMP '86 Symposium - Engineering Applications of New Composites	Univ. of Patras	Patras, Greece
1-5 Sep 86	Symposium	IUTAM	Paris, France
7-12 Sep 86	ACS 192nd Natl. Mtg.	ACS	Anaheim, CA
8-11 Sep 86	Fabricating Composites '86 Conf. & Exposition	CoGSME & SME	Baltimore, MD
22-26 Sep 86	1st World Congress on Computational Mechanics (WCCM) of the Intl. Assoc. for Computational Mechanics (IACM)	Univ. of TX	Austin, Tx
24 Sep 86	15th Videoconference In-Process Control for Manufacturing	IEEE Student Branch, RPI ECSE/CMPTT	Troy, NY

Table III-1 (continued)

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Calendar of Composites-Related Events

May 1, 1986 through April 30, 1987

DATES	MEETING	SPONSOR	PLACE
4-5 Oct 86	1986 Materials Science Seminar "Computer Simulations in Materials Science"	ASM MSD	Orlando, FL
4-9 Oct 86	ASM Materials Week	ASM	Lake Buena Vista, FL
7-9 Oct 86	1st Conf. on Composite Materials	ACS & Univ. of Dayton	Dayton, OH
7-9 Oct 86	18th Natl. SAMPE Tech. Conf.: Matls for Space: The Gathering Momentum	SAMPE	Seattle, WA
8-10 Oct 86	ORCAL '86 (Orange Cty Manufacturing & Metal-working Conf. & Expo.)	ASM & SME	Anaheim, CA
10 Oct 86	Fastening Advanced Composites Conf.	SME	Renton, WA
14-16 Oct 86	18th National Technical Conf.	SAMPE	Seattle, WA
20-22 Oct 86	Aircraft Systems, Design & Tech. Mtg.	AIAA/AHS/ASEE	Dayton, OH
28-30 Oct 86	MMC Spacecraft Survivability Tech. Conf.	DoD	Menlo Park, CA
2-5 Nov 86	Optical Methods & Composites	SEM	Keystone, CO
3 Nov 86	Test Methods & Design Allowables for Fiber Composites: 2nd Symposium	ASTM	Phoenix, AZ
10 Nov 86	Southwest Mechanics Lecture Series	-	Norman, OK
10-14 Nov 86	Intl. Conf. & Expo. on Castings	ASM	Chicago, IL

Table III-1 (continued)

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Calendar of Composites-Related Events

May 1, 1986 through April 30, 1987

DATES	MEETING	SPONSOR	PLACE
2-4 Dec 86	Composites Materials: Analysis Testing & Design	SEM	Chicago, IL
7-12 Dec 86	Winter Annual Mtg.	ASME	Anaheim, CA
7 Jan 87	Intl. Conf. on Constitutive Laws for Engineering Materials: Theory and Applications	-	Tucson, AZ
12-16 Jan 87	Gordon Conference on Composites	Gordon Conf.	Santa Barbara, CA
19-22 Jan 87	Composites in Manufacturing, 6th Conference & Exposition	CoGSME	Anaheim, CA
11 Mar 87	Workshop on Composite Materials - Interface Science	ONR	Leesburg, VA
30-31 Mar 87	ONR Review of SDI related composites work	ONR	College Park, MD
6-8 Apr 87	28th Structures, Structural Dynamics & Materials Conf.	AIAA/ASME/ ASCE/AHS	Monterey, CA
6-9 Apr 87	32nd Intl. SMPE Symposium & Exhibition	Society of Advanced Matls & Processing Engineering	Anaheim, CA
8 Apr 87	Composites: The Future is Now	Capital Region Tech. Development Council	Troy, NY
9-10 Apr 87	Dynamics Specifications Conference	AIAA	Monterey, CA
10 Apr 87	Supportability Seminar	CoGSME	Anaheim, CA

Table III-2

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Pertinent Professional Meetings Attended

May 1, 1986 through April 30, 1987

DATES	MEETING
12-13 May 86	ONR Workshop on Failure Mechanics (Prof. Dvorak), College Park, MD Prof. Dvorak presented the paper: "Fracture Mechanics of Metal Matrix Composites"
14 May 86	Symposium on Advanced Composite Materials (Prof. Dvorak), Schenectady, NY Prof. Dvorak presented the paper: "Analysis of Fatigue Cracking of Fibrous Metal Matrix Laminates"
19-21 May 86	27th Structures, Dynamics & Materials Conference (Prof. Loewy), San Antonio, TX Prof. Loewy presented the paper: "Application of the Principal Curvature Transformation to Nonlinear Rotor Blade Analysis"
2-3 Jun 86	SDIO/ONR Composites Consortium Program Review (Prof. Dvorak), Woods Hole, MA Prof. Dvorak presented the paper: "Damage in Metal Matrix Composites"
2-4 Jun 86	AHS Annual Forum (Prof. Loewy), Washington, DC
11-13 Jun 86	3rd Symposium on Nonlinear Constitutive Relations for High Temperature Applications (Prof. Krempl), Akron, OH Professor Krempl presented the papers: "The Viscoplasticity Theory Based on Overstress Applied to the Modeling of Nickel Base Super Alloy at 815^{o}C" "Cyclic Uniaxial and Biaxial Hardening of Type 304 Stainless Steel Modeled by the Viscoplasticity Theory Based on Overstress" "A Simplified Orthotropic Formulation of the Viscoplasticity Theory Based on Overstress"

Table III-2 (continued)

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Pertinent Professional Meetings Attended

May 1, 1986 through April 30, 1987

DATES	MEETING
16-20 Jun 86	10th U.S. National Congress of Applied Mechanics (Prof. Dvorak), Austin, TX Prof. Dvorak presented the paper: "Thermal Expansion of Elastic-Plastic Composite Materials"
23-25 Jun 86	3rd Japan-U.S. Conference on Composite Materials (Prof. Diefendorf), Tokyo, Japan. Professor Diefendorf presented the paper: "The Relationship of Structure to Properties in Carbon Fibers"
30 Jun - 4 Jul 86	4th International Carbon Conference (Prof. Diefendorf), Baden-Baden, Deutschen Keramischen Gesellschaft, West Germany Professor Diefendorf presented the paper: "The Chemical Vapor Deposition of Carbon Capillary Tubes II"
1-5 Sep 86	IUTAM Symposium (Prof. Dvorak), Paris, France Prof. Dvorak gave the Invited Lectures: "Thermomechanical Couplings in Solids" "Thermomechanical Deformation and Coupling in Elastic-Plastic Composite Materials"
21-22 Oct 86	AIAA/AHS/ASEE Aircraft Design Mtg (Prof. Loewy), Dayton, OH Prof. Loewy was a Panel Discussion Member
10 Nov 86	Southwest Mechanics Lecture Series (Prof. Krempl), Norman, OK Professor Krempl presented the paper: "Biaxial Fatigue and Deformation Behavior of Graphite/Epoxy Composites"
7-12 Dec 86	ASME Winter Annual Meeting (Prof. Dvorak), Anaheim, CA Prof. Dvorak gave the Invited Lecture: "Fatigue Damage Analysis in Metal Matrix Laminates"

Table III-2 (continued)

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Pertinent Professional Meetings Attended

May 1, 1986 through April 30, 1987

DATES	MEETING
7 Jan 87	International Conference on Constitutive Laws for Engineering Materials: Theory and Applications (Prof. Krempl), Tucson, AZ Prof. Krempl presented the paper: "Isotropic and Orthotropic Formulations of the Viscoplastic Theory Based on Overstress"
12-16 Jan 87	Gordon Conference on Composites (Prof. Sternstein), Santa Barbara, CA Professor Sternstein gave the Lecture: "Thermoplastic Matrix Composites"
11 Mar 87	ONR Workshop on Composite Materials - Interface Science (Prof. Dvorak), Leesburg, VA Prof. Dvorak presented the paper: "Cracks Approaching Interfaces: The Image Crack Method"
30 Mar 87	ONR SDI Review (Prof. Dvorak), College Park, MD Prof. Dvorak presented the paper: "Analysis of Metal Matrix Composites for Spacecraft Applications"
31 Mar 87	ONR Review of SDI Related Composites Work (Prof. M. Shephard), College Park, MD Professor Shephard gave the Lecture: "Nonlinear Finite Element Modeling of Composites"
6-7 Apr 87	28th Structures, Dynamics & Materials Conference (Prof. Loewy), Monterey, CA

Table III-3

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Composites-Related Meetings/Talks Held at RPI

May 1, 1986 through April 30, 1987

SUBJECT	SPEAKERS (RPI)	DATE
SHORT COURSE: Advanced Composite Materials and Structures	Prof. O. Bauchau Prof. R. Diefendorf	7/21-25/86
Structure Failures & Their Impact on Engineering Knowledge	L. Coffin	9/2/86
	SPEAKERS (RPI)	
Workshop on Composite Materials and Structures for Rotorcraft	O. Bauchau M. Darlow R. Diefendorf R. Loewy S. Winckler	9/10-11/86
Inhomogeneous Swelling & Solvents/Solids/Stress Interactions in Multiphase	S. Sternstein	10/2/86
Damage Monitoring, Life Prediction & Life Extension of Engineering Structures	L. Coffin	10/21/86
	SPEAKERS	
NASA/AFOSR Site Visit and Program Review	O. Bauchau R. Diefendorf G. Dvorak E. Krempl R. Loewy V. Paedelt M. Shephard S. Sternstein S. Winckler	12/18-19/86

Table III-3 (continued)

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Composites-Related Meetings/Talks Held at RPI

May 1, 1986 through April 30, 1987

SUBJECT	SPEAKERS	DATE
Theory of Viscoplasticity Based on Over-stress with Applications	David Yao Doctoral Dissertation	2/11/87
Minimizing Residual Stresses in Injection Molded Parts	Ming J. Liou M. I. T. Cambridge, MA	2/12/87
Pultruded Fiberglass-A Structural Alternative	Russ Whitfield Morrison Molder Fiber Glass Co. Bristol, VA	2/27/87
Failure Criterion of Fiber Reinforced Plastics and Optimum Fiber Orientations	Prof. K. Ikegami Tokyo Institute of Technology Tokyo, Japan	2/27/87
Servo-Controlled Testing and Materials Modelling	Dr. E. Krempl R. P. I.	3/23/87
Localization of Plastic Deformation	Prof. A. S. Douglas Johns Hopkins Univ.	3/24/87
Presentation of U.S. Army Engine Developmental Research Program	Dr. J. Acurio	4/15/87

Table III-4

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Composites-Related Visits to Relevant Organizations

May 1, 1986 through April 30, 1987

Faculty Member	Purpose of Visit	Location	Date(s)
G. Dvorak	Colloquium: "Damage Mechanics of Composite Materials"	Northwestern Univ Evanston, IL	5/2/86
G. Dvorak	Presented paper: "Fracture Mechanics of Metal Matrix Composites"	U. of MD College Park, MD	5/12-13/ 86
G. Dvorak	Symposium: "Analysis of Fatigue Cracking of Fibrous Metal Matrix Laminates"	G.E. Schenectady, NY	5/14/86
R. Diefendorf	Presented Seminar: "Carbon Fibers From Mesophase Pitch"	Rockwell Science Ctr., Thousand Oaks, CA	7/11/86
O. Bauchau R. Diefendorf R. Loewy	Tour of Facilities & Technical Discussion	U.S. Composites Corp., Rensselaer Technology Park, No. Greenbush, NY	7/29/86
R. Loewy	Discussion of Structural Dynamics Research	Jet Propulsion Lab. Pasadena, CA	8/6/86
M. Shephard	Presented Seminar: "Progress on Automated Finite Element Modeling"	Pratt & Whitney Aircraft, Hartford, CT	9/18/86
E. Krempl	Presented Seminar: "Biaxial Fatigue and Deformation Behavior of Graphite Epoxy Composites"	University of Delaware, Newark, DE	9/19/86
G. Dvorak R. Diefendorf R. Loewy S. Sternstein	Discussion of Langley R. C. research program in composites	NASA Langley R.C. Hampton, VA	11/3/86

Table III-4 (continued)

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Composites-Related Visits to Relevant Organizations

May 1, 1986 through April 30, 1987

Faculty Member	Purpose of Visit	Location	Date(s)
E. Krempl	Presented Lecture: "Biaxial Fatigue and Deformation Behavior of Graphite/Epoxy Composites"	University of Oklahoma, Norman, OK	11/10/86
G. Dvorak	Colloquium: "Plasticity of Composite Materials"	Texas A&M Univ College Sta, TX	11/11/86
G. Dvorak	Colloquium: "Plasticity of Composite Materials"	Rice University Houston, TX	11/12/86
G. Dvorak	Colloquium: "Recent Developments in Plasticity of Fiber Metal Matrix Composites	Yale Univ. New Haven, CT	1/21/87
G. Dvorak	Symposium: "Bimodal Plasticity Theory of Composite Materials"	U. of Florida Gainesville, FL	1/28-30/87
M. Shephard	Presented Seminar: "Automated Finite Element Modeling"	Grumman Aircraft Bethpage, NY	2/6/87
G. Dvorak	Presented Seminar: "Recent Developments in Plasticity of Composite Materials"	U. of CA Berkeley, CA	2/23/87
S. Sternstein	Presented Seminar: "Thermoplastic Matrix Composites"	U. of Connecticut Storrs, CT	3/8/87
R. Diefendorf	Presented Seminar: "Carbon Fibers"	SUNY, Buffalo, NY	4/2/87
R. Diefendorf	Presented Seminar: "Chemical Vapor Deposition"	Sohio, Niagara Falls, NY	4/6/87
G. Dvorak	Presented Seminar: "A Bimodal Plasticity Theory of Composite Materials"	Brown Univ. Providence, RI	4/6/87

Table III-4 (continued)

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Composites-Related Visits to Relevant Organizations

May 1, 1986 through April 30,
1987

Faculty Member	Purpose of Visit	Location	Date(s)
S. Sternstein	Presented Seminar: "Matrix Dominated Mechanical Properties of Composites"	TRW Research Ctr Los Angeles, CA	4/10/87
R. Diefendorf	Presented Sach's Memorial Lecture: "Composite Processing"	Syracuse University Syracuse, NY	4/21/87
G. Dvorak	Presented Seminar: "Recent Developments in Composites Plasticity"	Lawrence Livermore Labs., Livermore, CA	4/23/87

Table III-5

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Brown Bag Lunch Schedule

May 1, 1986 through April 20, 1987

DATE	TOPIC	RESP. FACULTY
02-May	Administrative Report	Loewy
	Edge Failures	Sham
	Fabrication Technology	Bundy/Hagerup/Paedelt
05-Sep	Administrative Report	Loewy
	Fracture Toughness in Thermoplastic Matrix Composites	Sternstein
	Failure in Metal Matrix Composites	Dvorak
12-Sep	General Discussion -	
	Rpt on RPI Workshop on Composites in Rotorcraft	Loewy/Diefendorf/ Bauchau/Winckler
19-Sep	Administrative Report	Diefendorf
	Chemical Vapor Deposition	Diefendorf
	Anisotropic Beam Theory	Bauchau
26-Sep	General Discussion -	
	Preparation of Ceramic Fibers	Interrante
03-Oct	Administrative Report	Loewy
	Time-Dependent Deformation of Comp.	Krempl
	Numerical Analysis of Composites	Shephard
10-Oct	General Discussion -	
	High Temperature Deformation Behavior	Krempl
17-Oct	Administrative Report	Diefendorf
	Fabrication Technology	Bundy/Hagerup/Paedelt
	Ceramic Matrices - Prep. & Properties	Doremus
24-Oct	General Discussion -	
	Mechanics of Damage in Composites	Sternstein
31-Oct	Administrative Report	Diefendorf
	Intermetallic Matrix Fabrication Tech.	German
07-Nov	General Discussion -	
	Processing at Very High Temperatures	Doremus
14-Nov	Administrative Report	Loewy
	Organometallic Precursors to Ceramics	Interrante

Table III-5 (continued)

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Brown Bag Lunch Schedule

May 1, 1986 through April 20, 1987

DATE	TOPIC	RESP. FACULTY
21-Nov	General Discussion - Mechanics of Damage in Composites	Krempl
28-Nov	Thanksgiving Holiday (No Mtg)	
05-Dec	Administrative Report High Temperature Chemistry in Ceramic Matrix Composites	Diefendorf Wiedemeier
12-Dec	General Discussion - Carbon/Carbon and CVD	Diefendorf
16-Jan	Administrative Report General Discussion: RP-3 Design Evolution	Diefendorf Paedelt
23-Jan	Administrative Report Anistropic Beam Theory Failure in Metal Matrix Composites	Loewy Bauchau Dvorak
30-Jan	General Discussion - Unsymmetric Laminates	Winckler/Bauchau
06-Feb	No Meeting	
13-Feb	Administrative Report Modal Analysis of RP-2 Sailplane	Diefendorf Swaybill
20-Feb	Administrative Report Fabrication Technology Fracture Toughness in Thermoplastic Matrix Composites	Loewy Paedelt Sternstein
27-Feb	Administrative Report Guest Speaker Failure Criterion of Fiber Reinforced Plastics and Optimum Fiber Orientations	Loewy Prof. K. Ikegami Tokyo Institute of Technology
06-Mar	Administrative Report Failure in Metal Matrix Composites Numerical Analysis of Composites	Diefendorf Dvorak Shephard/Lambropoulos
13-Mar	General Discussion - Mechanics of Damage in Composites	Sternstein/Krempl

Table III-5 (continued)

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Brown Bag Lunch Schedule

May 1, 1986 through April 20, 1987

DATE	TOPIC	RESP. FACULTY
20-Mar	No Meeting (Spring Break)	
27-Mar	General Discussion - Project Progress on the U.R.I. Program	Diefendorf
03-Apr	Administrative Report	Diefendorf
	Chemical Vapor Deposition	Diefendorf
	Time-Dependent Deformation of Comp.	Krempl
10-Apr	Administrative Report	Diefendorf
	Anistropic Beam Theory	Bauchau
	Progress in Failure Analysis	Sham
17-Apr	General Discussion - High Temperature Deformation Behavior	Krempl/Winckler
24-Apr	Administrative Report	Loewy
	Fracture Toughness in Thermoplastic Matrix Composites	Sternstein
	Numerical Analysis of Composites	Shephard
	Visitor: Steven Smith, Courtaulds Ltd., England (Mfg'r. of Carbon Fibers)	

Table III-6

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Review of Research Center Interactions

May 1, 1986 through April 30, 1987

Faculty Member	Purpose of Visit	Location	Date(s)
R. Diefendorf G. Dvorak R. Loewy S. Sternstein	Discussion of Langley R. C. research program in composites	NASA Langley R.C. Hampton, VA	11/3/86
R. Loewy	Discussion of Composites research with Dr. M. Greenfield	NASA HDQS Washington, DC	11/19/86
R. Loewy	Discussion of Composites research with Drs. A. Amos, G. Haritos and M. Salkind	AFOSR HDQS Washington, DC	11/19/86
R. Loewy	Discussion of Composites research with Dr. D. Mulville	NASA HDQS Washington, DC	1/12/87
R. Diefendorf G. Dvorak R. Loewy S. Sternstein	Discussion of Composites research programs at Lewis R.C.	NASA Lewis R.C. Cleveland, OH	2/6/87

During the week of July 21-25, 1986, RPI offered, for the seventh time, a special short course in composite materials and structures. Seventeen graduate engineers from government and industry enrolled. In addition to the RPI speakers shown in Table III-3, Prof. L. Phoenix of Cornell University, Mr. Bob Riley of McDonnell Aircraft and Dr. Stephen Tsai of the Air Force Material Laboratories lectured. The announcement brochure, listing lecturers and the subject matter is attached as an appendix to this report, and the participants and their organizations are listed in Table III-7.

The international workshop on composite materials and structures for rotorcraft, also shown in Table III-3, was conducted at RPI on 9/10-11/86 at the suggestion of the Army Research Office. A list of attendees, including 61 representatives of industry, government and academia, is shown in Table III-8 and the agenda for the workshop is appended. This by-invitation-only meeting was considered sufficiently successful that follow-on workshops are being considered for future years.

Table III-7

COMPOSITE MATERIALS AND STRUCTURES PROGRAM

Short Course: Composite Materials and Structures
Participants and Affiliations

July 21, 1986 through July 25, 1986

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Burlington, VT 05402

Robert Filler
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McDonnell Douglas Helicopter Co.
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Gainesville, VA 22065

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Carl Husen
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Donald Johnson
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Contraves Goerz Corp.
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Brian McKillop
Engineer
Fiber Materials, Inc.
Biddeford Industrial Park
Biddeford, ME 04005

Steve Nelson
Stress Engineer
Heath Tecna Aerospace Co.
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Kent, WA 98032

Eric Preissner
Aerospace Engineer
Naval Air Development Center
Code 6055
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Eric Rahnenfuehrer
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Richard Soloski
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Allan Stanley
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Table III-7 (continued)

COMPOSITE MATERIALS AND STRUCTURES PROGRAM

Short Course: Composite Materials and Structures
Participants and Affiliations

July 21, 1986 through July 25, 1986

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Max Young
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Table III-8

COMPOSITE MATERIALS AND STRUCTURES PROGRAM

RPI Workshop on Composite Materials and Structures for Rotorcraft

Rensselaer Polytechnic Institute
Rotorcraft Technology Center

September 10 & 11, 1986

Attendees

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Mr. Boaz Avitzur
Watervliet Arsenal
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US Army Aerostructures Directorate
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Rensselaer Polytechnic Institute
Troy, NY 12181

Prof. Marco Borri
Cntr for Advancement of Computational Mechanics
Georgia Institute of Technology
School of Civil Engr
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Washington, DC 20332

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Hampton, VA 23665

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PART IV

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REFERENCES

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PART V

PERSONNEL, AUTHOR INDEX

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Wiberley, Stephen E., Ph.D.	Professor and Chairman of Chemistry

Senior Investigators

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Diefendorf†, R. J., Ph.D. (Fabrication, resin matrix, fiber behavior, interfaces)*	Professor of Materials Engineering
Dvorak†, G., Ph.D. (Metal matrix composites, damage, fracture & fatigue of composites)*	Professor and Chairman of Civil Engineering
Krempl, E., Dr.Ing. (Fatigue studies, failure criteria)*	Professor of Mechanical Engineering, Aeronautical Engineering & Mechanics and Director of Cyclic Strain Laboratory
Shephard, M. S., Ph.D. (Computer graphics, finite element methods)*	Associate Professor of Civil Engineering and Associate Director, Center for Interactive Computer Graphics
Sternstein†, S. S., Ph.D. (Failure analysis, matrix behavior, moisture effects)*	William Weightman Walker Professor Polymer Engineering

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† Member of Budget Committee together with Co-Principal Investigators

AUTHOR INDEX

RPI WORKSHOP ON COMPOSITE MATERIALS AND STRUCTURES FOR ROTORCRAFT

FINAL PROGRAM SCHEDULE

9/10/86
8:15-8:45 **WELCOME** - *Dr. Judd Diefendorf*

KEYNOTE ADDRESS: ***Dr. Wolf Elber***, Chief Materials and Structures Area, U.S. Army AATD, Hampton, Virginia "Communication-Integration: Keys to Getting There"

Session I: CHAIRMAN - ***Samuel Garbo (Sikorsky Aircraft)***
Rotor Technology

8:45-10:15

*"Structural Analysis and Test Verification of A Bearingless Main Rotor", *K. Pfeifer and M. Adam*, Messerschmitt-Boelkow-Blohm Gmbh, Munich, Germany.

*"Composite Rotors at MDHC", *R. Murrill and M. Frengley*, McDonnell Douglas Helicopter Co., Tempe, Arizona.

"Finite Element Modeling of Composite Rotor Blades with Finite Rotation and Warping Effect", *A. D. Stemple, Y. H. Kim and S. W. Lee*, University of Maryland, College Park, Maryland.

10:15-10:30 **B R E A K**

Session II: CHAIRMAN - ***Lawrence Rehfield (Georgia Institute of Technology)***
Rotors: Tension/Torsion Coupling and Tailoring

10:30-12:30

"Tension/Torsion Coupling in Composite Rotors", *S. Winckler*, Center for Rotorcraft Technology, Rensselaer Polytechnic Institute, Troy, New York.

"Application of Composite Materials for Improved Rotor Blade Performance", *M. W. Nixon*, Aerostructures Directorate, AVSCOM, Langley Research Center, Hampton, Virginia.

"Experimental Identification of Stiffness Coupling Terms for a Composite Blade Spar", *A. A. Salzberg and I. Chopra*, University of Maryland, College Park, Maryland.

*"Experimental Investigations of the Torsional Stiffness of Axially Loaded Isotropic and Composite Beams", *M. Degener*, DFVLR, Braunschweig, Germany.

***INVITED PAPERS**

12:30-1:45 **L U N C H**

LUNCHEON ADDRESS: ***Kenneth Grina***, Vice President Engineering, Boeing-Vertol
"The Composite Helicopter: One Industry View"

Session III: CHAIRMAN - ***William Harris (McDonnell Douglas Helicopter Co.)***
Airframe Performance Life and Crash Worthiness

1:45-3:45 *"Technology of Sikorsky's ACAP", *J. Goldberg*, Sikorsky Aircraft, Stratford, Connecticut.

*"Application of Composites to the Multi Service V-22 Osprey", *D. Hart*, Boeing Vertol, Philadelphia, Pennsylvania.

"ACAP Safety-of Flight Experience Relating to Qualification of Composite Airframes", *D. T. Deibler*, Aviation Applied Technology Directorate, U.S. Army Aviation Research and Technology Activity, Fort Eustis, Virginia.

"Crash Energy Absorbing Composite Helicopter Structure", *G. L. Farley*, Aerostructures Directorate, AVSCOM, Langley Research Center, Hampton, Virginia.

3:45-4:00 **B R E A K**

Session IV: CHAIRMAN - ***Robert Pinckney (Boeing Vertol)***
Generic Structural Elements

4:00-6:00 "Evaluation of Composite Components on the Bell 206L and Sikorsky S-76 Helicopters", *D. J. Baker*, Aerostructures Directorate, AVSCOM, Langley Research Center, Hampton, Virginia.

"Postbuckled Composite Panels", *L. L. Levine*, Structure Technology, Sikorsky Aircraft, Stratford, Connecticut.

"Postbuckled Composite Primary Structure: Creating the Technology Base", *L. W. Rehfield, A. D. Reddy and W. K. Daniel*, Center for Rotary Wing Aircraft Technology, Georgia Institute of Technology, Atlanta, Georgia.

"Supercritical Composite Shafts", *M. S. Darlow*, Center for Rotorcraft Technology, Rensselaer Polytechnic Institute, Troy, New York.

6:00-6:30 **TRAVEL to TROY CLUB**

6:30 **C O C K T A I L S   A N D   B A N Q U E T**

BANQUET SPEAKER: ***Mike Dubberly***, U.S. Naval Systems Command, Washington, D.C.
"Composite Structures on Navy Rotorcraft"

***INVITED PAPERS**

Session V: CHAIRMAN - **Reis Alsmiller (Bell Helicopter)**
Fatigue and Damage Tolerance

9/11/86
8:15-10:15 *"Fatigue Qualification Requirements for Composite Structures in Army Rotorcraft", *R. Arden*, AVSCOM, St. Louis, Missouri.

"The Sensitivity of Kevlar/Epoxy and Graphite/Epoxy Structures to Damage from Fragment Impact", *P. A. Lagace and D. S. Cairns*, Technology Laboratory for Advanced Composites, Dept. of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, Massachusetts.

"Damage Tolerance of Composite Structures", *O. A. Bauchau*, Center for Rotorcraft Technology, Rensselaer Polytechnic Institute, Troy, New York.

"Toughness and Impact Resistance of Three-Dimensionally Braided Fiber Reinforced Metal Matrix Composites", *A. P. Majidi and T. W. Chou*, Center for Composite Materials, University of Delaware, Newark, Delaware.

10:15-10:30 **B R E A K**

Session VI: CHAIRMAN - **Leonard Marchinski (duPont)**
Delamination and Fracture Toughness

10:30-12:30 "Delamination Durability of Composite Materials for Rotorcraft: Analysis, Characterization and Design", *T. K. O'Brien*, Aerostructures Directorate, AVSCOM, Langley Research Center, Hampton, Virginia.

"Analysis, Prediction and Prevention of Edge Delamination in Rotor System Structures", *W. S. Chan* and L. W. Rehfield***, *Bell Helicopter Textron, Inc., Fort Worth, Texas and **Georgia Institute of Technology, Atlanta, Georgia.

"Delamination in Tapered Composite Structures under Tensile Loading", *J. C. Fish and S. W. Lee*, Department of Aerospace Engineering, University of Maryland, College Park, Maryland.

"Comparison of Fracture Toughness of Carbon Fiber/J-1 Thermoplastic Matrix to Carbon Fiber/Epoxy Matrix Composites after Ballistic Penetration", *W. G. Degnan*, Sikorsky Aircraft, Stratford, Connecticut.

12:30 **L U N C H**

A D J O U R N

***INVITED PAPERS**