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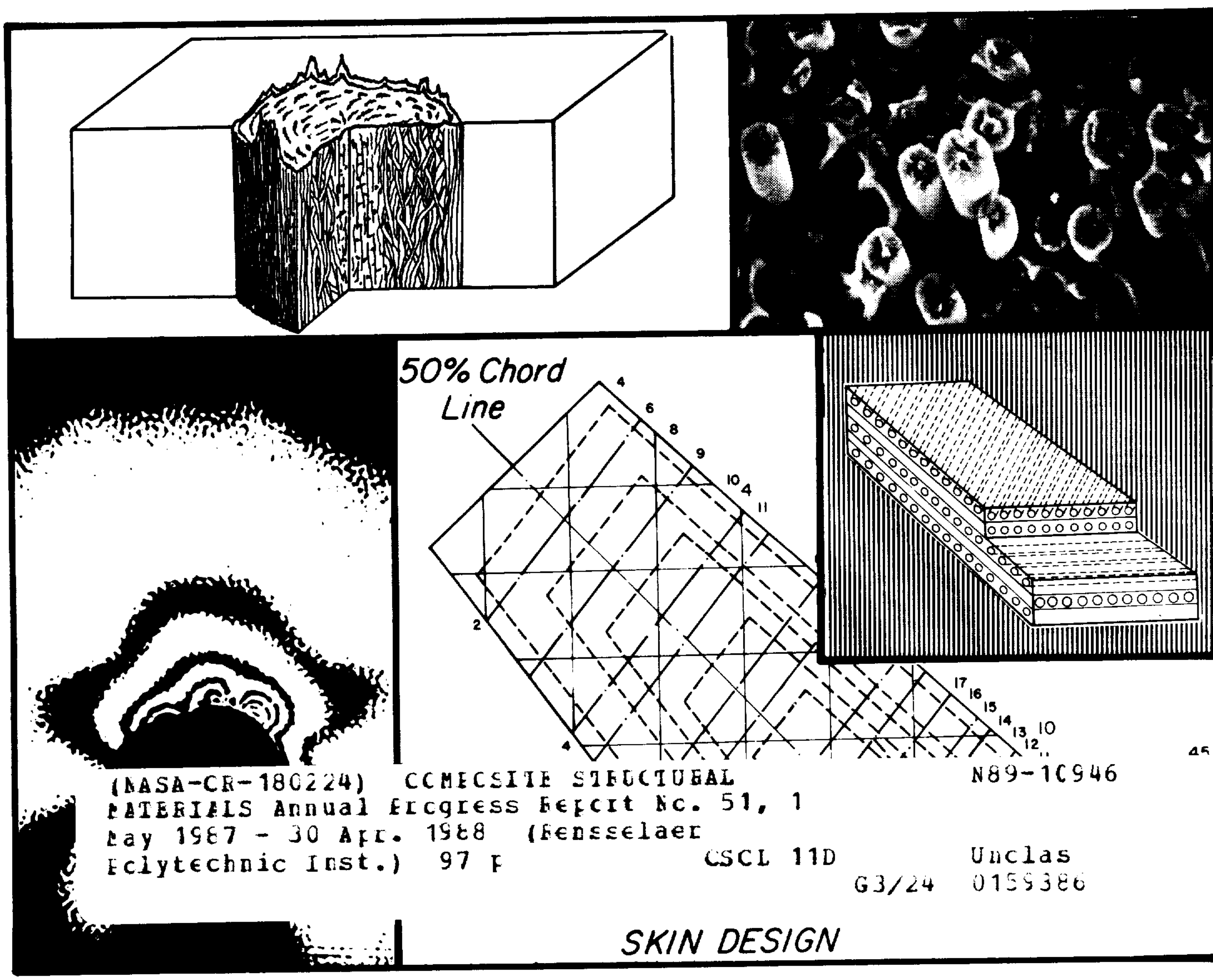

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May 1, 1987 through April 30, 1988

COMPOSITE STRUCTURAL MATERIALS

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PART I

INTRODUCTION

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INTRODUCTION

NASA and AFOSR, as part of a broad research initiative in composites, have sponsored a decade-long program at Rensselaer whose purpose has been to develop critical advanced composites technology in the areas of physical properties, structural concepts and analysis, manufacturing, reliability and life prediction. Specific goals in this program have changed over the years 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.

The overall concept of RPI's program has been unusual for a university in several important aspects. First, the nature of the program has been comprehensive. A relatively few, carefully chosen areas of investigation have been probed in depth, but, taken together, they provide coverage of a wide spectrum of composite materials and structures issues. Among earlier projects dropped are those investigating the behavior of generic structural elements, new methods of non-destructive inspection, fabrication science and technology and applicable, generally useful computer methodology developments. On the other hand in the later years of the program the expansion of temperature ranges has added a new dimension to the spectrum of composite issues.

Second, interactions among faculty contributing to program objectives have been 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 has been largely at the working level, and administrative, scientific and technical decisions made, for the most part, independent of considerations normally associated with academic departments. This kind of involvement over the years of the program included faculty, staff and students from chemistry, civil engineering; electrical, computer and systems 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, developed increasingly in the program's later years, is the interaction between appropriate members of NASA's staff of Research Center scientists and engineers and those active in the program at RPI. This required identification of individual researchers within NASA centers whose areas of interest, specialization and active investigation are in important ways related to those of RPI faculty supported under the subject grant. A program of active interchange was then encouraged and the means by which such interaction could be fostered was sought. Benefits which resulted 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 has been 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 has been a multi-faceted program planned and managed so that some of the best and brightest students would be drawn into the study of advanced structural composites, and so that they and scientists and engineers in a number of pertinent disciplines at RPI would interact, both among themselves and with counterpart NASA Center researchers, to achieve its goals. Research in the 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.

As new directions were added to RPI's program, particularly with limited funds and personnel, older ones needed to be dropped even though useful advances were being made in those projects. A number of studies involving the older resin matrix manufacturing processes, directionally solidified eutectics, and a continuum theory description of edge-initiated delamination failures have all been phased out over the past three years. In the last year, 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; eg those fibers and matrices capable of maintaining structural integrity at higher temperatures. Issues related to the fabrication of non-resin matrix composites and the micro, mezzo and macromechanics of thermoplastic and metal matrix composites also have been emphasized.

Following a site visit by NASA on 10/6-7/87 (see Appendix A for agenda and list of attendees) Rensselaer was told that NASA would phase out the subject program in favor or pursuing new university research program initiatives. Accordingly, there would be no new funding under the subject grant, and it would on May 1, 1988 enter a transition phase the implementation of which was the original intent of the three-year step funding arrangement.

The progress made on the subject grant under its last year, ie from May 1, '87 to April 30, '88 is reported in the following pages. That research is in accordance with the final proposal under the subject grant, NGL-33-018-003, RPI number 389(71R)104(1B), entitled "Interdisciplinary Materials Research".

PART II

RESEARCH

II RESEARCH

A. STUDIES OF CHEMICAL VAPOR DEPOSITION EFFECTS ON CARBON FIBER PROPERTIES AND OF ASSOCIATED PROCESSES

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 two fold: to determine the effects of carbon layers, established by chemical vapor deposition (CVD), on the mechanical properties of pitch-based carbon fiber and to investigate means of manufacturing carbon/carbon structural elements. One specific question is the extent to which a carbon coating can fill or "heal" those surface flaws which contribute to low stress failures. Perhaps more realistically what could occur is a "blunting" of preexisting crack tips. Another concern was to determine if, using various deposition parameters, a decrease in the interlayer compliance could be achieved, thereby contributing to better transverse properties, higher modulus and increased strain to failure. Finally, the effect of the structure of the carbon coating on fiber properties was studied by using different deposition gases.

STATUS

Carbon fibers, made from a pitch precursor, are becoming increasingly important because they can be produced with a wide range of desired mechanical properties. However, these fibers, and carbon fibers in general, suffer from premature failure due to the presence of surface flaws. Also, the inherently low interlayer shear strength of graphite contributes to poor transverse shear strength of the fiber. Higher final heat treatment temperatures, used to increase the fiber modulus, cause microstructural changes in the fiber and affect preferred orientation and crystallite stack height. The two parameters increase in a parallel fashion, and while the former contributes to higher modulus values, unfortunately the latter contributes to lower interlayer coupling and lower strength.

A chemically vapor deposited coating of carbon is often used to rigidize a three dimensional weave of carbon fibers in preparation for matrix impregnation during the production of carbon/carbon composites. While some work has dealt with carbon coated fibers and brittle surface deposits, the effects that these treatments have on fiber structure and properties have not been studied. The importance of understanding these changes in relation to composite performance cannot be overlooked, since properties generally are estimated from the constituent properties measured before processing.

Typical C/C samples and components are produced using woven carbon fiber fabric. The use of woven cloth allows easy fabrication of flat plates and other such component parts. However, producing tubes from woven cloth results in a part with a seam. While this can be compensated for during the design process, a more elegant and structurally sound solution is to form the fiber preform using filament winding or braiding.

During the preceding period, CVD-single carbon fiber experiments with various furnace parameters and gases showed that modulus improvements were obtained, with proper dwell times and temperatures in either methane or dicyclopentadiene, and that these improvements were more a function of coating structure than coating or "sheath" thickness.

PROGRESS DURING THE REPORTING PERIOD

Dupont E-294 pitch-based carbon fibers were used as substrates for most of the continuing deposition work. It has a characterized radial structure and known surface flaw types. A jig was manufactured to enable deposition to occur on either single fibers or groups of filaments (tows). Parametric variations such as temperature, pressure, gas flow rates, and time of treatment were extended to gain better understanding of the penetrative ability of the gas into the fiber and also the microstructure of the deposit. Additional single filament tensile testing was carried out to determine mechanical properties; and SEM, X-ray, and optical microscopy were utilized to determine surface topology and deposition microstructure. Table II-A-1 identifies the CVD runs performed, and the average of mechanical properties measured in tests on the resulting fibers. In this table, t is run time, T deposition processing temperature, P chamber pressure (in Torr), F reactive gas flow (Chemical formulae for the gas used is shown immediately following the flow-rate number), E is the average of the measured Young's modulus, σ the

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RUN #	t (hr)	T (C)	P (tr)	c (sccm)	E (Msi)	σ (ksi)	ef	DIA. (μ)
UNTREATED	-	-	-	-	30.2 + 2.0	292 + 28	0.01	10.2 + 0.3
DT051586	1	1000	2	50 CH4	29.0 + 2.3	309 + 46	0.01	10.1 + 0.5
DT051586	1	1000	2	50 CH4	26.9 + 0.9	237 + 45	0.009	7.36 + 0.3
T-300 DT052086	3	1000	2	50 CH4	50.8 + 4.9	293 + 45	0.005	11.4 + 2.1
DT052186	2	1000	2	50 CH4	30.9 + 2.0	322 + 43	0.01	11.1 + 0.4
DT061986	10	1000	2	50 CH4	32.0 + 2.7	330 + 36	0.01	10.9 + 0.3
DT062586	4	900	2	50 CH4	30.0 + 1.6	321 + 40	0.01	10.4 + 0.9
DT070186	7	900	2	50 CH4	26.6 + 2.1	316 + 48	0.01	10.4 + 0.7
DT070286	7	800	2	50 CH4	30.8 + 1.8	241 + 62	0.008	11.3 + 0.4
DT070886	4	1000	2	50 CH4	28.1 + 3.3	290 + 36	0.01	10.8 + 0.6
DT071086	10	900	2	50 CH4	27.0 + 3.1	307 + 45	0.01	10.5 + 0.5
DT072186	1	1100	2	50 CH4	22.7 + 2.9	214 + 31	0.009	10.6 + 0.8
DT072286	3	1000	2	50 CH4	29.7 + 2.1	284 + 59	0.01	10.9 + 0.8
DT080686	3	1000	0	0	12.0 + 1.9	246 + 37	0.02	10.7 + 0.8
DT100186	3	1000	2	50 CH4	25.0 + 1.9	199 + 30	0.008	10.0 + 0.4
DT100986	3	1000	5	1500 H2				
DT101386	3	1100	5	1500 H2				
DT012487A	1	1100	2	50 CH4	24.8 + 1.4	149 + 31	0.006	10.3 + 0.8
DT012487B	1	1600	1	50 CH4	47.2 + 6.1	373 + 58	0.007	11.2 + 0.5
DT012587	3	1000	1	100 CH4	28.2 + 0.9	340 + 34	0.012	10.0 + 0.3
DT012687	3	1000	2	50 CH4	30.0 + 1.5	326 + 40	0.011	10.6 + 0.8
FELTED DT012687	3	1000	2	50 CH4	29.6 + 1.7	299 + 40	0.01	10.8 + 0.8
DT020487	1	1600	0	0	45.9 + 1.4	292 + 25	0.006	9.5 + 0.4
DT020987	3	1000	0.5	800 CH4	24.9 + 3.1	200 + 33	0.008	10.5 + 0.5
DT021287	2	1000	10	1000 CH4 6900 H2	25.3 + 2.0	180 + 32	0.007	10.4 + 0.8
DT021787	0.02	1000	10	6000 H2	30.0 + 2.6	276 + 44	0.009	10.1 + 0.7
DT022187	0.25	1000	10	6750 H2	25.0 + 1.8	154 + 49	0.006	10.6 + 1.0
E-294 DT022187	0.25	1000	10	6750 H2	27.0 + 3.5	193 + 55	0.007	11.0 + 0.4
CONTROL DT022387	1	1000	200	300 CH4	31.0 + 2.2	313 + 39	0.009	10.8 + 0.7
DT022587	4	1000	0.2	50 CH4	27.0 + 3.5	206 + 39	0.007	10.5 + 0.6
DT022887	0.85	1600	1	50 CH4	40.5 + 7.6	272 + 56	0.007	11.2 + 1.2
DT032187	0.12	1600	2	50 CH4	37.3 + 4.5	230 + 40	0.006	10.3 + 0.5
E-294 DT032187	0.12	1600	2	50 CH4	38.2 + 4.1	126 + 32	0.003	10.3 + 0.4
SPB-066 DT032587	1.8	1000-1600	2	50 CH4	45.0 + 4.4	300 + 22	0.007	11.0 + 1.0
DT032687	1	1000	2	C10H8	28.4 + 1.6	232 + 31	0.008	10.5 + 0.4
DT041387	6.3	1000	5	C10H8	25.7 + 4.2	129 + 51	0.005	9.21 + 0.6
DT042787	4	1000	5	2C5H6	27.8 + 2.4	291 + 28	0.01	11.4 + 0.7
DT042887	3.5	1000	150	2C5H6	23.8 + 4.6	27 + 2.5	0.001	10.9 + 0.7
DT042987	3	1600	2	2C5H6	75.2 + 5.8	219 + 88	0.003	9.46 + 0.5

Table II-A-1: Summary List of CVD Treatments and the Average Results of Experiments Performed average of the ultimate tensile stress, e_f the corresponding strain at failure, and DIA, the average of the fiber diameters measured following CVD.

In some treatments that did not show evidence of a surface coating, increased average values of strength were observed. These results can be attributed to the filling or "healing" of inherent surface cracks in the pitch-based carbon fibers. Other strength improvements occurring in treatments with coatings of disceribIe thickness could be attributed to the "sheath" effect. One treatment in particular showed a large increase in average strength.

It is interesting to consider the strength of individual filaments prepared using the same CVD process, as shown in Fig. A-1. Compared to the average strength value for the untreated fiber of 292 ksi, some very high strengths were measured. Since strength decreases with increasing diameter, while strain to failure, e_f, remains fairly constant (See Figs. A-1 and A-2), it seems it is the initial layer that improved strength. This coating showed little evidence in SEM analysis, of brittle behavior. The possibilities associated with a coated fiber regarding strength are:

$$e_{f,\text{coating}} < e_{f,\text{fiber}} \quad \begin{cases} \text{good adherence - strength reduced} \\ \text{poor adherence - no effect} \end{cases}$$

$$e_{f,\text{coating}} > e_{f,\text{fiber}} \quad \begin{cases} \text{good adherence - strength improved} \\ \text{poor adherence - non-detrimental} \end{cases}$$

The coating in run #0124B (see Table II-A-1) appears to have a strain to failure greater than that of the underlying fiber; it therefore seems that the fiber's strain to failure, and thus its strength, was increased.

From the above it appears that "sheath effect" is an appropriate model to explain mechanical property changes caused by a discernible surface coating. Adherent and brittle surface coatings of measurable thickness lead to reduced strength values. Coatings with little adherence or those that do not exhibit brittle behavior result in no adverse property effects or, in some cases, in improved fiber strength and strain to failure.

Deposition that does not form measurable coatings improves strength and strain to failure, probably by filling and "healing" fiber surface flaws.

The combination of these effects indicates the potential for improvement of the in-situ carbon fiber properties over those of the fiber itself. This property enhancement may yield improvements in both the strength and strain to failure of carbon fiber composites.

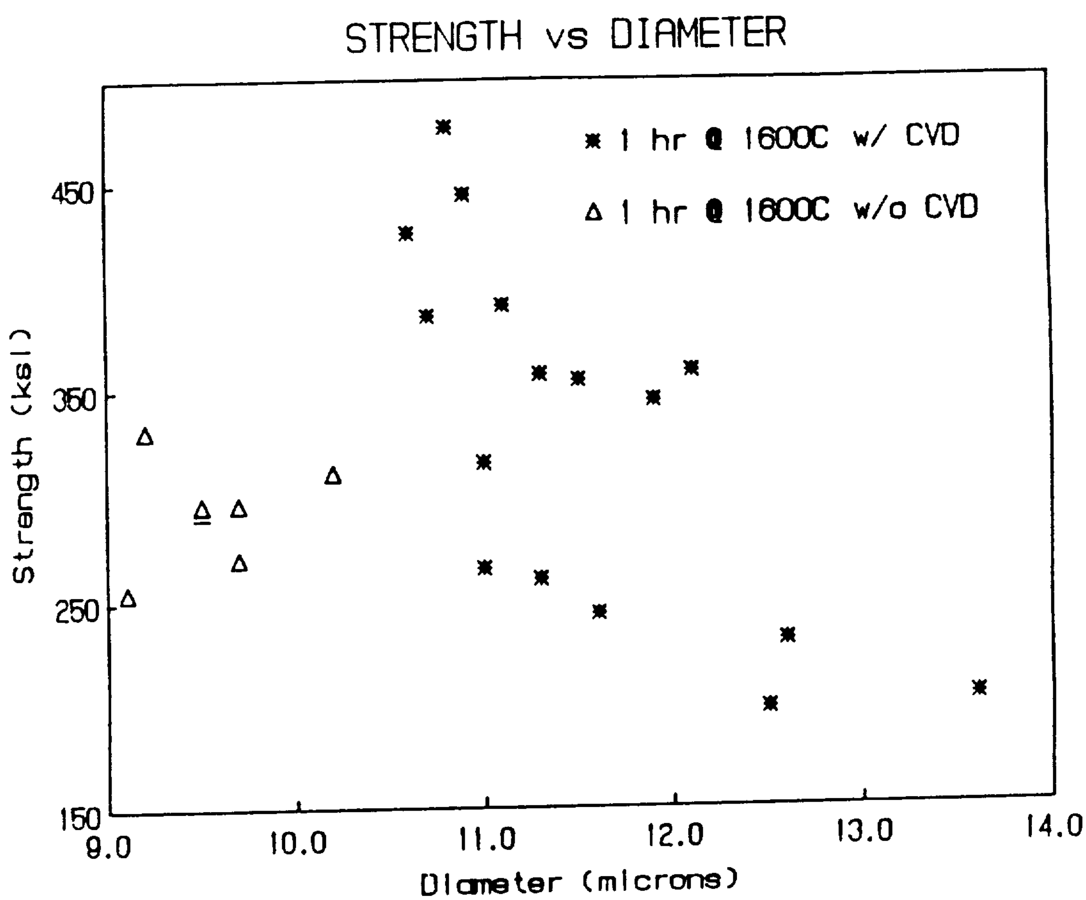

Fig. A-1 Strength vs Diameter Data for Treatment #0124B and #0204. (Deposition took place at time and temperature indicated with 1 torr total pressure and 50 sccm flow of Methane.)

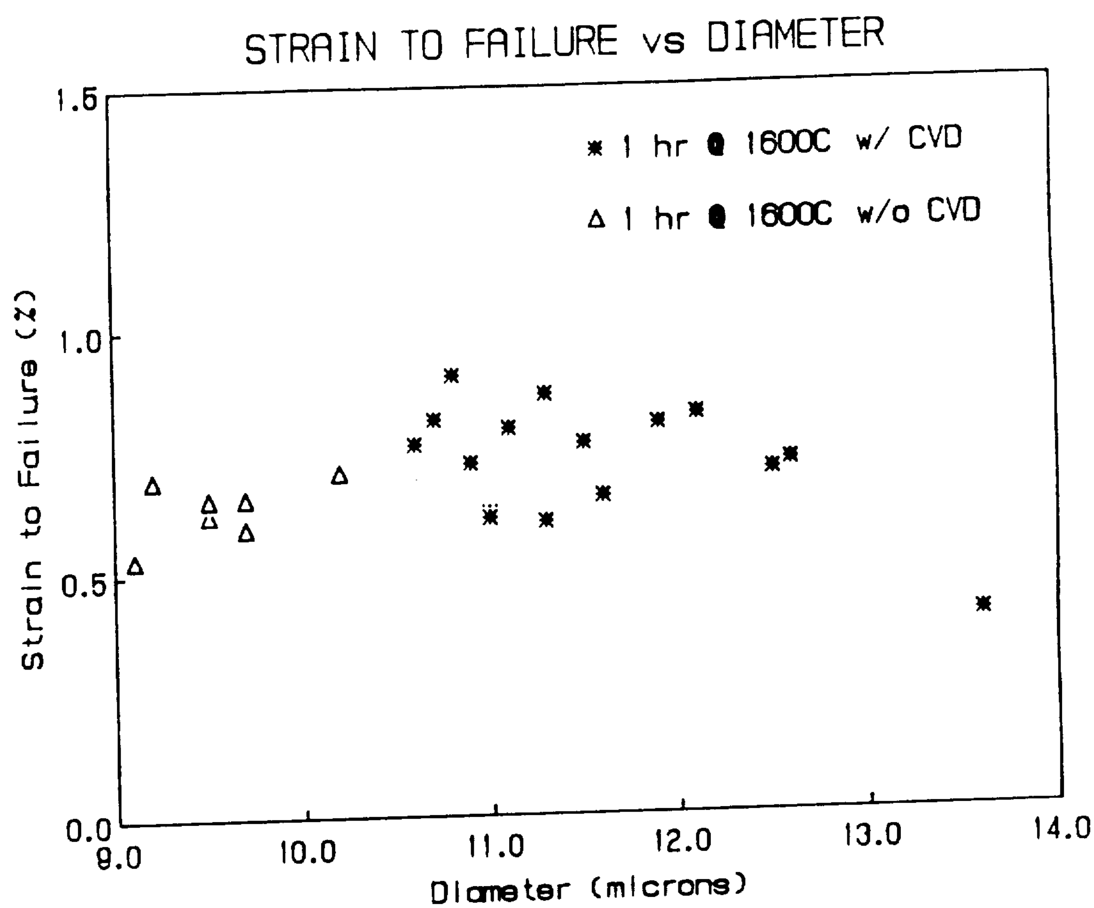

Fig. A-2 Strain to Failure vs Diameter Data for Treatment #0124B and #0204. (Deposition took place at time and temperature indicated with 1 torr total pressure and 50 sccm flow of Methane.)

For the fabrication studies, filament winding was used to produce a fiber preform of a carbon/carbon tube. Other than the obvious advantage of being able to produce seamless tubes, this approach also promises greater speed of preform manufacture and better control over fiber orientation and position. Using carbon fiber tow involves much less expense than woven cloth, and also allows the introduction of fibers which are not readily available in woven form. Many of the newest high strength/high modulus fibers are not yet available in woven form, nor are they likely to be easily woven in the future, due to their extreme mechanical properties.

Filament winding with dry fiber eliminates polymer binder/precursors to hold the individual preform plies together during initial chemical vapor deposition. This technique ensures pure carbon matrix material at the fiber/matrix interface, and allows the interface region to be modified without concern for impurities related to the pyrolysis of a polymer binder.

The tubular geometry also has other advantages. It is well suited to mechanical testing in which various combined loading states are required. It has no free edges, thus easing analysis and allowing more accurate test results. Since the response of C/C in a variety of environments is also a major consideration, the tubular test specimen facilitates an internal environment. Finally, the tubular geometry lends itself well to the CVI process. The gas flow pattern in a furnace of cylindrical geometry allows uniform densification of tubular samples. Thus, this seemingly complex geometry can actually be as easy or easier to infiltrate and densify than a flat woven plate.

Holding the preform in the correct shape without a binder requires that the mandrel must be left in place during deposition. Mandrel material must then be capable of temperatures beyond 1500C and be non-reactive with the composite being produced. Extruded graphite rods were thus used as mandrels, initially 12" in length and 1" in diameter.

A tube was first produced using only dry graphite lubricant as a release agent. The resulting tube, which was not fully densified, could not be removed from the graphite mandrel. As a replacement for the dry graphite lubricant release agent, a sheet form of graphite was chosen. This sheet material, "Grafoil", manufactured by Union Carbide, was obtained in a 0.010" thickness. Grafoil is an oriented graphite sheet material with a very metallic look due to a high degree of in-plane orientation. This orientation means that bonding to the surface is difficult, and that even if surface bonding occurs, shear within the sheet should facilitate release. The principal concern with the use of this material was the possible rigidization of the structure during the processing. This concern proved to be unfounded, however, and Grafoil provided a positive release mechanism for all the tubes produced subsequently.

Grafoil was wrapped around the mandrel, with no overlap, prior to filament winding. The preform was then wound over the Grafoil, using a predetermined fiber angle and winding program. Winding was accomplished on a McClean-Anderson W-70 filament winder. The first tube wound over Grafoil was strictly a test of the Grafoil as a release material and as such was produced with three differing thicknesses. This variation in thickness along the tube length was to allow investigating the depth of carbon penetration during infiltration. The following three tubes with a fiber orientation of $\pm 45^{o}$ were all produced using a single bundle coverage on the mandrel. While the middle 5" of each tube was of uniform thickness, each end was built up in a taper. This taper started at the tube wall thickness (~0.025") and increased to ~0.25" at the tube end. The taper was included to model the grip arrangement necessary for use in tension-torsion testing. Upon completion of each wind, the mandrel was cut to 8" in length to allow insertion in the CVD vessel, and the preform and mandrel were positioned in the graphite resistance heated furnace. All runs used a pressure of 5Torr and a methane flow rate of 1000sccm. The processing temperature was varied from 1300C to 1500C and dwell times from 3 hours to 15 hours. A total of four tubes were produced to show the feasibility of this technique.

The results of attempts to wind tube preforms from carbon fiber tow were generally positive. Two fiber types were used to show the practicality of incorporating both a common high strength fiber (Celion 3000) and a new ultra high strength fiber (Toray T1000). Use of Celion 3000 showed that the technique is appropriate for common fiber types; the use of Toray T1000 shows the previously mentioned potential for utilizing and testing new generation fibers not normally found in C/C composites.

During the winding process, considerable care was taken to minimize fiber breakage. Even so, the amount of breakage which did occur had to be dealt with after the densification step. Two different wind patterns were chosen for the two Celion 3000 samples to show the variation in the effective weave available using filament winding.

Deposition of the carbon matrix was accomplished in a two step operation. First the filament wound preforms were run for 7 hours at 1300°C/5Torr/1000sccm, followed by 4 hours at 1500°C/5Torr/1000sccm. These parameters were chosen to minimize the time necessary to densify these prototype tubes to an accepable level. They were not intended as providing optimum mechanical properties or infiltration. The initial 7 hours was intended to give adequate infiltration; the 4 hours at 1500°C was included to quickly lay down a surface coating.

Upon completion of the initial densification, the tubes did not have a smooth outer surface due to the fiber breakage which occurred during winding. These broken fibers were subsequently removed by light sanding while the tube was chucked in a lathe. At the same time the end tapers were machined to final tolerance and angle. Following this machining operation the tube and mandrel were again placed into the furnace and another run of 4 hours at 1500°C/5Torr/1000sccm was performed. The final tube was easily removed from the graphite mandrel, leaving the layer of Grafoil in place on the inner surface of the tube.

All tubes are relatively rigid and show good densification in the thin test area. The end tapers, which are up to 0.25" thick, are not completely infiltrated but are sufficiently dense for demonstration purposes. Different manufacturing techniques or deposition parameters are necessary to give complete densification of these thicker sections. The final thickness of the tubular section (discounting the Grafoil) is approximately 0.025".

PLANS FOR THE UPCOMING PERIOD

The results showing improved fiber properties as a result of extremely thin deposited coatings indicate that a micro-composite introduced at the fiber/matrix interface may substantially improve the strain to failure of the overall composite. Chemical vapor deposition allows such discrete coatings to be applied under controlled conditions. Thus, in the future, CVD work investigating multiple, fine interlayers will be pursued.

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

"Correlation of Stack Height in Mesophase and Isotropic Pitches", with K. J. Chen, Proceedings of the XVIIIth Biennial Conference on Carbon, Worcester, MA, pp. 527-528, July 19-24, 1987.

"Deformation Modes in Carbonaceous Mesophase", with K. J. Chen and D. F. Taggart, Proceedings of the XVIIIth Biennial Conference on Carbon, Worcester, MA, pp. 413-414, July 19-24, 1987.

"Preferred Orientation of Mesophase Pitch", with K. J. Chen, Proceedings of the XVIIIth Biennial Conference on Carbon, Worcester, MA, pp. 292-293, July 19-24, 1987.

"Carbon/Graphite Fibers", Engineered Materials Handbook, Vol. I - Composites, ASM International, pp. 49-53, Nov. 1987.

"Continuous Carbon Fiber Reinforced Carbon Matrix Composites", Engineered Materials Handbook, Vol. I - Composites, ASM International, pp. 911-914, Nov. 1987.

"Asymmetric Composites", with D. W. Radford and S. J. Winckler, Kovove Materialy 26 - Bratislava, Czechoslovakia pp. 209-213, February 1988.

B. INELASTIC DEFORMATION OF METAL MATRIX LAMINATES

Sr. Investigator: E. Krempl

INTRODUCTION

The overall behavior of purely elastic, anisotropic composite laminates under combined stretching and bending deformations is frequently modeled by classical laminate theory[1]*. The present research has the objective of introducing a simplified orthotropic viscoplasticity theory (VBO)[2] which is intended as a replacement for the orthotropic elasticity theory in lamina analysis. Included in the phenomena to be modeled are rate dependence, creep, relaxation and tension-compression asymmetry. These phenomena can all be found in the mechanical behavior of metal matrix composites.

STATUS

The senior investigator and his students have used the unified viscoplasticity theory based on overstress to generate effective constitutive models for the nonlinear, multiaxial, time dependent, and tension-compression asymmetric behavior of composite laminates [2-4]. A simple inelastic laminate theory, called AVBOL, was specially developed to describe the isothermal, in-plane deformation behavior of metal matrix composite laminates[3] using the orthotropic viscoplasticty theory described in Ref. 2. No yield surfaces and no loading/unloading conditions are used.

PROGRESS DURING REPORTING PERIOD

The simple inelastic laminate theory (AVBOL) for in-plane loading using the viscoplasticity theory based on overstress [3] has now been extended to the flexural behavior of metal matrix composite laminates and will be described in a forthcoming report [5]. In a manner similar to the classical laminate theory, any lay-up may be considered in this new theory to contribute to the relations between bending moment and plate curvature. In addition, however, the present theory includes the modeling of creep, relaxation, rate sensitivity and tension-compression asymmetry.

* References are found in the list shown on page 77 of this report.

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Material constants and functions of the theory were determined for Borsic/Al ply[3] and are the basis for the predictions of the bending behavior shown in Figs. B-1, B-2 and B-3. In Fig. B-1 the moment-curvature relation for a constant rate of curvature $\overset{o}{K}_1 = 0.1\ (ms)^{-1}$ is shown for a $[\pm 45]_s$ lay-up. The resulting stress-strain curves in the directions of the $+45^o$ ply and the -45^o ply are depicted in Fig. B-2. The behavior of the same lay-up in a four-point bending test is shown in Fig. B-3. In this case, the load rate, $\overset{o}{P}$, which leads to a linearly increasing moment, is prescribed. These predictions could be checked against experiments; unfortunately none appear to be available.

In Ref. 3 the tension off-axis behavior of Borsic/Al was simulated by the theory. It was shown that the theory is capable of reproducing the behavior found in Ref. 6 (see also the last progress report on this grant; August '87.) Since then, two other papers on stress-strain behavior of metal matrix composites were located in the literature. Ref. 7 reports on the tension and compression off-axis behavior of FP/Al at room temperature. Figs. B-4 through B-7 show the simulation of this test by AVBOL. It can be seen that the theory reproduces the tension-compression asymmetric and off-axis behavior very well.

Experiments using B/Al specimens were reported in Ref. 8. Included are the measurements of transverse strains and zero-to-tension (R = 0) cycling. The simulations for these tests are reported in Fig. B-10. Of particular significance is the observation that AVBOL, which assumes constant Poisson's ratio, does provide a good fit to the data, see Fig. B-9. Fig. B-10 shows that the simulations of zero- to-tension cycling by AVBOL are comparable to the plasticity theory used in Ref. 8.

PLANS FOR THE UPCOMING PERIOD

The Anisotropic Viscoplasticity Theory Based on Overstress will be developed further to include cyclic hardening or softening behavior at the ply level. We anticipate running several numerical examples to illustrate the applicability of the theory.

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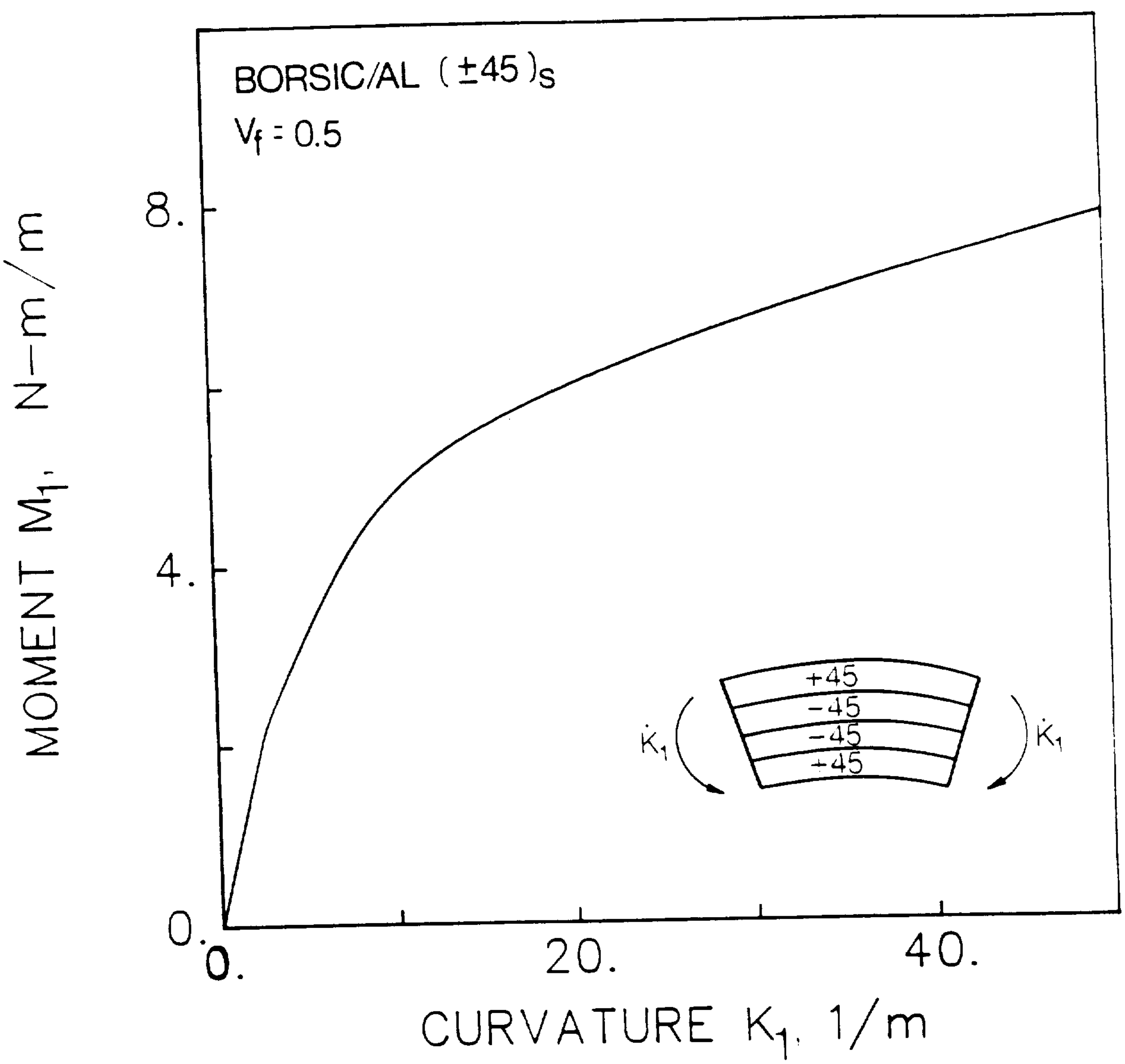

Fig. B-1 Prediction of the Simplified Inelastic Laminate Theory, AVBOL, [5]. (Moment-curvature curve for the $[\pm 45]_s$ laminate, made of Borsic/Al [6], subjected to a curvature rate, $\dot{K}_1 = 0.1\ (\mathrm{ms})^{-1}$.)

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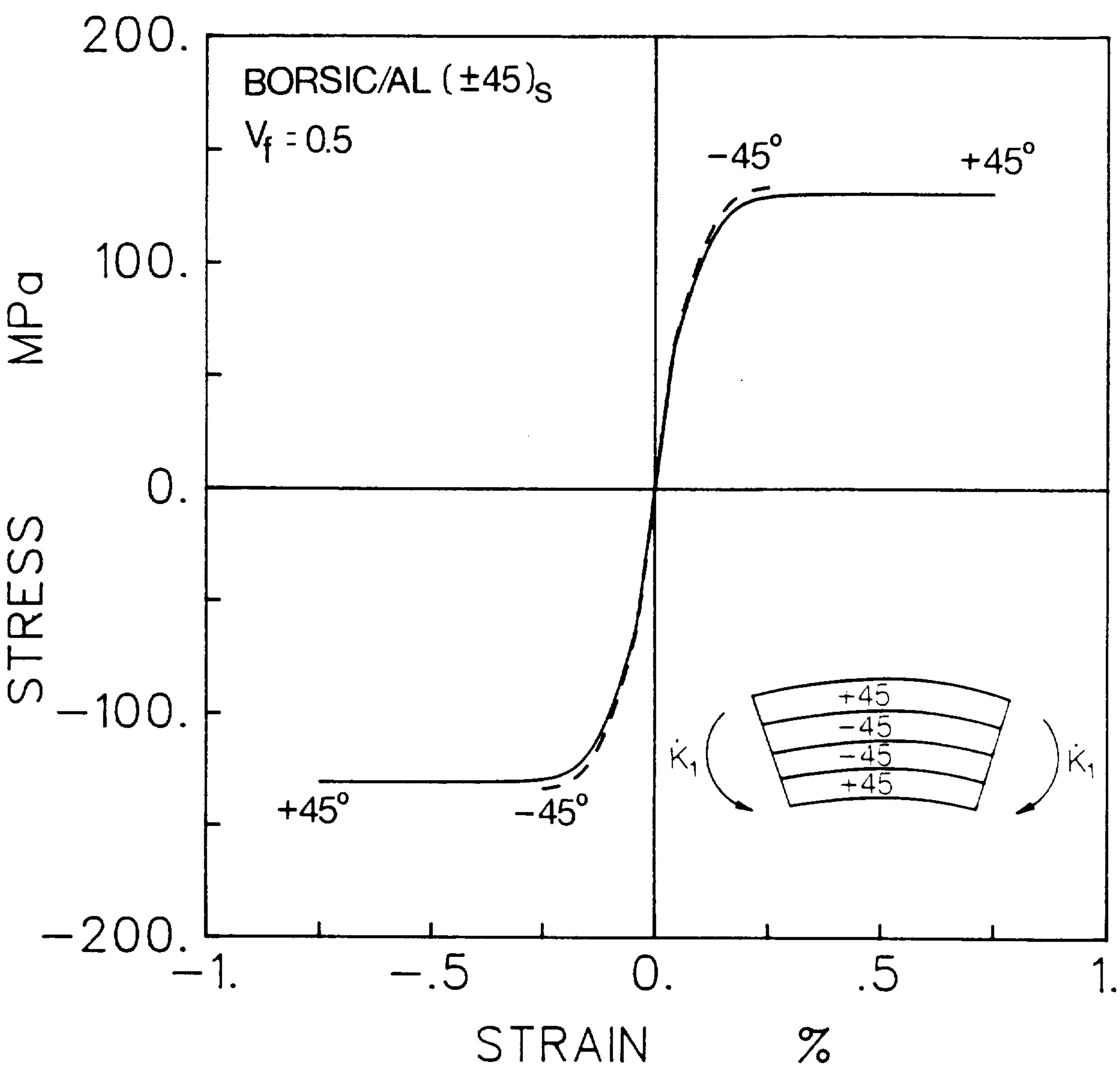

Fig. B-2 Induced Stress-Strain Curves in the One-Direction of Each Ply of the $[\pm 45]_s$ Laminate Shown in Fig. B-1.

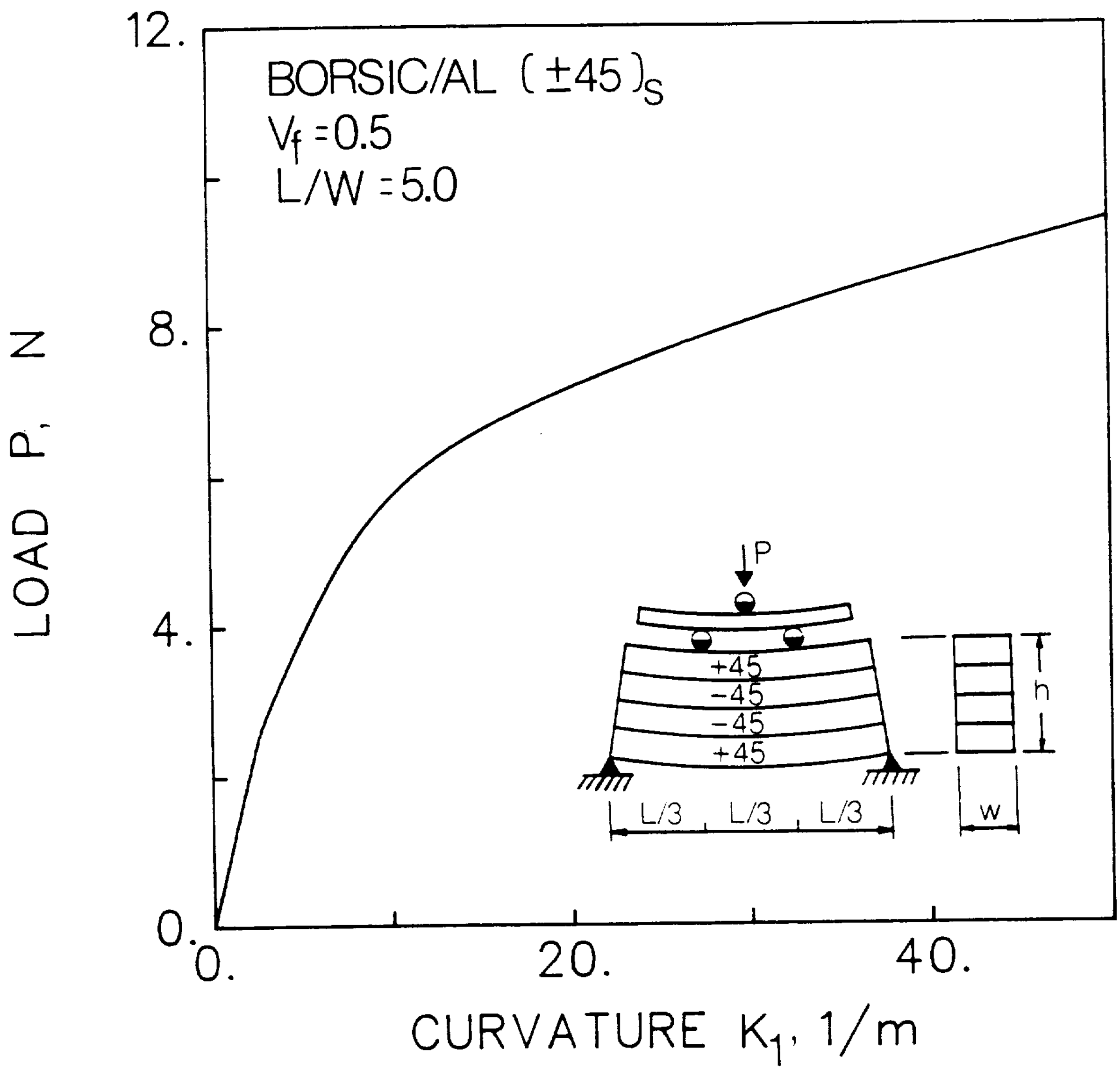

Fig. B-3 Prediction of the Simplified Inelastic Laminate Theory, AVBOL, [5]. (Load-curvature curve for the $[\pm 45]_s$ laminate, subjected to a four-point-bend test with load rate, $\dot{P} = 1.2 \times 10^{-1}$ N/s.)

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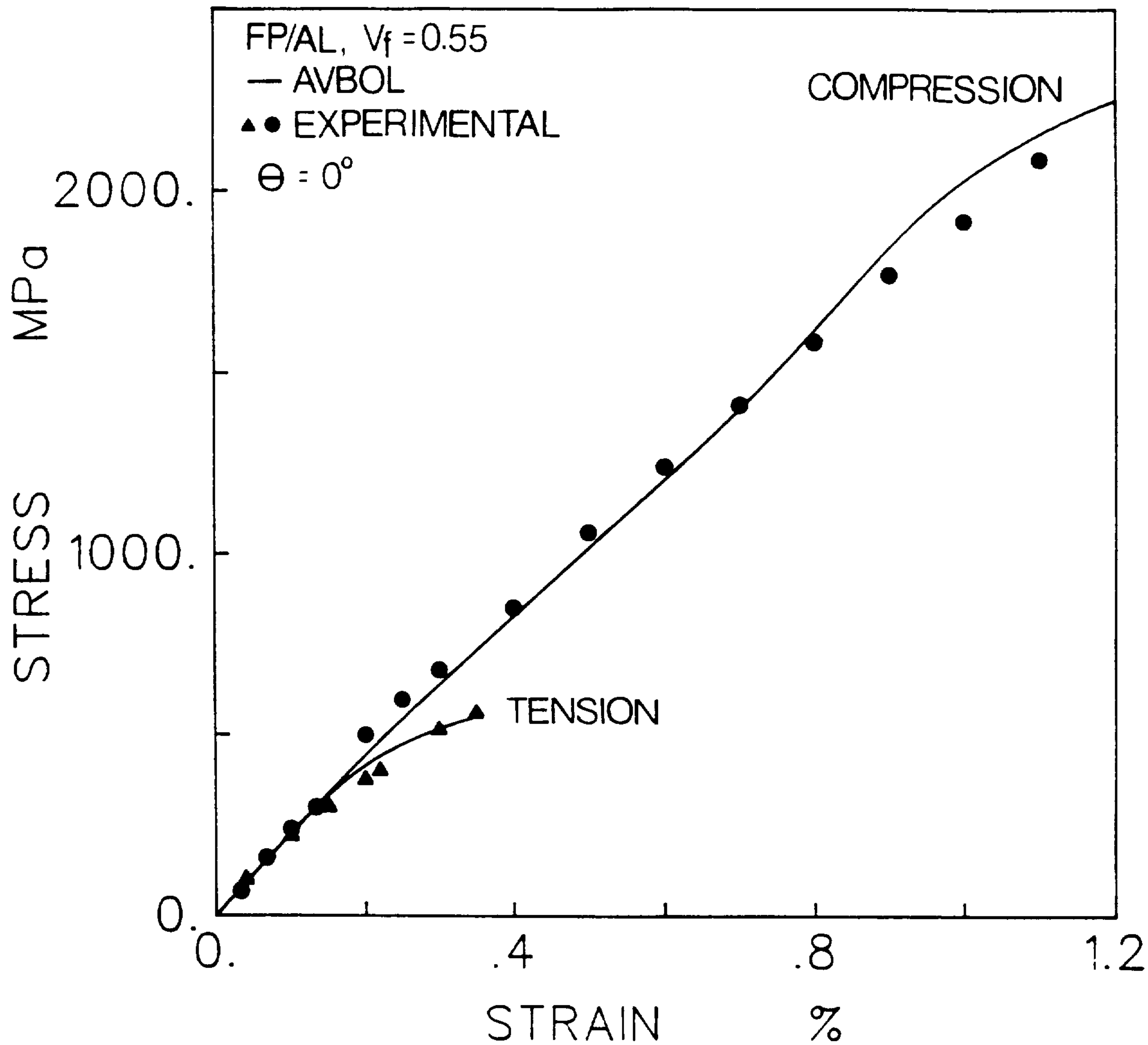

Fig. B-4 Tension-Compression Asymmetric Stress-Strain Curves for FP/Al Ply [7] in the Fiber Direction, $\theta = 0^{o}$. Strain Rate $|\epsilon_1| = 10^{-4}\ s^{-1}$.

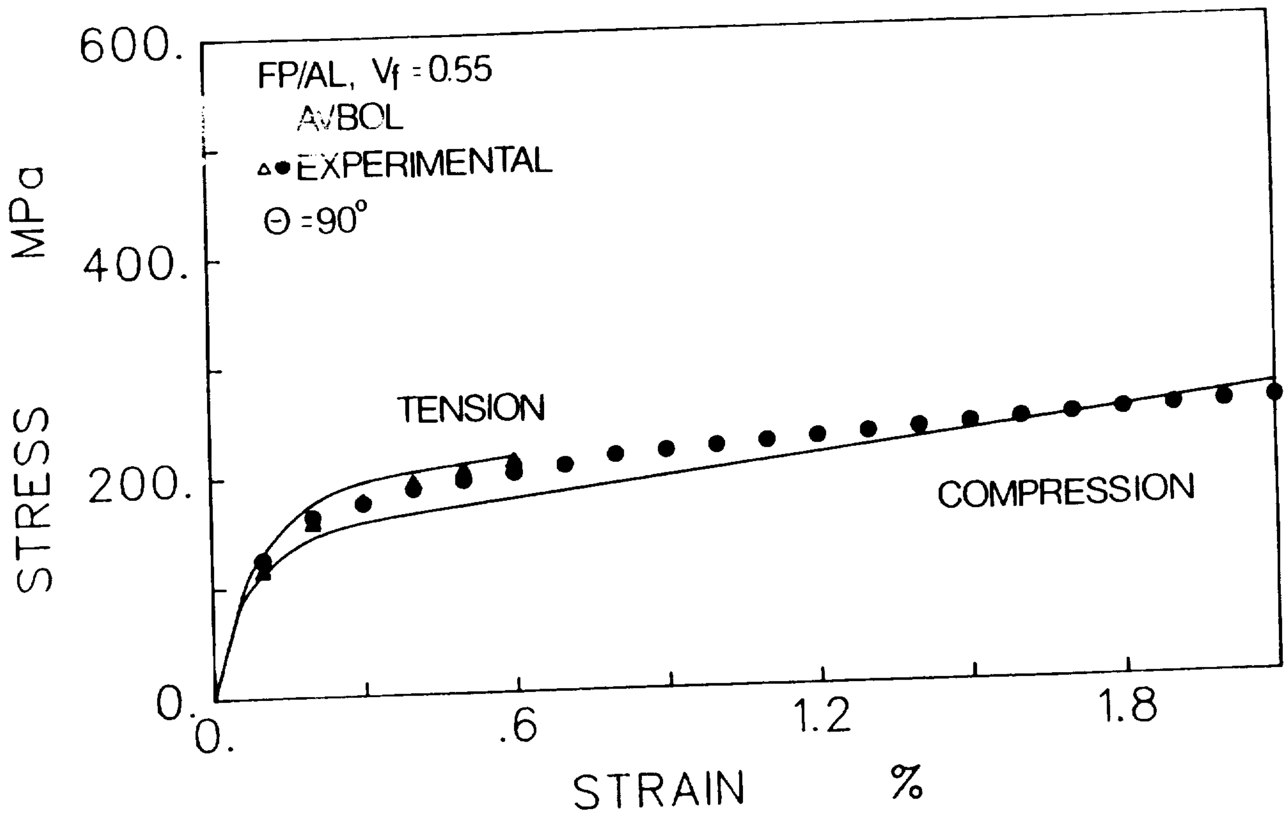

Fig. B-5 Tension-Compression Asymmetric Stress-Strain Curves for FP/Al Ply [7] in the Traverse Direction, $\theta = 90^{o}$. Strain Rate $|\epsilon_1|=10^{-4}\ s^{-1}$.

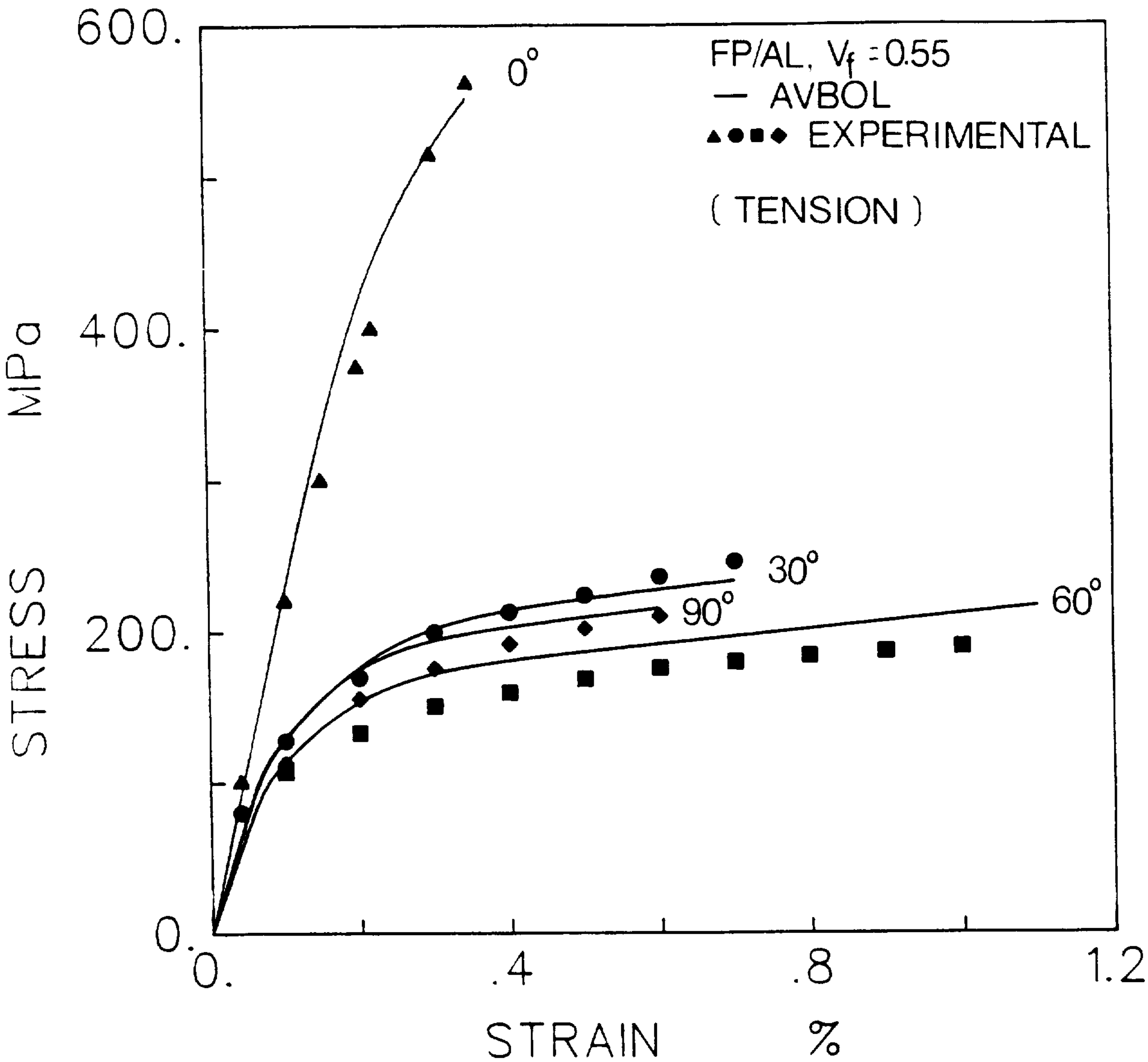

Fig. B-6 Tension-Compression Asymmetric Stress-Strain Curves for FP/Al Ply [7] in the Fiber Direction, $\theta = 0^{o}$. Strain Rate $|\epsilon_1| = 10^{-4}\ s^{-1}$. (Tensile loading at indicated angles to fiber axis.)

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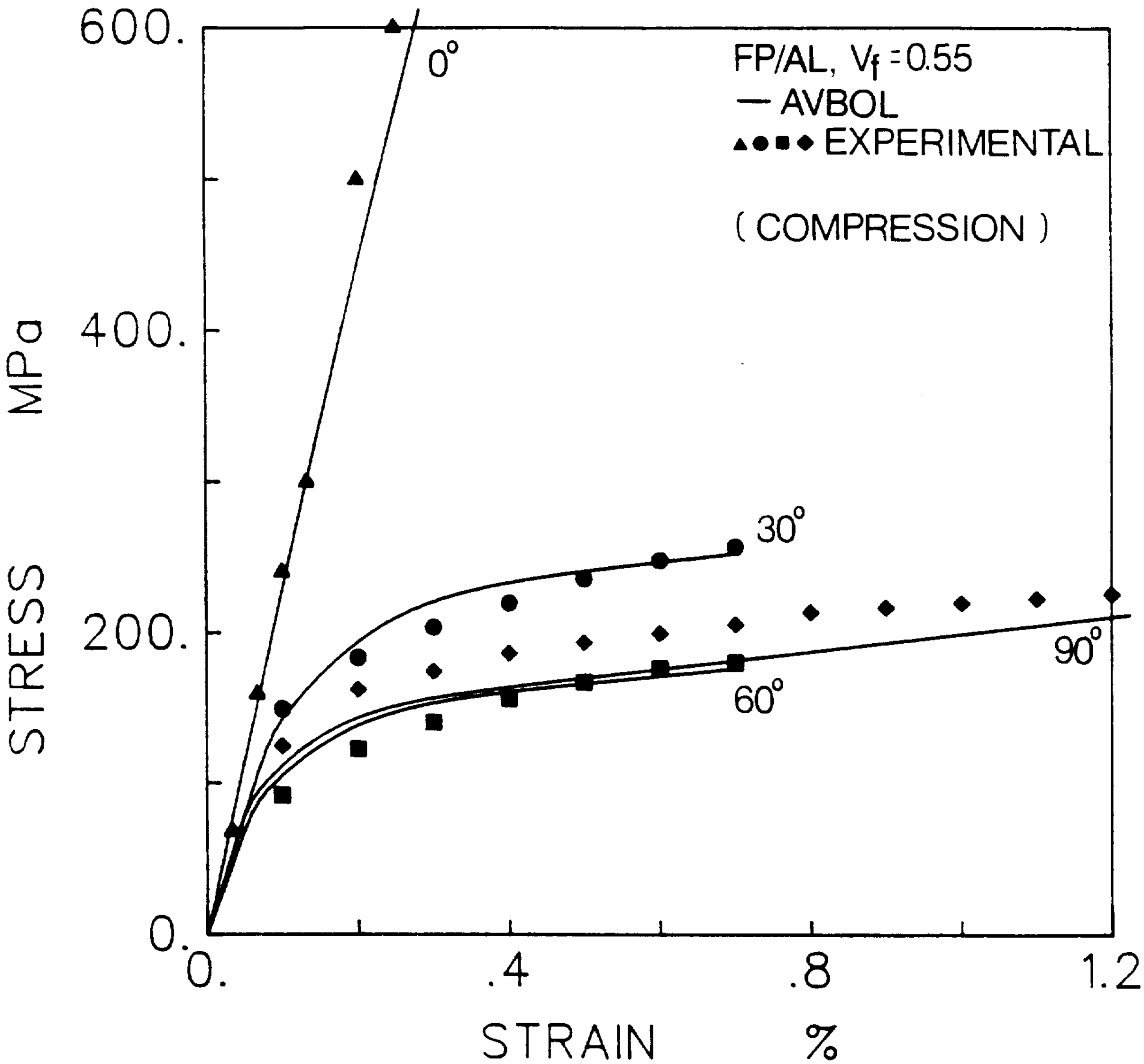

Fig. B-7 Tension-Compression Asymmetric Stress-Strain Curves for FP/Al Ply [7] in the Fiber Direction, $\theta = 0^{\circ}$. Strain Rate $|\epsilon_1| = 10^{-4}\ s^{-1}$. (Compressive loading at indicated angles to fiber axis.)

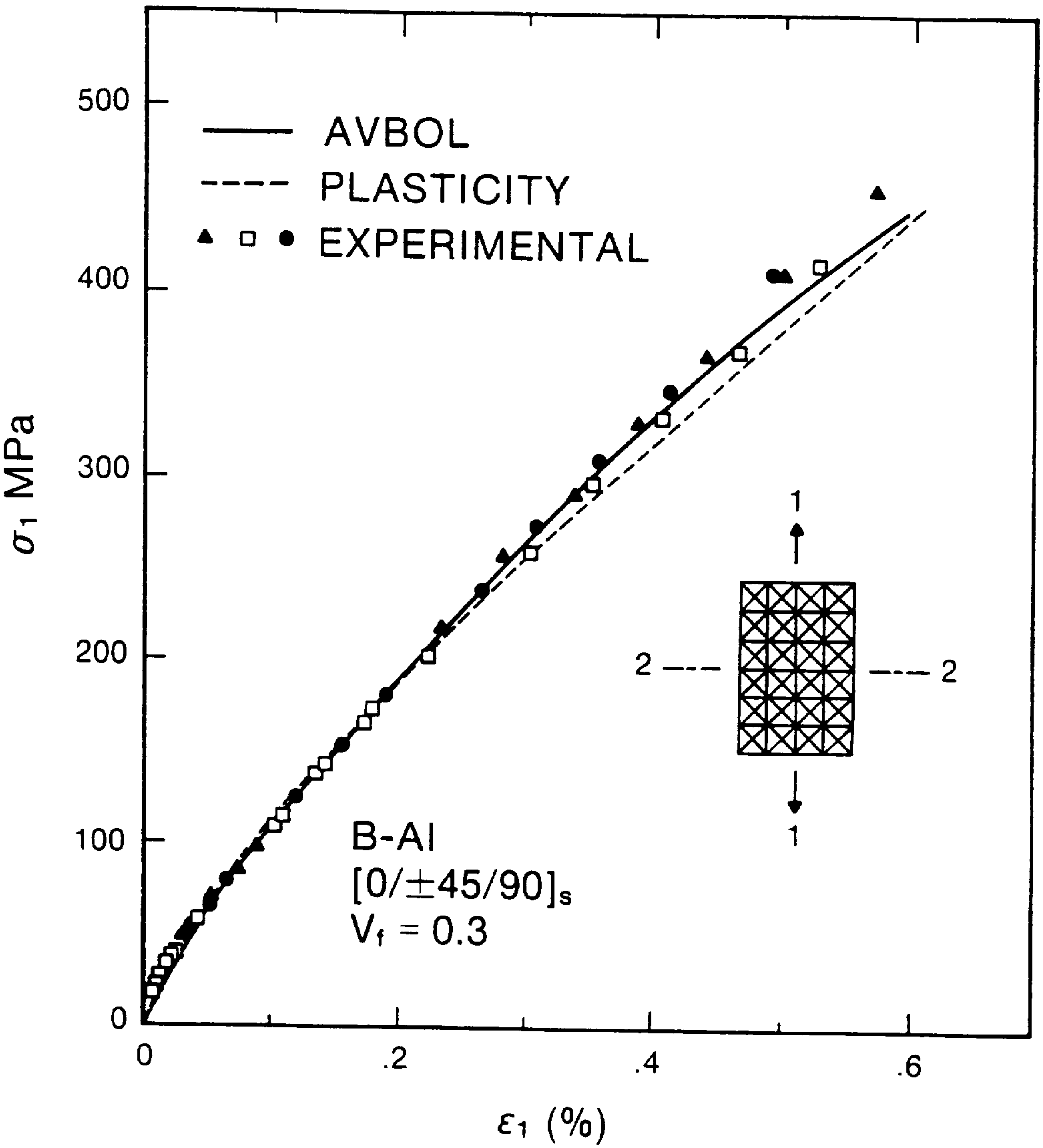

Fig. B-8 Stress-Strain Curves for B/Al $[0/\pm45/90]_s$ Laminate, $V_f = 0.3$. (Comparisons are made between the present theory, using a strain rate, $\epsilon_1 = 10^{-1s}\ s^{-1}$, and the plasticity analysis and experimental data reported in [8].)

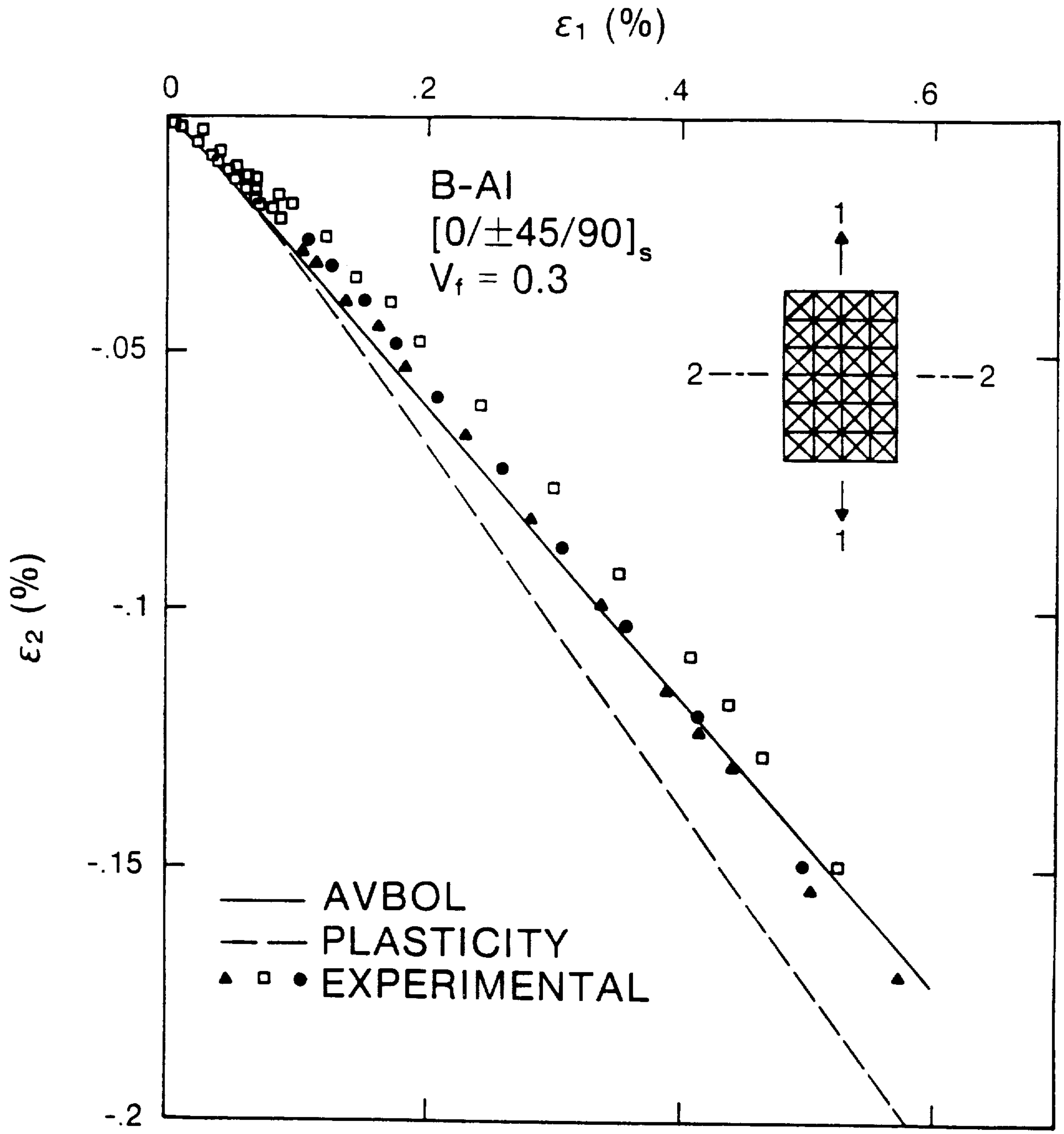

Fig. B-9 Transverse vs. Longitudinal Strain. Comparing results obtained using AVBOL (with the assumption of constant poisson's ratio) with test results.

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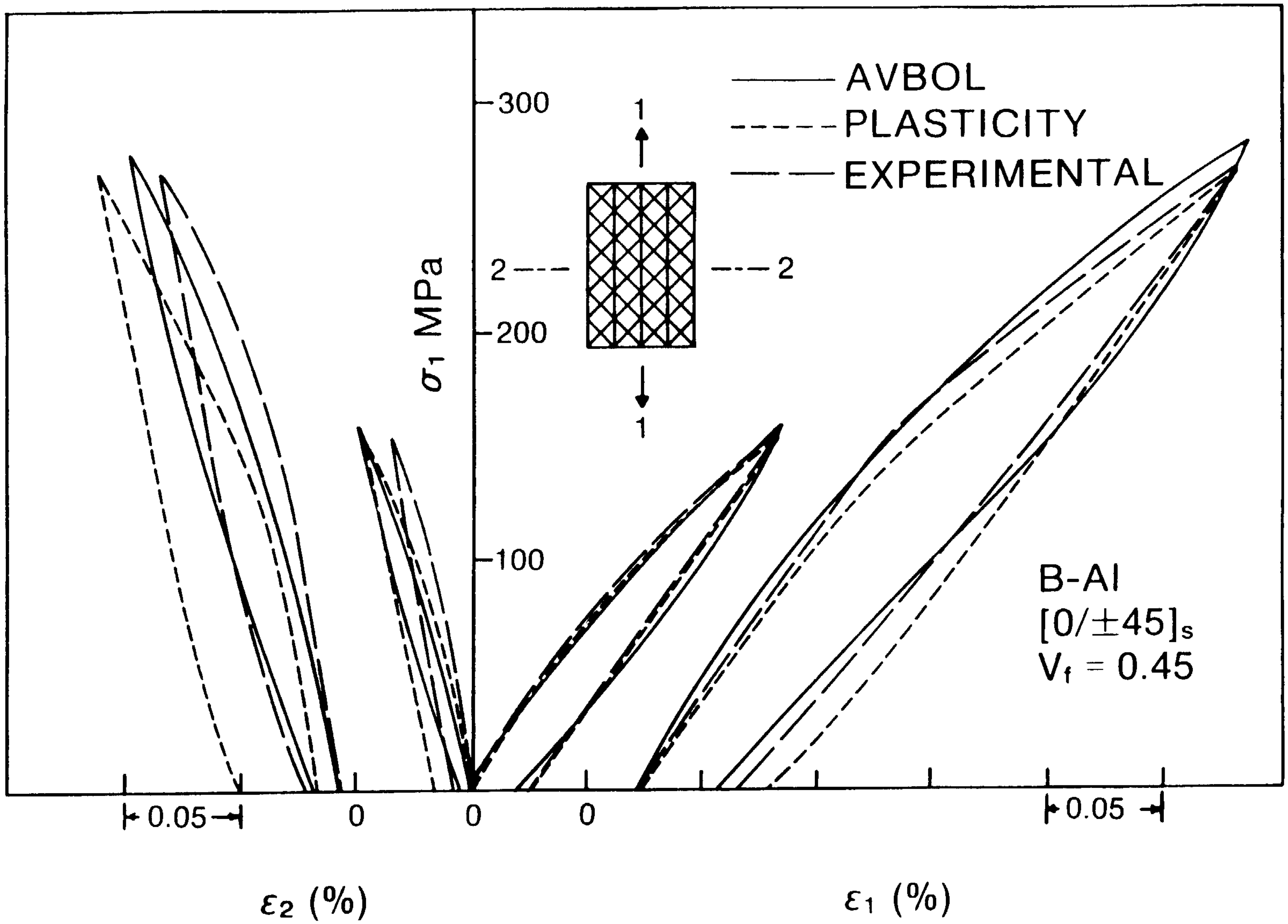

Fig. B-10 Stress-Strain Curves for B/Al $[0/\pm45/90]_s$ Laminate, $V_f = 0.3$. (Showing comparisons among the present theories and test results, using two cycles of tensile Loading and Unloading applied to a B/Al $[0/\pm45]_s$ laminate with $V_f = 0.45$ [8].)

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

"Thermal, Viscoplastic Analysis of Composite Laminates", (with K. D. Lee), presented at Symposium on High Temperature/High Performance Composites, Materials Research Society, Reno, NV, April 1988, to appear in the Proceedings (1988).

"A Simplified Orthotropic Formulation of the Viscoplasticity Theory Based on Overstress", (with M. Sutcu), Nonlinear Constitutive Relations for High Temperature Applications - 1986, Proceedings of a Symposium, Univ. of Akron, OH, June 11-13, 1986, NASA Conference Publication 10010, 89-95, (1988).

C. ANALYSIS OF FATIGUE DAMAGE IN FIBROUS MMC LAMINATES

Sr. Investigator: G. Dvorak

INTRODUCTION

Fatigue damage in metal matrix composite material systems such as B/Al and SiC/Ti is typically caused by repeated plastic straining of the matrix under applied cyclic loading. After many deformation cycles (5×10^4 or so), low-cycle fatigue cracks start to grow in the matrix. Transverse ply cracks aligned in the direction of the fiber are the principal mode of damage. Such cracks lead to a substantial reduction in stiffness and strength, especially in laminates with many off-axis plies. Under constant cyclic loading, the damage process eventually reaches a steady saturation state in which the damaged laminate deforms only elastically. The part of the strain cycle which originally caused plastic straining is now accommodated by opening and closing of cracks. In other words, the damage process is a mechanism that the laminate uses to reach a shakedown state.

STATUS

Our earlier work on fatigue damage mechanics of laminated metal matrix composite plates has been completed during the reporting period. Our current work on time-dependent deformation of MMC laminates at high temperatures is concerned with developing micromechanical models for predicting the overall response of plies and laminates. In this research we utilize our experience with time-independent deformation of MMC's. Specifically, each ply reinforced by fibers of high shear stiffness, such as Al_2O_3, B, SiC, or W, is expected to deform in two distinct modes. Of particular interest in time-dependent deformation is the matrix-dominated mode which is activated by transverse normal and shear strains and by longitudinal shear stresses. In this mode, the response of the composite can be represented by a continuum-slip model which allows smooth plastic straining to take place on hypothetical slip planes which are parallel to the fiber axis. In addition,. there is a fiber-dominated mode that is activated by high normal stresses in the fiber direction.

Progress During the Reporting Period

In the fatigue damage program, we have extended the earlier shakedown analysis results for crossply laminates to angle-ply laminates. Figs. C-1 to C-3 illustrate the essential results. The first two figures show relaxation surfaces of the laminate in strain space. These surfaces are of elliptical shape in the undamaged state, but they expand if a lamina contains open cracks. Accumulation of damage under plastic straining causes expansion of these surfaces to the size needed to contain the strain range the laminate experiences under applied cyclic loads. The surfaces also translate, due to the cyclic plastic strains, to positions from which the strain cycle accommodation can be accomplished with a minimum amount of damage in each ply. The damage needed for the relaxation surface expansion in the plies determines the change of stiffness of the laminate in the saturation damage state. Fig. C-3 shows such stiffness changes in a specific B/Al laminate as a function of the applied stress range. Experimental data points from an earlier investigation by Dvorak and Johnson are plotted together with the theoretical prediction.

In the part of the work which pertains to time-dependent deformation of MMC laminates, the bimodal plasticity theory discussed in the introduction was extended to the viscoplastic range. Main emphasis was again on the matrix dominated mode. We have examined several viscoplasticity theories based on overstress, particularly those proposed by Chaboche, Eisenberg, and Krempl. All these theories admit certain equilibrium curves or surfaces which bound a region in stress space in which loading produces only negligible plastic strains. Such surfaces move and deform in stress space during general loading. Viscoplastic strain rate is found experimentally to be a function of the distance between the actual stress and the equilibrium stress. These and other aspects of the theories were applied in our attempts to model the matrix-dominated mode. Figs. C-4 and C-5 show the initial yield surfaces of a high-temperature laminate in two different stress planes. While the matrix behavior is taken in the Mises form, the lamina surfaces have very different shapes which do not particularly resemble the Mises ellipse, since the shape depends on the specific deformation mechanism activated in a ply under overall loads. The internal envelope of these surfaces is the initial equilibrium surface of the laminate. The matrix-dominated mode (MDM) branches are seen to form this internal envelope. That confirms that the onset of viscoplastic deformation in individual plies of the laminate will take place in the MDM. Many additional facets of the viscoplastic behavior of composite laminates

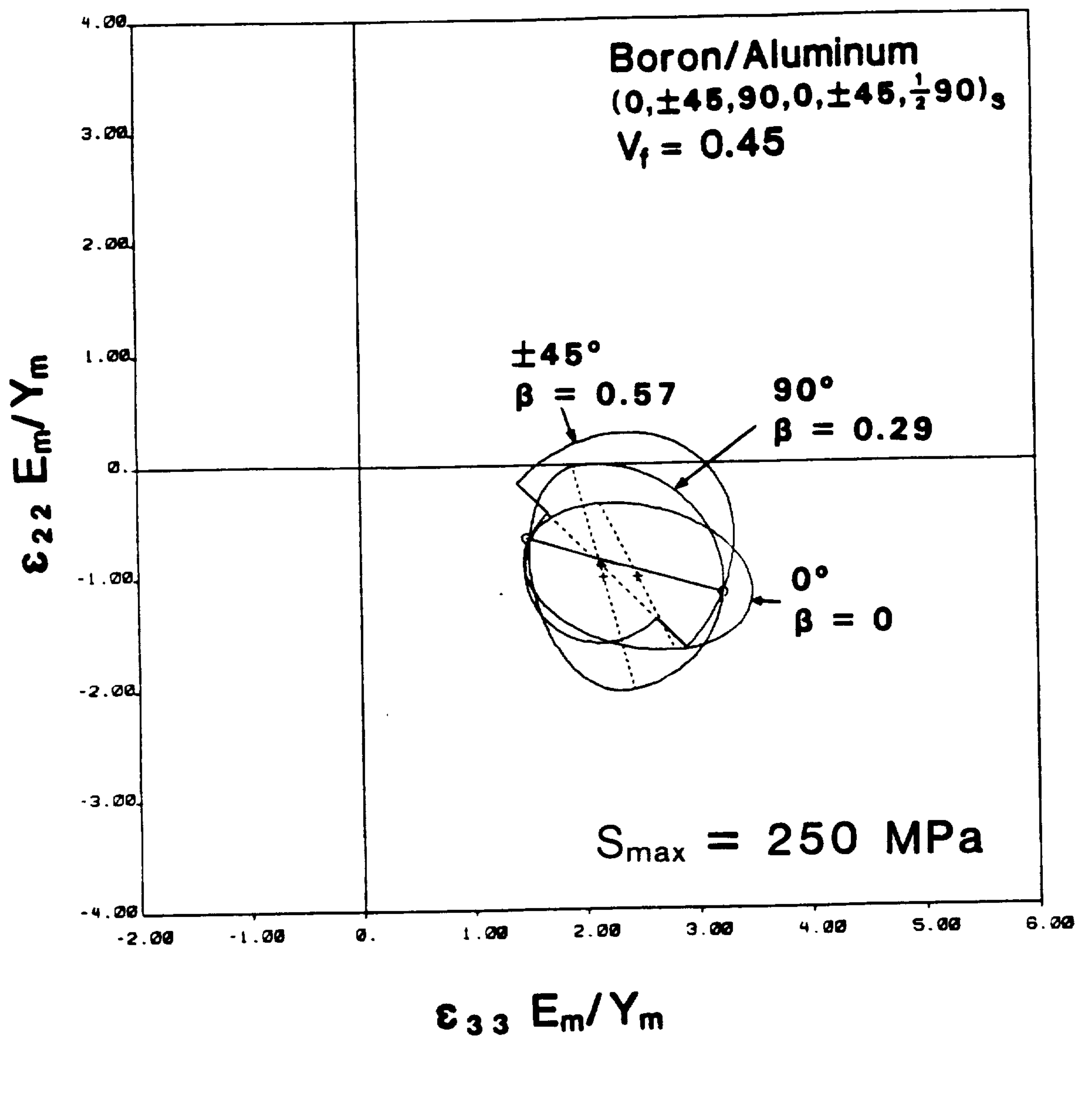

Fig. C-1 Expanded and Translated Relaxation Surfaces of a B/Al Laminate in Saturation Damage State. (A uniaxial tension/tension stress cycle was applied in the x_3 direction; S_{min} = 25 MPa, S_{max} = 250 MPa.)

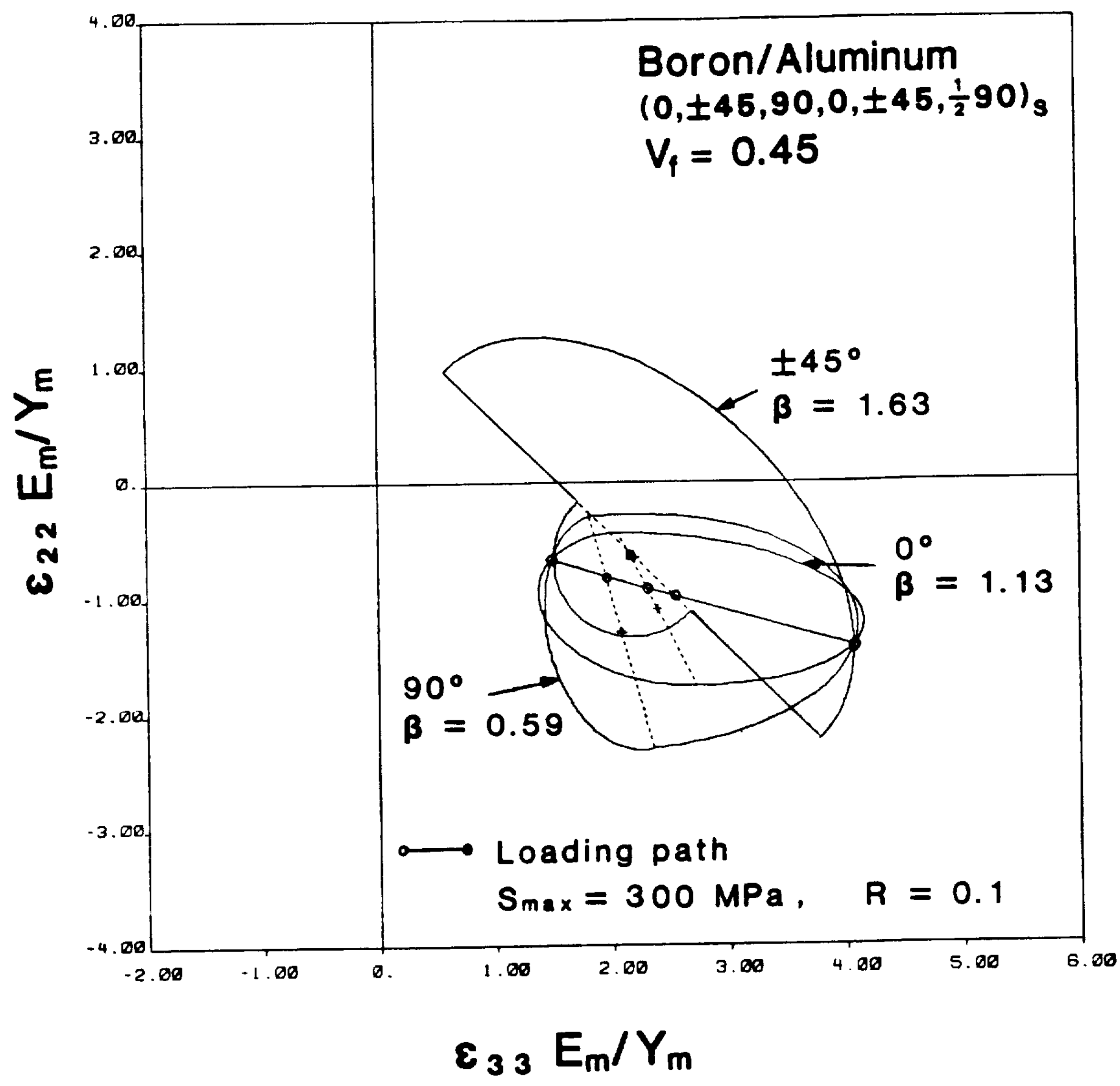

Fig. C-2 Expanded and Translated Relaxation Surfaces of a B/Al Laminate in Saturation Damage State. (A uniaxial tension/tension stress cycle was applied in the x_3 direction; S_{min} = 30 MPa, S_{max} = 300 MPa.)

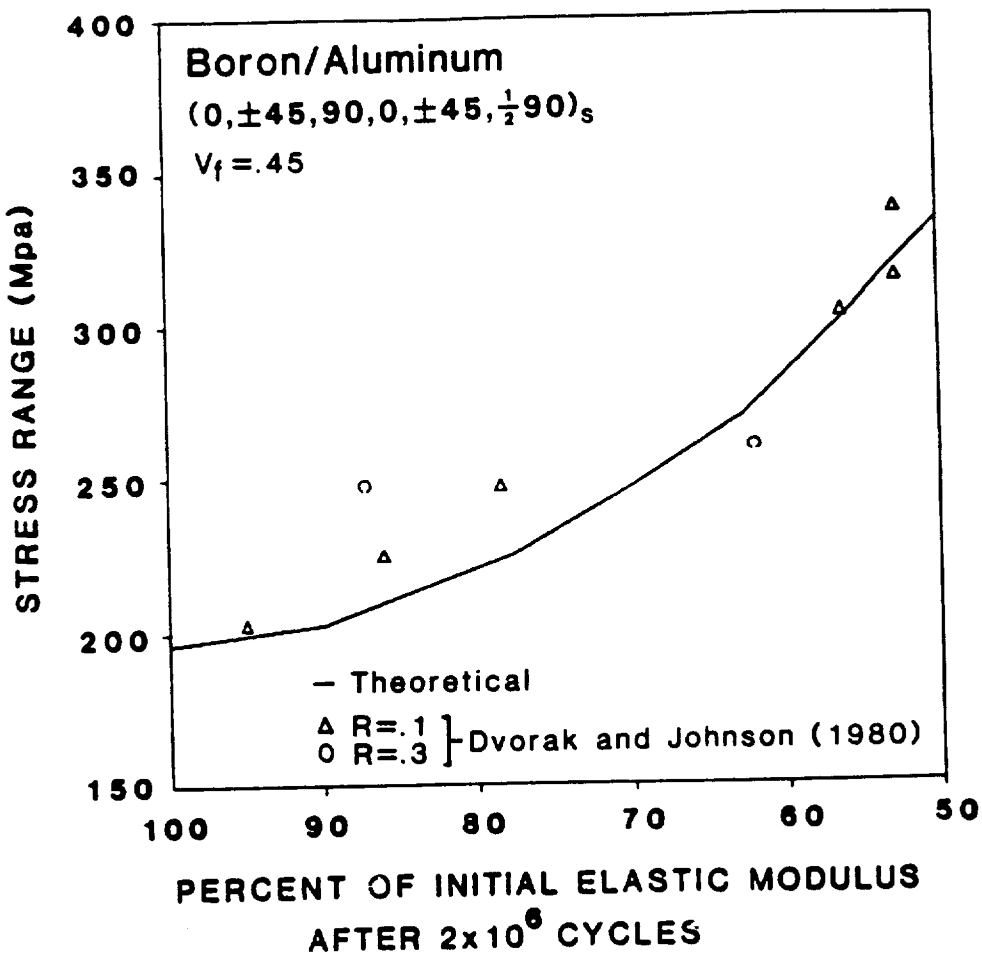

Fig. C-3 Predicted and Experimentally Measured Stiffness Changes in the Laminate at Different Magnitudes of the Applied Stress Range. ($R = S_{min}/S_{max}$)

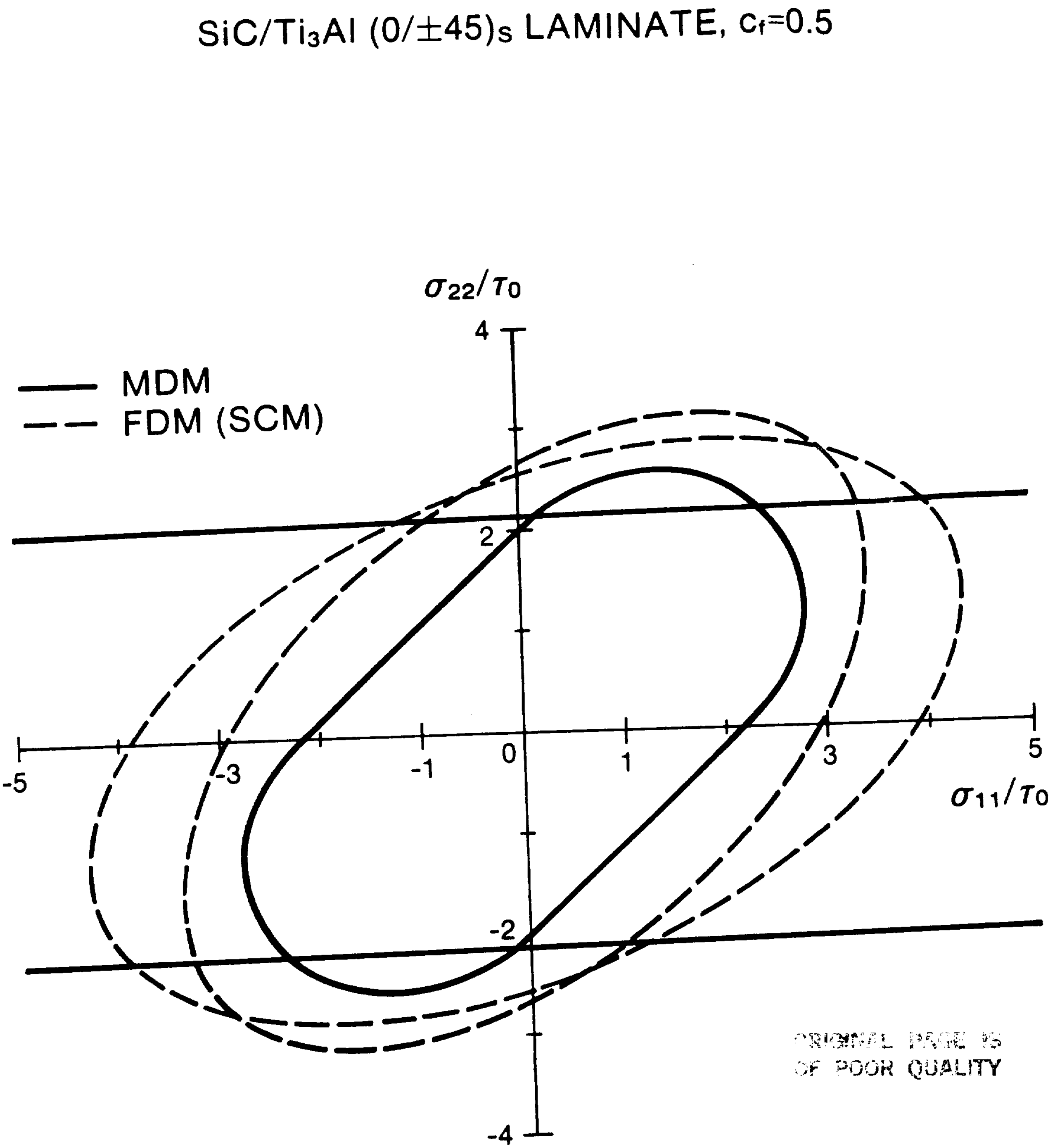

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Fig. C-4 Initial Yield Surfaces of Individual Plies in an Angle-Ply Laminate in Fiber and Matrix Dominated Deformation Modes (FDM & MDM, respectively). The x_1 axis coincides with the 0^o direction; x_2 is the transverse in-plane coordinate.

SiC/Ti_3Al (0/±45)s LAMINATE, c_f=0.5

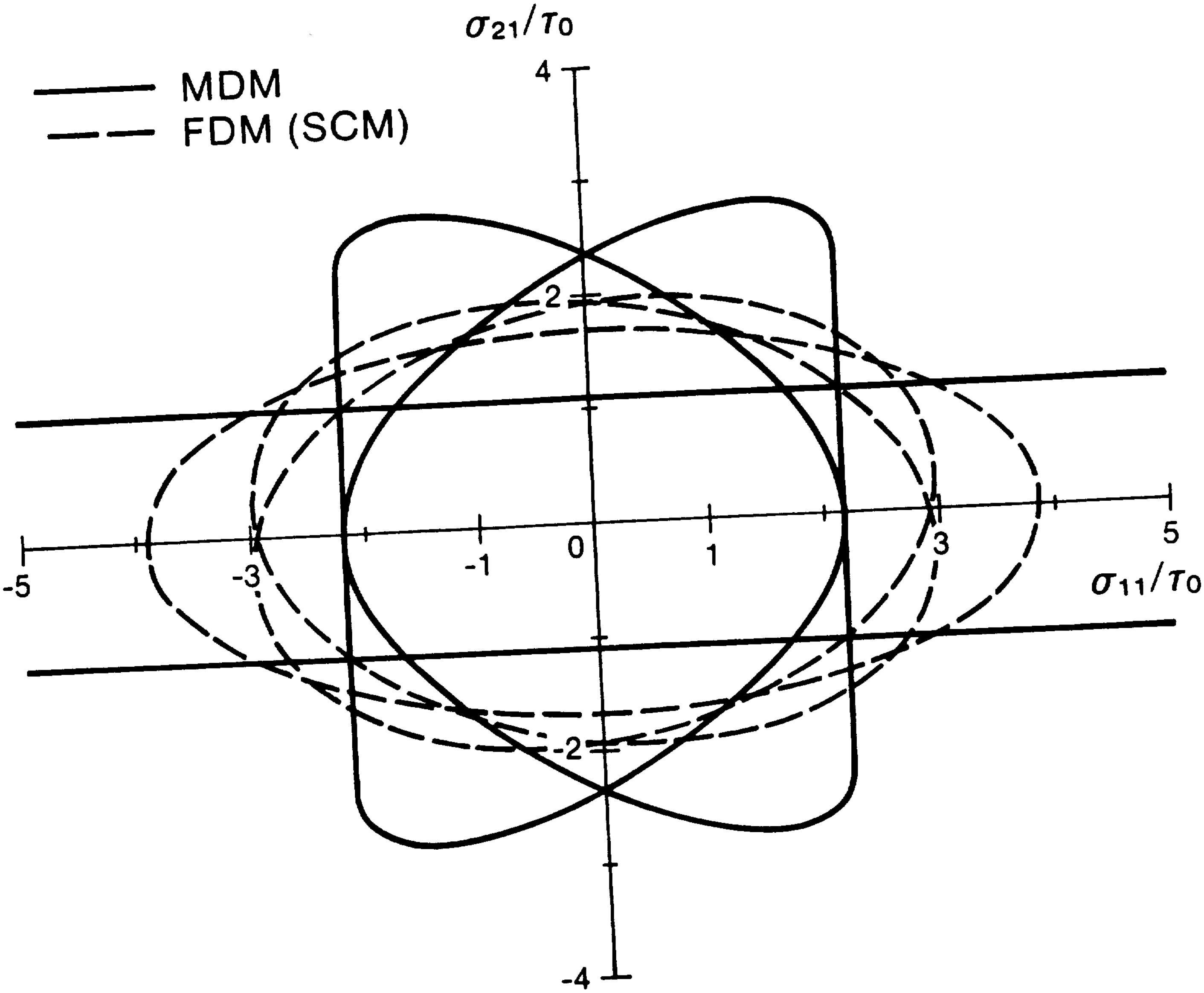

Fig. C-5 The Yield Surfaces of Fig. C-4 shown in a Different Coordinate Plane. (σ_{21} is the in-plane shear stress; σ_{11} is the axial normal stress in 0° direction.)

have also been explored.

PLANS FOR THE UPCOMING PERIOD

In the 1988-89 stage of the program, we hope to continue and conclude the above work on time-dependent deformation of fibrous MMC laminates. A related AFOSR supported investigation now under way is expected to produce experimental data which will be used to verify and extend the above results.

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

"Dual Estimates of Instantaneous Properties of Elastic-Plastic Composites", (with J. C. Teply) in Continuum Models of Discrete Systems, ed. by A. J. M. Spencer, A. A. Balkema Press, Rotterdam, The Netherlands, pp. 205-216, 1987.

"The Effect of Fiber Breaks and Aligned Penny-Shaped Cracks in the Stiffness and Energy Release Ratio in Unidirectional Composites", (with N. Laws), International Journal of Solids and Structures 23, No. 9, pp. 1269-1283, 1987.

"A Bimodal Plasticity Theory of Fibrous Composite Materials", (with Y. A. Bahei-El-Din), Acta Mechanica, Vol. 38, 1987.

"Plasticity of Whisker-Reinforced Composites", (with Y. A. Bahei-El-Din and R. S. Shah), Proceedings of the Canadian Congress of Applied Mechanics CANCAM'87, University of Alberta, Edmonton, Alberta, May 31-June 4, 1987.

"Bounds on Overall Instantaneous Properties of Elastic-Plastic Composites", (with J. Teply), Journal of Mechanics and Physics of Solids, No. 1, pp. 29-58, 1988.

"Plasticity Effects in Metal Matrix Composites", Gordon Research Conference, Ventura, CA, Jan. 11-15, 1988.

"Plasticity Theory of Fibrous Composite Materials", (with Y. A. Bahei-El-Din), Metal Matrix Composites: Testing, Analysis and Failure Modes, W. S. Johnson, editor, American Society for Testing and Materials, Philadelphia, PA., April 1988.

D. DELAMINATION FRACTURE TOUGHNESS IN THERMOPLASTIC MATRIX COMPOSITES

Sr. Investigator: S. S. Sternstein

INTRODUCTION

In recent years, research activities dealing with the compression behavior of thermoplastic matrix composites has increased significantly due to their increased toughness over some thermoset systems. However, little widespread agreement exists as to mechanisms and the contributions of the individual material constituents to these mechanisms. In particular, the effects of nonlinear time dependent matrix behavior and nonuniform microstructure are not fully understood. The research program reported here has been designed to clarify the roles of these two characteristics.

STATUS

An experimental study of the compression strength of unidirectional thermoplastic matrix composites was recently completed at Rensselaer. In order to explain certain phenomena observed here and elsewhere, analytical modeling has also been under- taken. Specifically, the following studies are either in progress or are planned to be undertaken in the immediate future for laminates with thermoplastic matrices:

1) A mathematical description of the nonuniform microstructure of unidirectional composite laminates (UDCL's) is in progress.

2) An investigation of the effects of nonuniform fiber volume fraction (V_f) on out-of-plane compression behavior of idealized linear elastic samples is in progress.

3) An analysis of inplane compression behavior accounting for (a) those nonlinear viscoelastic matrix properties characteristic of thermoplastics and (b) in-plane fiber waviness is in progress.

4) Finite element analyses of certain aspects of the above mentioned problems are planned as a joint effort with Dr. M. S. Shephard.

PROGRESS DURING THE REPORTING PERIOD

Efforts this period have concentrated on analysis of experimental compression data for the effects of nonuniformity of microstructure and nonlinear viscoelastic matrix behavior, as well as some preliminary analytical modeling. Micrograph measurements were taken on UDCL compression samples in attempts to quantify fiber waviness, but are incomplete as they contain only measurements of local angular misalignment and no information concerning wavelength. This work on area-description of microstructure has, therefore, been extended with the goal of obtaining a general mathematical description of fiber shapes and packing which accounts for both waviness and nonuniformity. The purpose of such a description is to relate measured quantities to characteristics not directly observed, e.g., local misalignment angle to wavelength relations and local volume fraction (V_f).

Analysis of compression test data recently taken indicates that nonuniformity in V_f causes significant variations in loading throughout a UDCL specimen. This sort of preferential loading, if incorporated in an analytical model, would predict failures at loads lower than failure loads predicted using a model which assumes uniform loading of all representative internal units. Analytical confirmation of this phenomena has begun with a linear elastic model taking into account variations in V_f through the thickness of the sample. Preliminary results concur with the widely observed asymmetry in compression behavior (i.e., strain gages on both sides of a nominally symmetric sample giving different readings as failure approaches).

Additional data has shown, further, that a "lag effect" occurs in curves of stress-strain just prior to failure, indicating some pre-catastrophic viscoelastic behavior. An effort has begun to relate nonlinear viscoelastic matrix properties and in-plane fiber waviness to pre-catastropic in-plane behavior. A suitable constitutive equation recently developed is being used for this effort. The equation has just been tested in a finite element formulation using the ABAQUS code and simulating delamination. It has exhibited satisfactory nonlinear, rate dependent effects.

PLANS FOR THE UPCOMING PERIOD

In the next reporting period, the following tasks will be emphasized:

1) Concluding the study of the effects of variations in V_f on out-of-plane behavior of a linear elastic sample.

2) Continuing the study of microstructural variation and nonlinear viscoelastic matrix properties on in-plane behavior.

3) Extending existing finite element analyses to include the characteristics noted in Items 1 & 2 above.

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

"Mechanical Properties of Composites", presented at Alcoa Centennial Symposium on Micromechanics, Hilton Head, S. C., June 8, 1987.

"Mechanical Properties of Thermoplastic Matrix Composites" presented at Shell Laboratories, Houston, TX, October 1, 1987.

"Deformation - FTIR Studies on H-Bonded Polymers", (with C. S. Van Buskirk), presented at Federated American Spectroscopy Society Meeting, Detroit, MI, October 7, 1987.

"Thermoplastic Matrix Composites: Finite Element Analysis of Mode I and Mode II Failure Samples", (with R. Bankert, L. Lambropoulous and M. Shephard) presented at ASTM meeting, Bal Harbor, FL, October 18, 1987 (in press).

"Matrix Dominated Deformations and Failure in Thermoplastic Matrix Composites", (with C. Buhrmaster and K. Srinivasan) presented at ASTM meeting, Bal Harbor, FL, October 19, 1987.

"A Micrographic Study of Bending Failure in Five Thermoplastic/Carbon Fiber Composite Laminates", (with S. W. Yurgartis) Journal of Materials Science, Vol. 23, pp. 1861-1870, 1988.

"Polymer Creep", (with C. S. Van Buskirk), Encyc. of Polymer Sci. and Engr., Vol. 12, Second Edition, J. Wiley & Sons, pp. 470-486, 1988.

E. NUMERICAL INVESTIGATION OF THE MICROMECHANICS OF COMPOSITE BEHAVIOR

Sr. Investigator: M. S. Shephard

INTRODUCTION

The goal of this work is to provide finite element capabilities which, coupled with an experimental program, will provide an increased understanding of the behavior of composite materials. The first step in the numerical simulation effort deals with the development of nonlinear time-dependent constitutive relations for thermoplastic materials and their integration within a large scale nonlinear finite element code. Use of mixing models to accommodate the proposed constitutive model for thermoplastic matrix matrials is next addressed. In particular, the Periodic Hexagonal Array (PHA) model is to be implemented. It is noted that the microstructure and nonlinear constituent properties which govern macromechanical properties also influence micromechanical or local processes such as fracture. As a mixing model, the PHA representation can be expected to predict overall properties, but not local processes, at least not fully. Similarly, classical fracture mechanics cannot account for the complex local material properties. It, therefore, appears necessary to devise analyses which focus attention on the local failure area while still incorporating the characteristic anisotropy and material nonlinearities.

STATUS

Focus has continued to be placed on the application, and, when needed, development of advanced finite element modeling techniques to be applied to the analysis of composite behavior. The base finite element tools being used are the ABAQUS nonlinear finite element program [9] and the finite quadtree automatic mesh generator [10]. These procedures are being used to perform advanced macromechanical and micromechanical analyses as part of a joint project with Professor Sternstein. (See Section D of this report.)

PROGRESS DURING REPORTING PERIOD

Efforts during the reporting period were two-fold. One activity concentrated on the completion and testing of the Periodic Hexagonal Array (PHA) model for thermoplastic composites. In the second, parameters which influence stress distributions ahead of a delamination tip were investigated

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down to the micromechanical level. The specific case studied was a classical Double Cantilever Beam (DCB) specimen.

As suggested in the introduction to this progress report, experiments have shown the macromechanical response of composite structures to be nonlinear due to nonlinear behavior of the matrix material at a microstructure level. Any analysis intended to include nonlinear composite material behavior must, therefore, consider the micro- mechanical behavior of the constituents. Our approach is to provide a realistic constitutive relation, accounting for the nonlinear behavior of the matrix materials, and an appropriate mixing model. The Periodic Hexagonal Array (PHA) model[11,12] appeared to be suitable, and it has now been successfully implemented by inclusion into the ABAQUS nonlinear finite element code via User Defined Subroutines[9].

Preliminary results from tests of the PHA mixing model incorporating nonlinear, time-dependent matrix constitutive relations have been obtained during the last reporting period. These studies focused on capturing matrix dominated properties. Fibers were assumed to behave in a linear elastic manner, and the matrix to follow a particular nonlinear time-dependent law[13]. A general 3-D analysis which is compatible with the 3-D inter-PHA formulation has been conducted at the time of this writing.

The case considered consists of a simple structure represented by two 8-noded 3-D elements subjected to uniaxial tension, in directions parallel and perpendicular to the fiber orientation. The load is applied via prescribed displacements at one edge, according to a constant strain-rate, and solution is by a 2x2x2 integration scheme. The geometry, boundary conditions and material properties are shown in Table II-E-1. Isotropic fiber properties were assumed initially, along with polycarbonate matrix properties.

A stress-strain curve calculated for this composite is plotted in Fig. E-1, and compared with the corresponding behavior of fiber and matrix independently subjected to the same type of loading (tension under constant strain rate of 0.01% per sec). Note that a very soft fiber (Young's modulus of 7.5 MPa) was chosen for this example to emphasize the effect of matrix properties. The results show that while the fiber response is linear elastic and the matrix nonlinear, composite behavior lies between, with slightly nonlinear behavior starting at the matrix onset of nonlinearity. The initial slope of the curve, which determines the elastic longitudinal modulus, follows approximately the well-known "Rule of Mixtures". As expected, the

Table II-E-I

Material Properties Used in General 3-D Analysis
(V_f = 0.55)

Fiber	Matrix
E_L = 7.5E + 10	K = 1.0E - 20
E_T = 7.5E + 10	α = 9.0E - 08
G_L = 3.0E + 10	β = 2.0E - 08
G_T = 3.0E + 10	G_1 = .88E + 10
ν = .25	G_2 = .88E + 09
	B = 4.1E + 10
	η = 1.0E + 16

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

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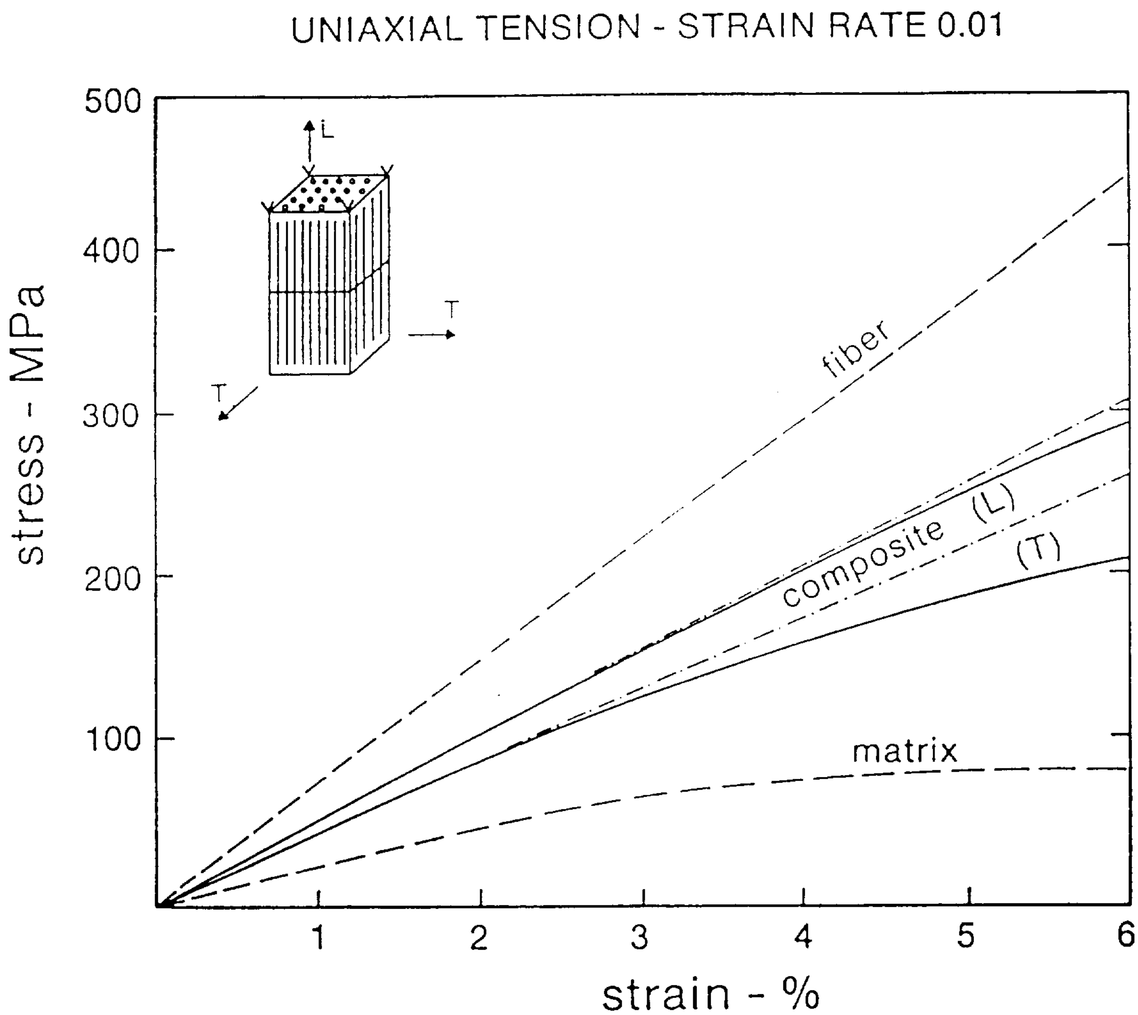

Fig. E-1 Longitudally and Transversely Loaded Uniaxial Composite.

longitudinal load (L) case behaves much as the fiber alone, since it is mainly fiber-dependent, while the transverse load (T) case response is closer to that of "neat" matrix behavior.

Specific features of thermoplastic matrix behavior (eg rate-dependence, differences between tension and compression) were investigated next as they affect overall composite behavior. Transverse uniaxial tests were analyzed (Fig. E-2) at three different tensile strain rates (1.0%, 0.01% and 0.0001% per sec) and one compression rate (0.01% per sec). Increasing loading rate causes higher overall response. Compressive response is stiffer than tensile response and becomes nonlinear at a higher stress level.

A simple shear test was also performed. Plots of axial shear stress versus the corresponding shear strain are shown in Fig. E-3 for the composite subjected to three different strain rates (1.0%, 0.01% and 0.0001% per sec). Fig. E-4 illustrates the relative behavior of the composite in axial and transverse shear compared to the behavior of the isotropic matrix and a transversely isotropic fiber subjected to axial and transverse shear. Here, again, the composite behavior lies between that of the fiber and matrix in both cases.

The micromechanical finite element studies are motivated by the fact that detailed knowledge of the local stress field in the vicinity of a crack or other flaw is needed to fully understand failure processes. As in macroscopic studies of nonlinear behavior, predicting local stress fields given loading history and flaw geometry, requires detailed knowledge of the material constitutive relations. Composite materials pose numerous additional problems. Among these, anisotropy causes considerable variation in fracture properties for flaws with different orientations; interaction of fibers and matrix, especially close to the crack tip, can be expected to play a major role in determining local stresses; local structural features, such as variations in fiber volume fraction and fiber waviness also must be accounted for. Clearly, a continuum fracture mechanics approach, based on smeared global properties which take no account of local microstructure, cannot accurately evaluate local stresses. The finite element method provides a useful tool which can be used to analyze the detailed stress fields around the crack tips in composites.

Modeling of the Double Cantilever Beam (DCB) cases chosen for analysis was aided by the finite quadtree automatic mesh generator[10]. This FEM tool

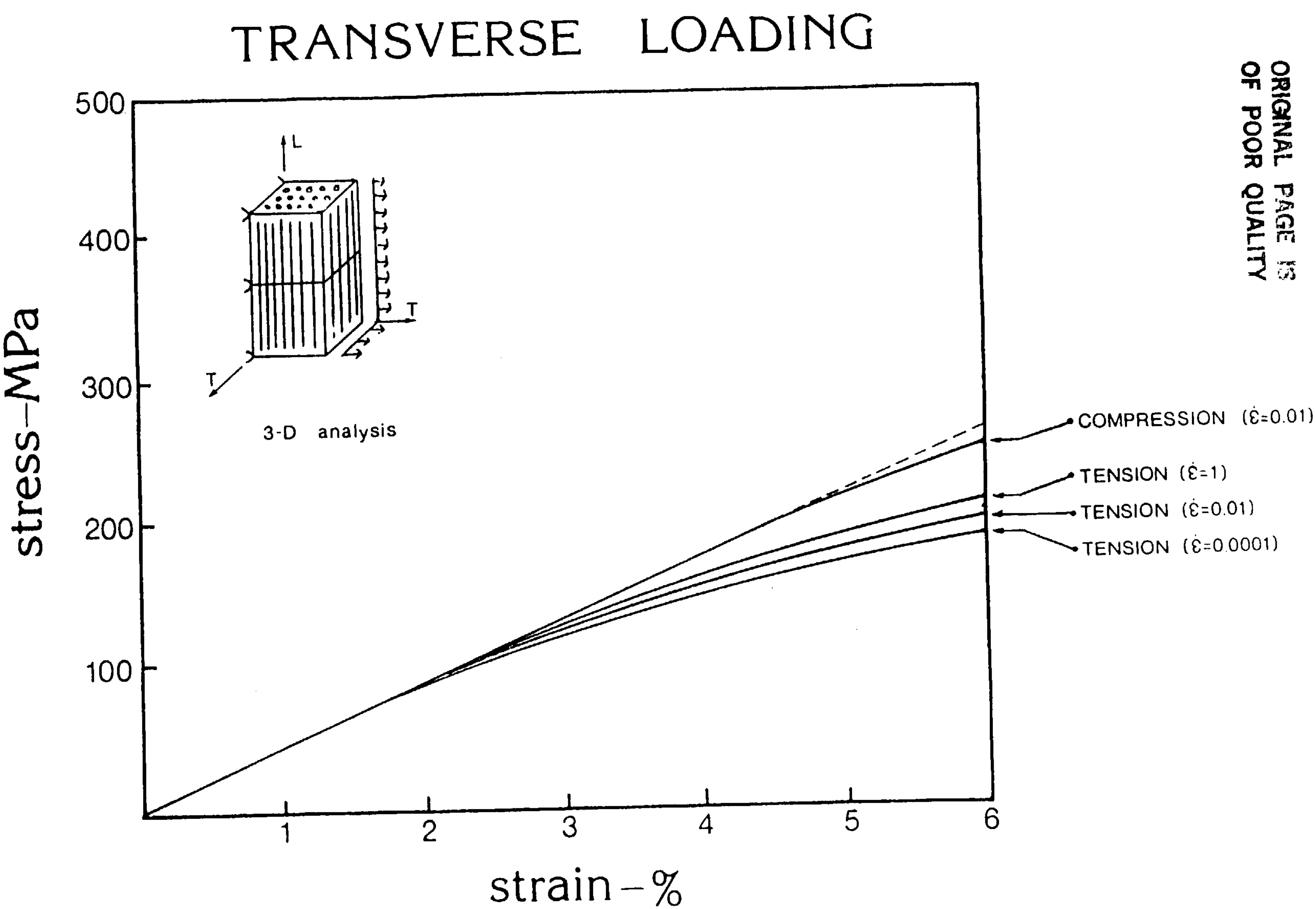

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Fig. E-2 Effect of Loading Rate and Direction for Transversely Loaded Uniaxial Composite.

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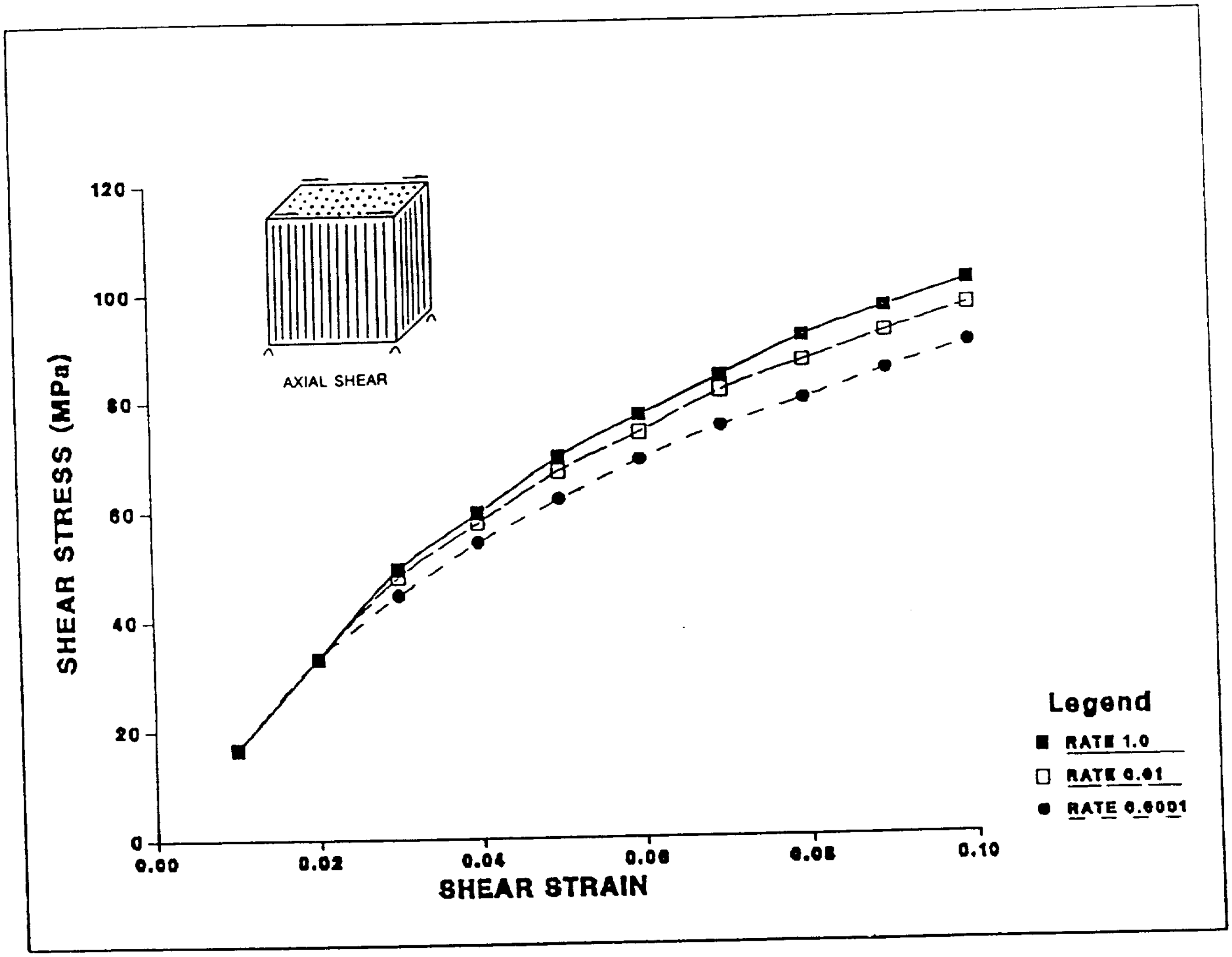

Fig. E-3 Axial Shear on Uniaxial Composite.

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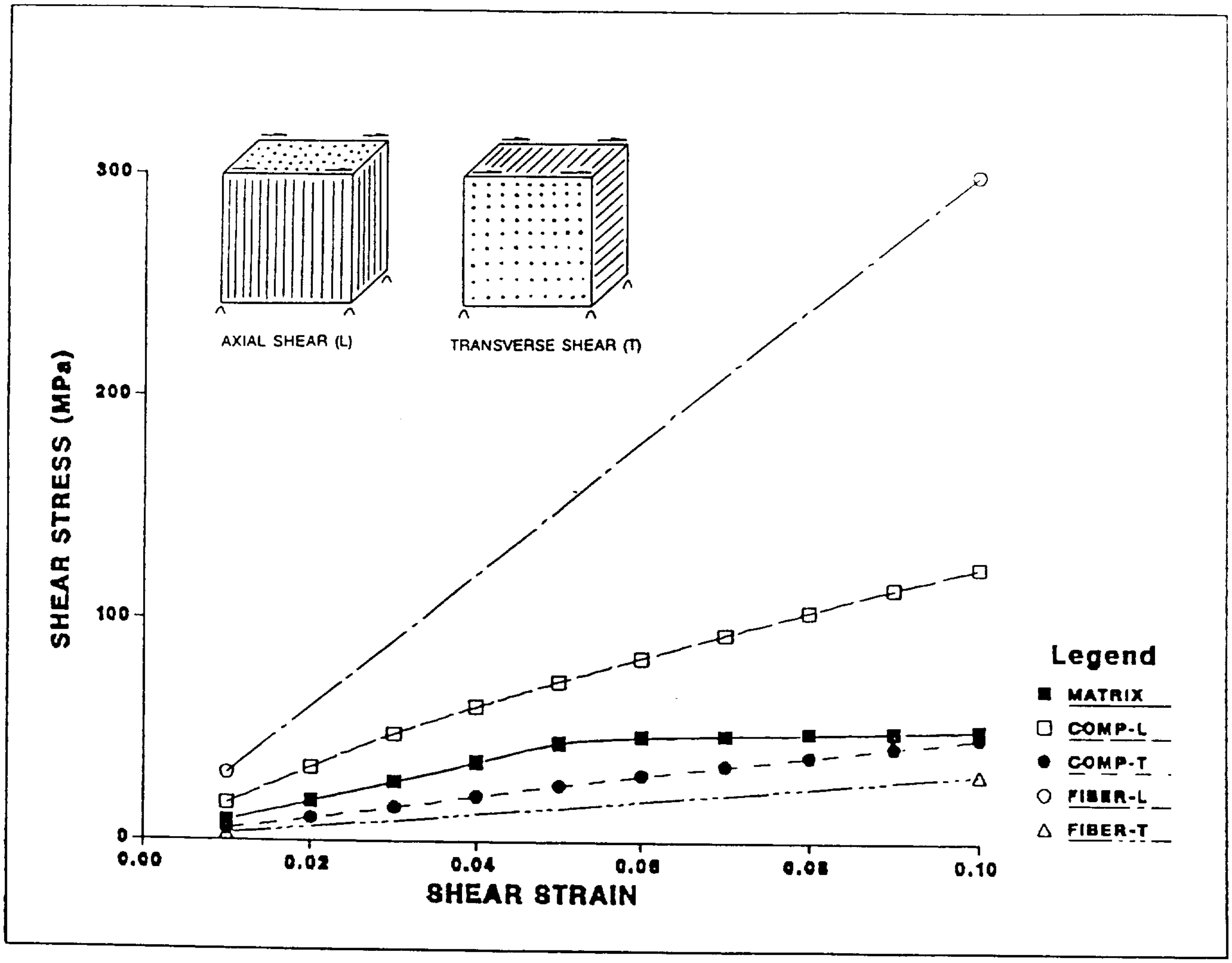


Fig. E-4 Axial and Transverse Shear on Uniaxial Composite with Transversely Isotropic Fibers.

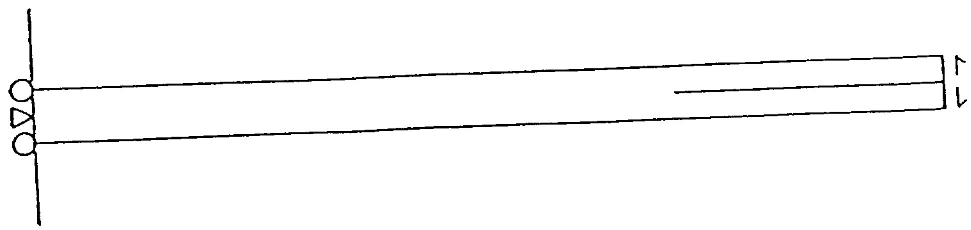
allowed for optimum refinement in the crack tip areas while keeping more cost-efficient, coarse meshes in far-field areas. The finite element models with homogeneous orthotropic material properties (Figs. E-5 and E-6) were then interfaced with the ABAQUS code. In this study, a blunted circular crack tip was used.

Classical fracture mechanics predicts that the highest stress concentration associated with a pure opening Mode I test will occur at the tip of the crack in an idealized homogeneous, isotropic, linear elastic material. However, for an orthotropic but still homogeneous, linear elastic material, the highest stress concentration was found to occur at the shoulder of the crack (Fig. E-7)[14]. Further, only a small amount of anisotropy (5:1) causes a significant shift of the stress concentration towards the shoulder (Fig. E-8).

Composite material imperfections, in the form of constant fiber misalignments or fiber waviness were also investigated. Constant fiber misalignment was simulated by specifying the orientation of the orthotropic homogeneous material properties to be off axis. For 5^o misalignment, the two highest stress concentrations at the shoulders of the crack showed a difference in magnitude of the order of 3:1 from top to bottom. (See Fig. E-9.) This variation is due primarily to local stress concentrations, since about 10 crack diameters away from the crack tip, the difference in stress between the top and bottom values due to anisotropy is only about 20%. (See Fig. E-10.)

Fiber waviness was simulated by assuming a sinusoidal distribution of the orthotropic material orientation along the length of the beam, while constant through the thickness and the width. Fig. E-11 illustrates how this representation of fiber waviness can be repositioned with respect to the crack tip. This is equivalent to crack advance in a medium with wavy material orientation. For each of those cases, the maximum principal stress at the top shoulder of the crack tip was monitored and its variation over one waviness period was found to be very close to a sinusoid. For a given period, L_o = 10mil, the maximum stress occurs at the top when maximum positive misalignment is at shoulder level, and the minimum stress occurs at the top when maximum negative misalignment is at shoulder level. The periodic nature of this problem makes it clear that the stress field is characterized by the maximum stress location continuously jumping from the top shoulder of the crack to the

MODE I



ORTHOTROPIC MATERIAL PROPERTIES

Longitudinal Young's modulus (E1) . . . . . 20000 Kips

Transverse Young's modulus (E2) . . . . . . 1000 Kips

In-plane Shear modulus. . . . . 500 Kips

Longitudinal Poisson's ratio 0.2

Transverse Poisson's ratio 0.4

Fig. E-5 Beam Geometry and Material Properties for Analysis.

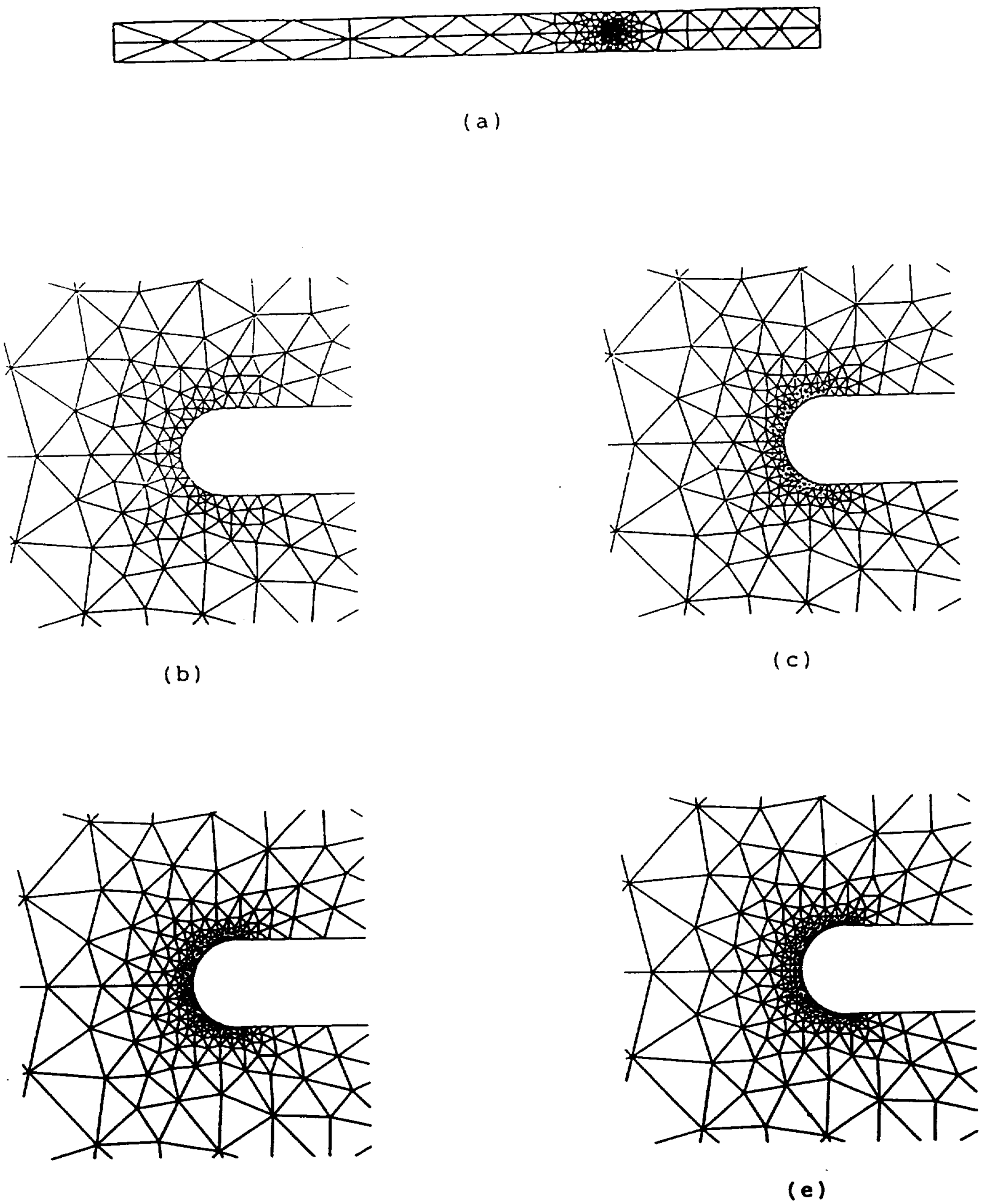


Fig. E-6 Finite Element Meshes for Beam. a) overall, and b,c,d,e) closeups of progressively finer meshes in the area of the crack tip.

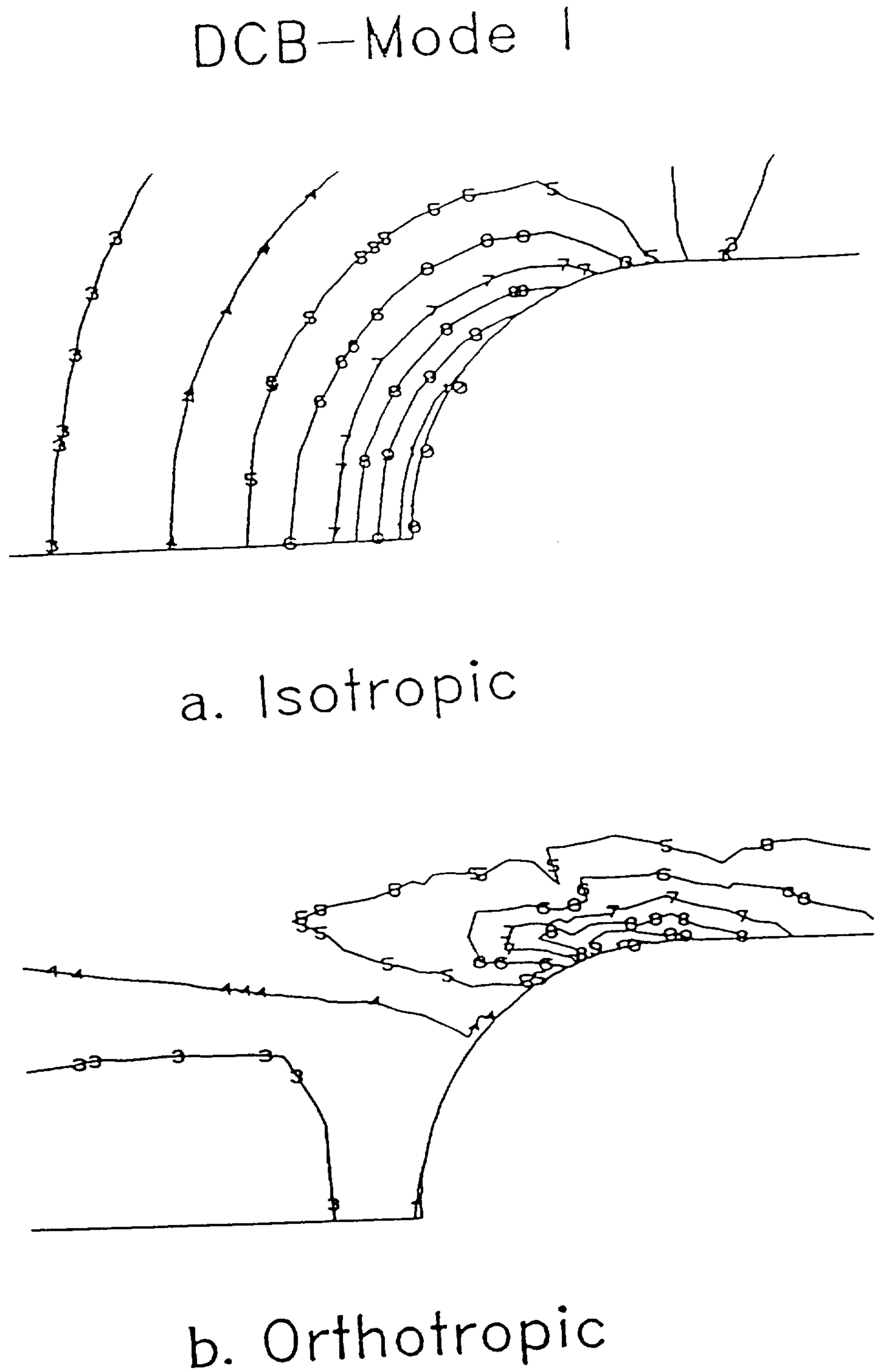


Fig. E-7 Maximum Principal Stresses at the Tip of the Crack Under Mode I Loading.

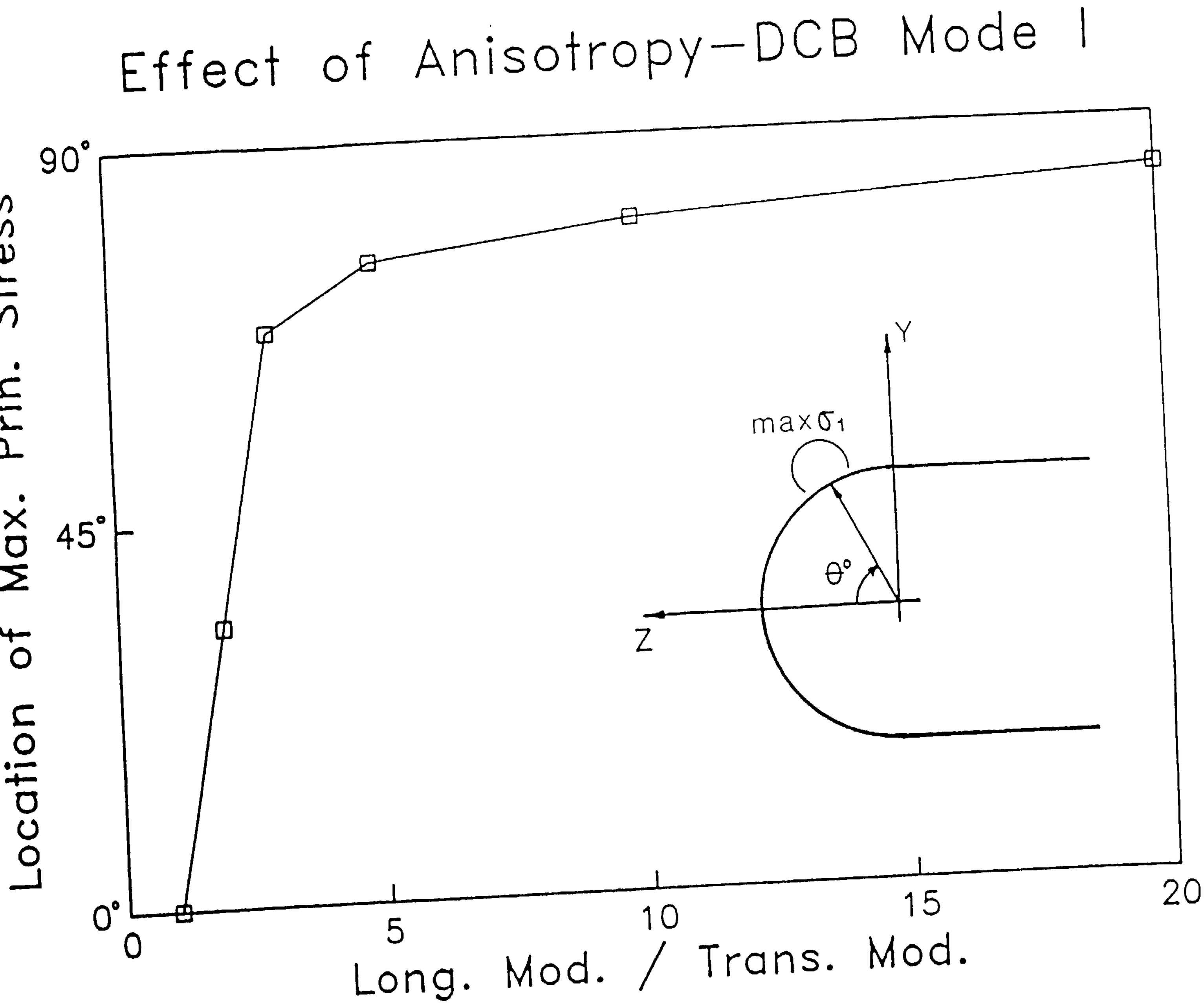
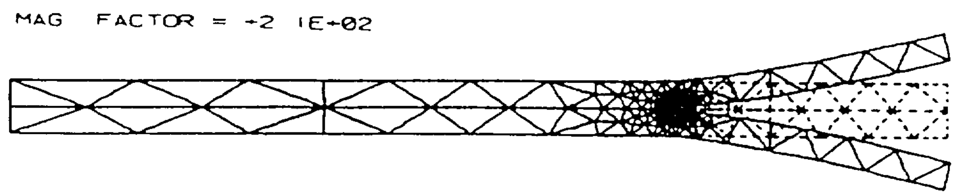
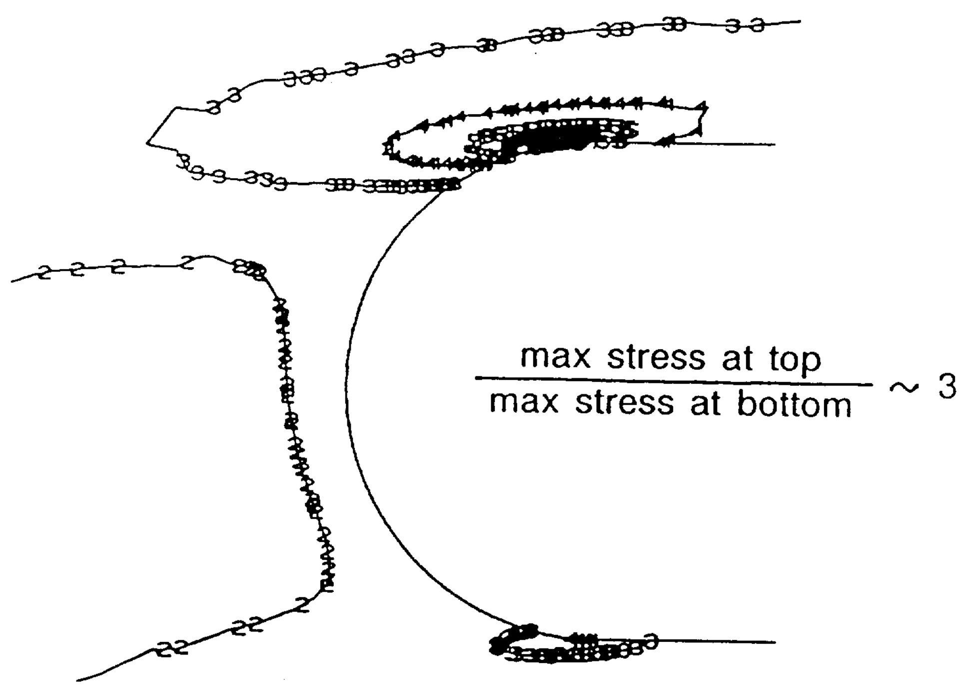


Fig. E-8 Location of Maximum Stress as a Function of Beam Anisotropy.

MODE I



CONSTANT FIBER MISALLIGNMENT OF 5 DEGREES



MAX PRINCIPAL STRESS CONTOURS AT THE CRACK TIP

Fig. E-9 Effect of 5 Degree Fiber Misalignment on Local Stresses.

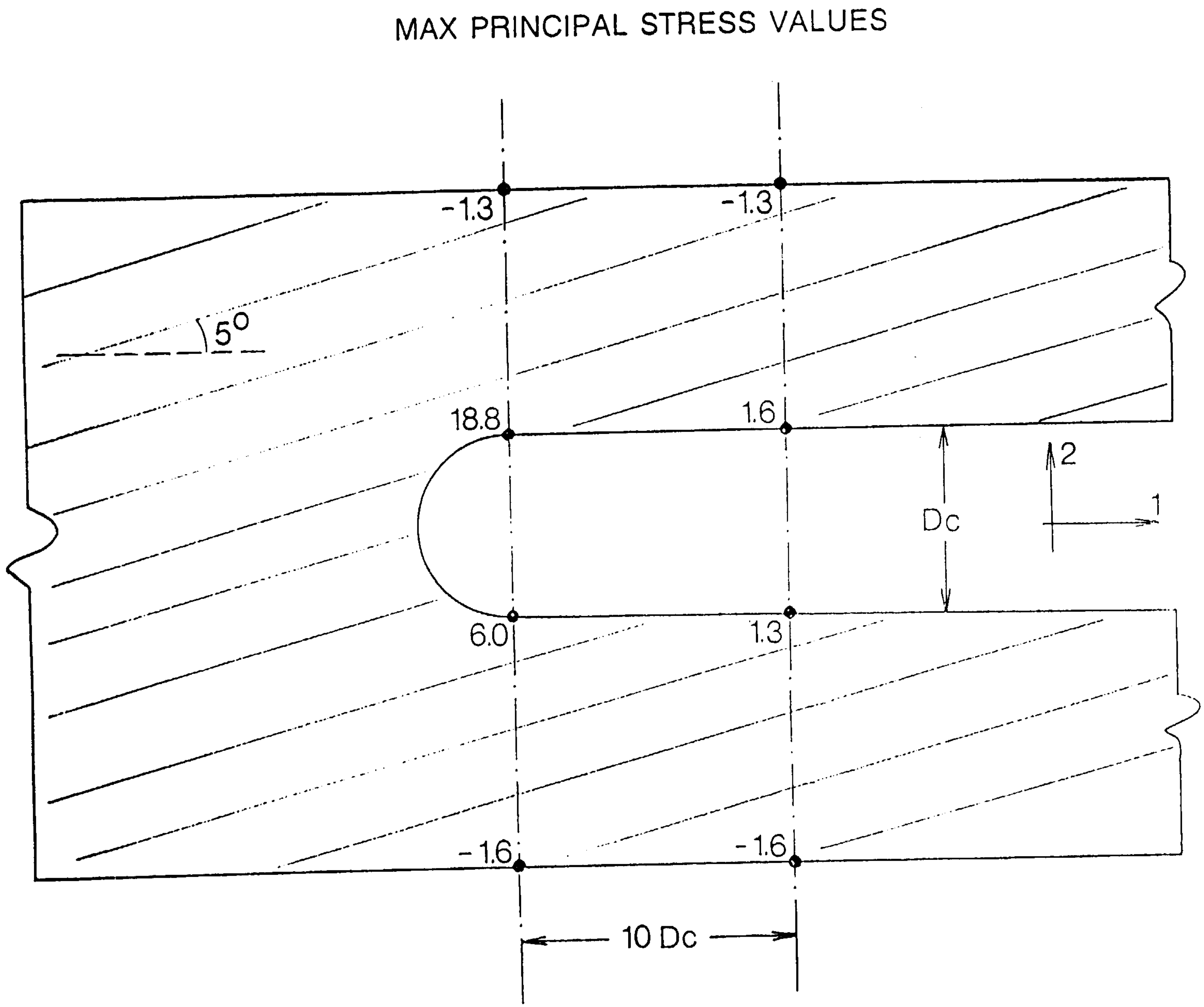


Fig. E-10 Effect of 5 Degree Fiber Misalignment a Small Distance From the Crack Tip (Note - the crack is not drawn to scale.)

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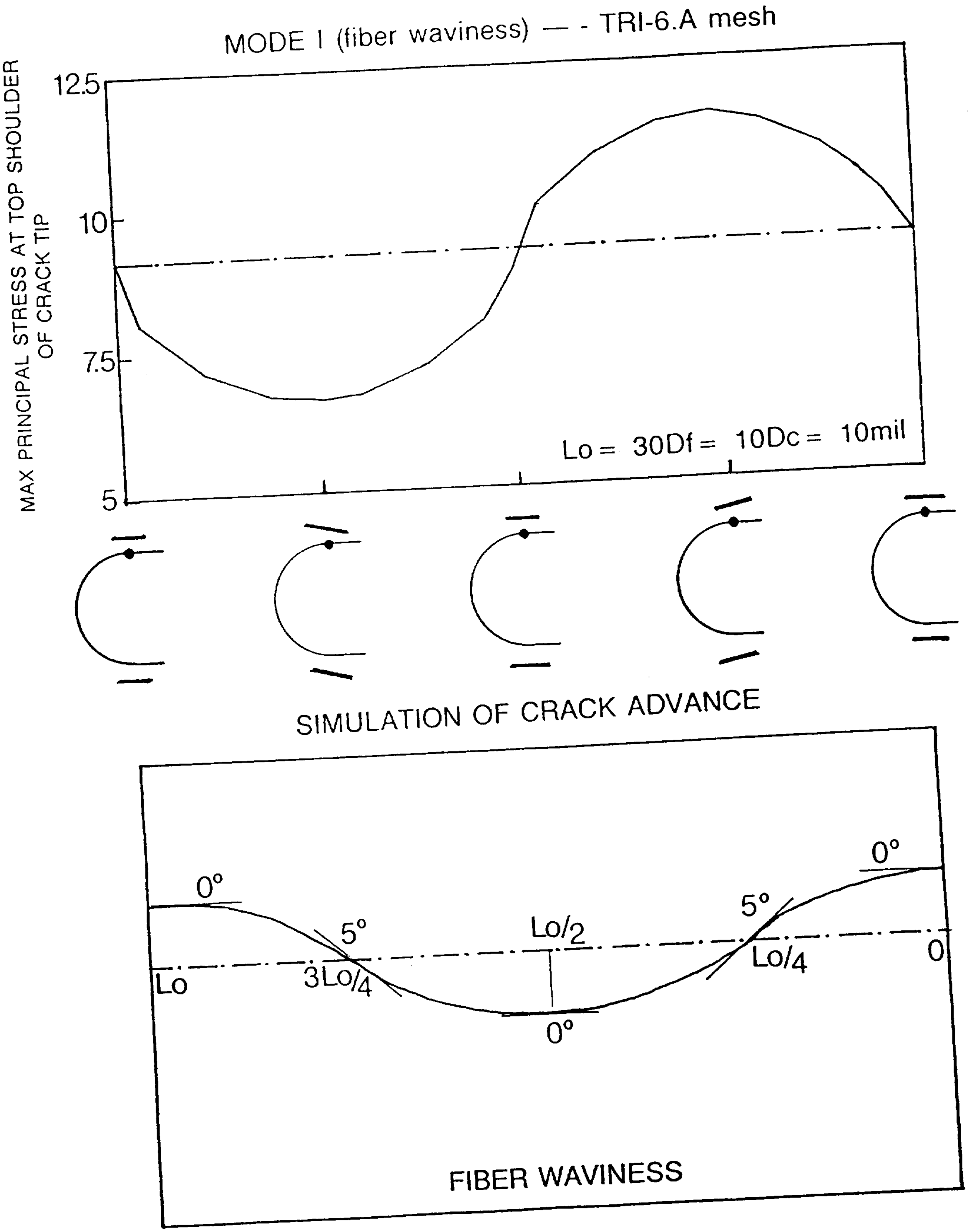

Fig. E-11 Fiber Waviness.

bottom. This might explain why jagged crack progagation has been observed even in Mode I (delamination) experiments. Fig. E-12 presents a collection of similar plots for three different values of period of the fiber waviness. All three periods have been normalized so that they can be plotted together. Results for an infinitely long period, which can be simulated by constant misalignment, are also presented. The shape of all these curves is similar but the difference between the maximum and minimum value of stress varies with the period. As the period increases (smoother waviness), the gap between maximum and minimum stress increases.

To show the significance of using a realistic material constitutive relation, the nonlinear time-dependent material model for thermoplastics, which was developed earlier, was incorporated into a detailed Mode II specimen analysis. The DCB specimen was subjected to bending loading, which produces an overall Mode II stress-state at the crack tip. A thin resin-rich layer with isotropic but nonlinear viscoelastic behavior was introduced in front of the crack tip, while orthotropic linear elastic material properties were used for the rest of the beam. Fig. E-13 presents, qualitatively, results for in-plane shear stress contours at three different steps of the loading history. This illustrates the progressive redistribution of stresses around the crack tip. Load factor 1 corresponds to the elastic range of the material's behavior, within which the response is fully symmetric. As stresses at both of the highest concentration areas increase and reach the onset of nonlinear response (load factor 6), significant variations are observed between top and bottom. The upper half of the crack tip which is under tension can no longer support stresses as high as the lower half which is under compression. This can be explained by the different behavior of the model in tension versus compression. For load factor 6 the compressive part is still in the linear elastic range, while the tensile portion has already entered the nonlinear range. When the compressive part also enters its 'post-yield' range (load factor 10), the stress distribution variations become even more dramatic.

These results imply that local variations in the microstructure, along with details of the material constitutive relation, are critical to the stress state near the crack tip. They do, therefore, strongly influence the measured fracture properties.

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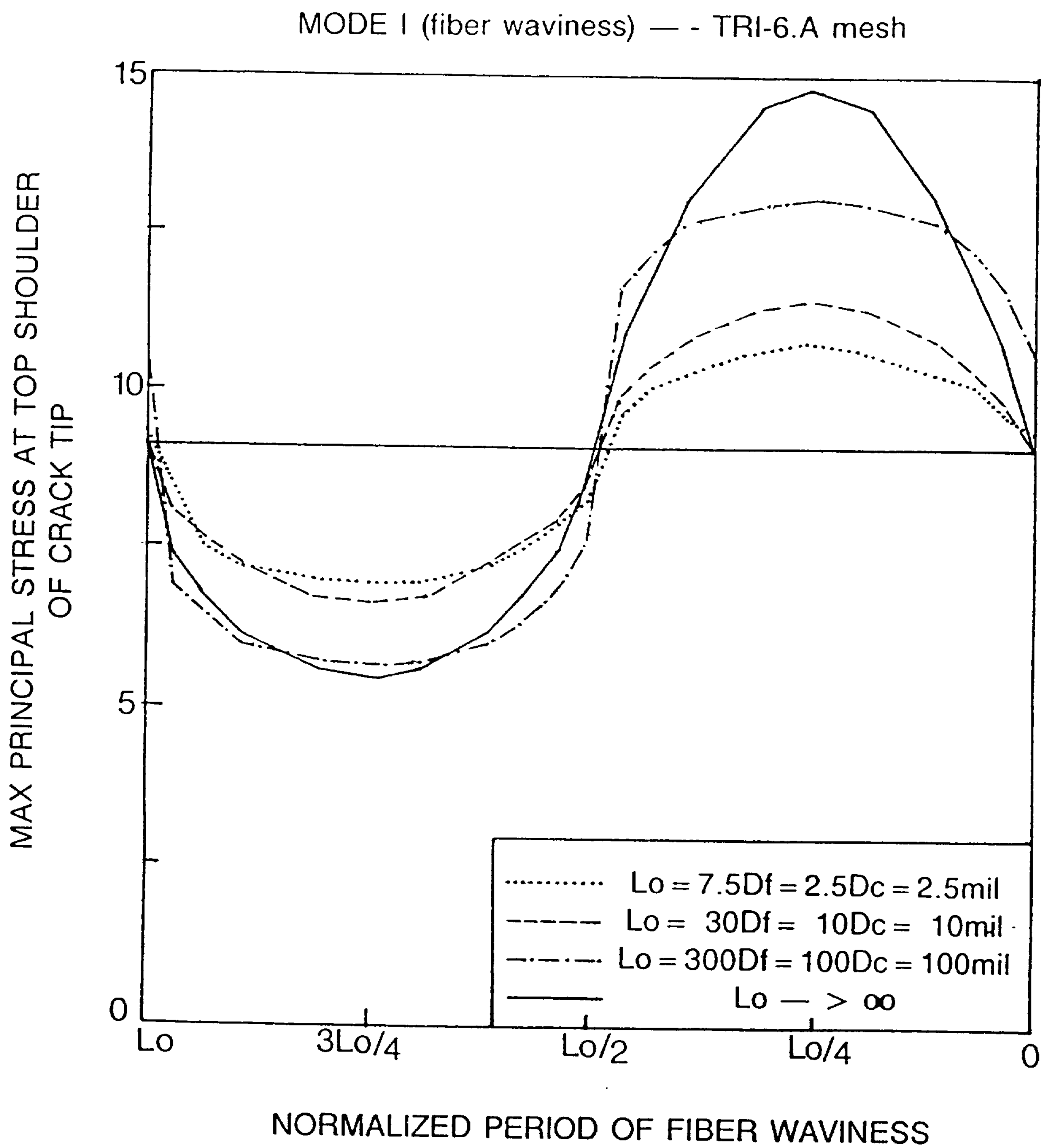
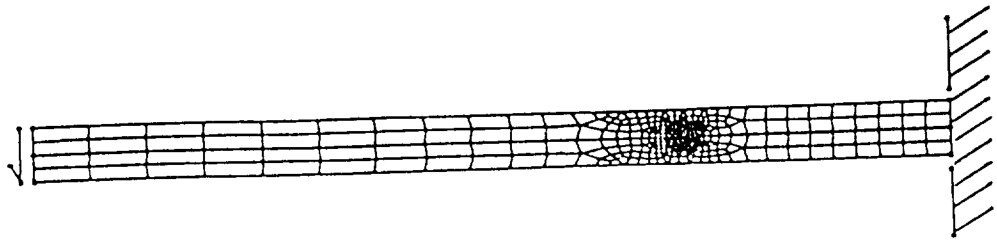
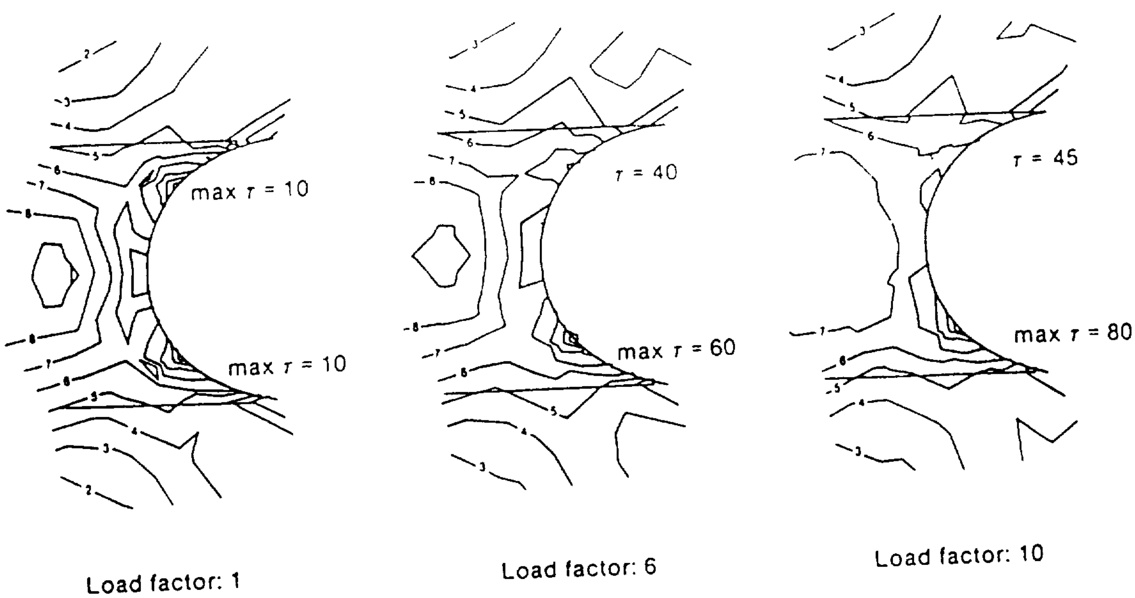


Fig. E-12 Effect of Period of Fiber Waviness on Peak Stress.



Overall specimen configuration



Close-up of shear stress contours at the crack tip for different levels of applied load

Fig. E-13 Introduction of Nonlinear Viscoelastic Thin Layer at the Crack Tip.

PLANS FOR UPCOMING PERIOD

Efforts have already begun and will continue in the area of computational efficiency in the prediction of macroscopic properties. In particular, the current need to use through-the-thickness discretization on the structural level can be eliminated by constructing a PHA model for application at the lamina level, for use with currently available laminated shell elements. In addition the PHA will soon be incorporated into the fracture studies to allow more complex material properties to be represented.

RECENT PRESENTATIONS AND PUBLICATIONS BY PROF. M. SHEPHARD ON THIS SUBJECT

"A Material Model for the Finite Element Analysis of Metal Matrix Composites", (with J. F. Wu, G. J. Dvorak and Y. A. Bahei-El-Din) Composites Science and Technology, submitted for publication, 1988.

"Composite Material Models in ABAQUS", (with N. D. Lambropoulos, J. F. Wu, S. S. Sternstein and G. J. Dvorak), ABAQUS User's Conference Proceedings, HKS, Providence, RI, 1988, pp. 211-226.

"Nonlinear Finite Element Modeling of Composites", ONR Contractor's Review, Santa Barbara, CA., Sept. 30, 1987.

"Finite Element Modeling of Composite Behavior", General Electric, Pittsfield, MA., Feb. 2, 1988.

PART III

TECHNICAL INTERCHANGE

TECHNICAL INTERCHANGE

Technical meetings, both on- and off-campus, provide for the interchange of technical information. Table III-1 provides a calendar of pertinent meetings during the reporting period and Table III-2 shows the meetings attended by RPI composites program faculty/staff/students during the same interval. Some on-campus meetings, with special visitors or 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 continued to make once-a-week luncheon programs worthwhile. These meetings have been held among the faculty and graduate students involved (listed in Part IV. Personnel - of this report) during the academic year. They 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. They 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 BBL programs as held during this reporting period.

During the week of July 27-32, 1987, RPI offered, for the eighth time, a special short course in composite materials and structures. Twenty-six graduate engineers from government and industry enrolled. In addition to RPI speakers, Mr. Bob Riley of McDonnell Aircraft and Dr. Stephen Tsai of the Air Force Material Laboratories lectured as shown in Table III-3. The announcement brochure, listing lecturers and the subject matter, is attached as an appendix to this report. The participants and their organizations are listed in Table III-6.

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Table III-1

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Calendar of Composites-Related Events

May 1, 1987 through April 30, 1988

DATES	MEETING	SPONSOR	PLACE
1987			
May 18-20	43rd Annual Forum	AHS	St. Louis, MO
May 31	Canadian Congress of Applied Mechanics	CANCAM	Edmonton, Alb, CN
Jun 7-8	Centennial Symposium on Micromechanics	ALCOA	Hilton Head, SC
Jun 15	Mechanics Conference	Army	West Point, NY
Jun 23-24	Advanced Composites Prog. Review	SDIO/IST	Woods Hole, MA
Jul 13-15	Materials Research Council Mtg on High Temperature Composites	DARPA	LaJolla, CA
Jul 19-24	18th Biennial Conference on Carbon	Worcester Polytechnic	Worcester, MA
Sep 20-23	24th Annual Meeting	Soc. of Engrg.	Salt Lake City, UT
Oct 16	12th Mechanics of Composites Review	U.S.A.F.	Ft. Lauderdale, FL
Oct 18-19	Symposium on Advances in Thermoplastic Matrix Composite Materials	ASTM	Bal Harbor, FL
Nov 3-6	Fiber-Tex 87	-	Greenville, SC
Nov 30-Dec 5	1987 Fall Meeting	Materials Res. Soc.	Boston, MA
Dec 7-9	Composites in Mfg Conf.	COG/SME	Long Beach, CA
Dec 14-15	Annual Winter Mtg.	ASME	Boston, MA
1988			
Jan 1-12	Winter Workshop	URI	Santa Barbara, CA
Jan 11-15	Gordon Research Conf.	DARPA	Ventura, CA

Table III-1 (concluded)

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Calendar of Composites-Related Events

May 1, 1987 through April 30, 1988

DATES	MEETING	SPONSOR	PLACE
Jan 17-20	12th Annual Conf on Composites and Advanced Ceramics	American Ceramic Soc.	Cocoa Beach, FL
Mar 2	Composites Overview '88	RPI	Troy, NY
April 18-20	29th Structures Structural Dynamics & Materials Conf.	AIAA/ASME/ ASCE/AHS	Williamsburg, VA
April 25-26	Symposium on Metal Matrix Composites: Testing, Analysis and Failure Modes	ASTM	Sparks, NV
April 5-9	Symposium on High Temperature/High Performance Composites	Matls Res Soc	Reno, NV

Table III-2

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Pertinent Professional Meetings Attended

May 1, 1987 through April 30, 1988

DATES	MEETING
1987	
5/18-20	43rd AHS Annual Forum (Profs. Diefendorf & Loewy), St. Louis, MO.
5/31-6/4	Canadian Congress of Applied Mechanics (CANCAM '87) (Prof. Dvorak*), Edmonton, Alberta.
6/7-8	Alcoa Laboratories Centennial Symposium on Micro Mechanics: (Profs. Dvorak & Sternstein*), Hilton Head, SC.
6/15	Army Mechanics Conference (Prof. Dvorak*), West Point, NY
6/23-24	SDIO/IST Advanced Composites Program Review (Prof. Dvorak*), Woods Hole, MA.
7/13-15	DARPA Materials Research Council Meeting on High Temperature Composites (Prof. Dvorak*), La Jolla, CA.
7/19-24	XVIIIth Biennial Conference on Carbon (Prof. Diefendorf*), Worcester, MA.
9/20-23	Society of Engineering Science 24th Annual Meeting, (Prof. Dvorak*), Salt Lake City, UT.
10/7	Federated American Spectroscopy Society Meeting (Prof. Sternstein*), Detroit, MI.
10/16	U.S. Air Force, Twelfth Mechanics of Composites Review (Prof. Dvorak*), Ft. Lauderdale, FL.
10/18	Deformation & Failure of Thermoplastic Composite Materials, ASTM Meeting (Prof. Sternstein*), Bal Harbor, FL.
11/3-6	Fiber-Tex-87, (Prof. Diefendorf*), Greenville, SC.
11/30-12-5	Materials Research Society 1987 Fall Meeting, (Prof. Diefendorf*), Boston, MA.
12/7-9	Composites in Mfg, Society of Manufacturing Engineers, Composites Group, (Prof. Loewy), Long Beach, CA.

* Made presentation, chaired session, or was a panel member.

Table III-2 (continued)

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Pertinent Professional Meetings Attended

May 1, 1987 through April 30, 1988

DATES	MEETING
12/14-15	ASME Annual Winter Mtg (Prof. Dvorak*), Boston, MA.
1988	
1/11-15	Gordon Research Conf on Plasticity Effects in Composites (Profs. Dvorak & Sternstein*), Ventura, CA
1/12	URI Winter Workshop, (Prof. Diefendorf*), Santa Barbara, CA.
1/17-20	American Ceramic Society 12th Annual Conference on Composites and Advanced Ceramics, (Prof. Diefendorf*), Cocoa Beach, FL.
4/5-9	Materials Research Society 1988 Spring Meeting, (Prof. Diefendorf*), Reno, NV.
4/25-26	ASTM Symposium on Metal Matrix Composites: Testing, Analysis and Failure Modes (Prof. Dvorak* and Bahei-El-Din), Sparks, NV

* Made presentation, chaired session, or was a panel member.

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Table III-3

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

May 1, 1987 through April 30, 1988

SUBJECT	SPEAKERS/VISITORS	DATE
Role of Materials in Manufacturing Productivity	Dr. R. Komanduri N.S.F. Washington, DC	5/1/87
Shear Localization in Viscoplastic Solids	Kwon Hee Kim Dept. of Mech. Eng. M.I.T.	5/8/87
SHORT COURSE: Advanced Composite Materials and Structures	Prof. O. Bauchau (RPI) Prof. R. Diefendorf (RPI) Prof. G. Dvorak (RPI) Dr. S. Tsai - USAFML Mr. B. Riley - McDonnell Aircraft	7/27-31/87
Carbon Fibers Technology	Prof. R. Diefendorf (RPI) Dr. T. Iwahashi Dr. E. Komaki Dr. T. Miyamori Dr. Y. Nishimoto Dr. K. Okuda } Japanese Fiber Industry Delegation	7/27/87
Composites Research at RPI and Northrup	Dr. W. Biricik Dr. D. Luippold Northrup Aircraft	9/6/87
Developments in Two Surface Plasticity Theory	Dr. D. McDowell Woodruff School of Mech. Eng. G.I.T.	9/22/87
Damage Mechanics and Its Applications	Prof. M. Chrzanowski Technical Univ. of Krakow Krakow, Poland	10/6/87
NASA/AFOSR Site Visit and Program Review	D. Tenney - LaRC L. Nichols - LeRC C. Chamis - LeRC D. Mulville - NASA Hqs.	10/6-7/87
Acousto-Elasticity and Ultrasonic Measurements of Residual Stresses	Dr. Y-H Pao Dept. of Theoretical & Applied Mechs. Cornell University	10/27/87

Table III-3 (continued)

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

May 1, 1987 through April 30, 1988

SUBJECT	SPEAKERS (RPI)	DATE
Constitutive Models for Crazes and Their Effects on Crack Growth in Glassy Polymers	Prof. C-Y Hui Dept. of Theoretical & Applied Mechs. Cornell University	11/3/87
The Use of Simplified Models for the Investigation of the Vibration Characteristics of Structural Elements Liable to Buckling	Prof. M. A. Souza Dept. of Civil Eng. PUC - Rio Rio de Janeiro, Brazil	11/4/87
Voids in Elastic-Plastic Shear Fields	Dr. D. Tracey U.S. Army Materials Technology Lab Watertown, MA	11/5/87
Scattering of Ultrasonic Waves by Cracks with Applications to Quantitative Non-Destructive Evaluation	Prof. J. Achenbach Northwestern University	2/3/88
Probabilistic Design with Brittle Materials	Mr. C. Johnson Corporate Research & Development General Electric Co. Schenectady, NY	2/11/88
Analysis of Damage in Composites	Prof. Z. Hashin Tel-Aviv University	2/19/88
Presentation to Wyman/Gordon Corp.	Prof. J. Diefendorf (RPI)	2/28/88
RPI Composites Center Overview '88	O. Bauchau (RPI) J. Diefendorf (RPI) G. Dvorak (RPI) E. Krempl (RPI) R. Loewy (RPI) S. Sternstein (RPI) S. Winckler (RPI)	3/2/88

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Table III-3 (continued)

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

May 1, 1987 through April 30, 1988

SUBJECT	SPEAKERS	DATE
Thermal-Mechanical Finite Element Modelling of Metal Forming Processes	Dr. M. Pietrzyk Dept. of Mech. Eng. Univ. of New Brunswick	3/22/88
Overstress Profiles Near Broken Fibers in a Unidirectional Fiber-Reinforced Composite	Mr. Dimitris Lagoudas Cornell University	4/4/88
Structures & Materials Requirements for Reusable Hypervelocity Vehicles, 10^{th} Annual P.E. Hemke Lecture	Dr. S. C. Dixon NASA Langley Res. Ctr.	4/12/88
A Continuum Damage Model	Prof. Y. Weitsman Mechanics & Materials Ctr. Texas A & M University	4/13/88
General Image Method Plane-Layered Elastostatic Medium	Mr. N. Fares Harvard University Cambridge, MA	4/18/88
Stress Intensity Factors Along Pinned Non-Straight Crackfronts	Mr. N. Fares Harvard University Cambridge, MA	4/18/88
Flaws Near a Bimaterial Interface - Some 3D Examples	Prof. L. Keer Dept. of Civil Eng. Northwestern University	4/20/88
Numerical Simulation of Fitting of Shrink Fits - A Thermomechanically Coupled Contact Problem	Prof. F. G. Kollman Technische Hochschule Darmstadt Federal Republic of Germany	4/20/88
A Continuum Theory of Creep Resistance for Particle-Strengthened Metals	Mr. Z-G Zhu Rutgers University	4/25/88

Table III-3 (concluded)

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

May 1, 1987 through April 30, 1988

SUBJECT	SPEAKERS	DATE
Modal Interactions in the Nonlinear Response of Structural Elements Theory and Experiment	Prof. A. Nayfeh Dept. of Engrg Science & Mechs. V.P.I. and State University	4/27/88

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	RPI/DARPA-ONR HiTASC Retreat	Lake Luzerne, NY	5/12/87
J. Diefendorf	Presented C&D Whitney Lecture on Science & Technology	Rensselaerville, NY	6/10-13/87
R. Loewy	To Discuss RPI Composites Program	Lockheed California Co., Burbank, CA	6/29/87
S. Sternstein	Invited Lecture "Mechanical Properties of Thermoplastic Matrix Composites"	Shell Labs Houston, TX	10/1/87
R. Loewy	To Discuss RPI Composites Program and Tour Facilities	Northrup Aircraft, Hawthorne, CA	10/30/87
S. Sternstein	To Deliver Seminar on "Mechanical Properties of Thermo-plastic Matrix Composites"	Lockheed California Co., Composites Ctr., Burbank, CA	1/7/88
J. Diefendorf	Presented the Talk "Deformation of Mesophase Pitches"	Pioneering Research Lab., E.I. duPont, Wilmington, DE	1/14/88
J. Diefendorf	Presented the Talk "Characterization of Pitches"	UTRC East Hartford, CT	1/15/88
S. Sternstein	To Deliver Seminar "Thermoplastic Matrix Composites"	G. E. Plastics Development Ctr. Pittsfield, MA	2/2/88
S. Sternstein	To give the Talk "Mechanical Properties and Modeling of Thermo-plastic Matrix Composites"	G. E. Aircraft Engine Div. Evandale, OH	2/18/88
J. Diefendorf	Presented Talk "Oxidation Resistant Carbon/Carbon Composites	General Dynamics Ft. Worth, TX	2/28/88

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Table III-4 (concluded)

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	Technical Discussion HiTASC Applications	General Electric Co. Aircraft Gas Turbine Engine Div., Evansdale, OH	2/18/88
J. Diefendorf	Presented Invited Seminar "Carbon Fibers"	UCLA Los Angeles, CA	4/1/88
R. Loewy	To Discuss RPI Composites Program and Tour Facilities	Douglas Aircraft Long Beach, CA	4/14/88
R. Loewy	To Discuss RPI Composites Program and Tour Facilities	Lockheed California Co., Composite Center Burbank, CA	4/15/88

Table III-5

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Brown Bag Lunch Schedule

May 1, 1987 through May 1, 1988

DATE	TOPIC	RESP. FACULTY
May 1	Administrative Report VISITORS: R. Jaros, F.M.C. Corp	R. Loewy
Sep 4	Admin. Report & Welcome Mechanics of Fatigue Damage in MMC Laminates VISITORS: Dr. W. Biricik & Mr. D. Luippold Northrup Corp.	R. G. Loewy E. C. J. Wung
Sep 11	Overview of Composites Research at RPI	All
Sep 18	General Discussion Topic: Mechanical Design Problems in Composites	O. Bauchau R. Loewy S. Winckler
Sep 25	Administrative Report Modeling Studies in Thermoplastic Matrix Composites	R.J. Diefendorf S.S. Sternstein M. Shephard
Oct 2	Administrative Report Progress and Plans for the RP-3	S.S. Sternstein V. Paedelt
Oct 9	General Discussion Trends in High Temperature Composites	G. Dvorak R.J. Diefendorf
Oct 16	Site Visit and Program Review Summary CVD & Carbon/Carbon Composites	R. G. Loewy R.J. Diefendorf
Oct 23	Administrative Report Fatigue in Composites	R.J. Diefendorf E. Krempl
Oct 30	Administrative Report Making Use of Thermal Deformations	S.S. Sternstein S. Winckler
Nov 6	General Discussion: Strength in the 3rd Dimension	S. Winckler S.S. Sternstein
Nov 13	Report on 12th Annual Mechanics of Composites Review Research on MMC	G. Dvorak G. Dvorak
Nov 20	Administrative Report CVD & Carbon/Carbon Composites	R.J. Diefendorf R.J. Diefendorf
Nov 27	Thanksgiving Recess	

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Table III-5 (continued)

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Brown Bag Lunch Schedule

May 1, 1987 through May 1, 1988

DATE	TOPIC	RESP. FACULTY
Dec 4	Administrative Report Thermoplastic Laminate Characteristics	S.S. Sternstein S.S. Sternstein M. Shephard
Dec 11	Administrative Report General Update of DARPA/ONR HiTASC Program	R.J. Diefendorf R.J. Diefendorf
Jan 22	Administrative Report General Discussion of Composite Laboratory Activities with Emphasis on Future Instruction and Research	R. Loewy R. Loewy V. Paedelt S. Winckler
Jan 29	Administrative Report Effective Behavior of Composites in the Presence of Imperfect Contact Between the Constituents Ballistic Damage Tolerance of Composite Shafts	R.J. Diefendorf Y. Benveniste O. Bauchau
Feb 5	Administrative Report Fatigue in Composites Report on COGSME Mtg.	R. Loewy E. Krempl R. Loewy
Feb 12	Administrative Report Progress on RP-3 Using Thermal Deformation	R. Loewy V. Paedelt S. Winckler
Feb 19	Administrative Report Testing of Notched Boron-Aluminum Specimens Acoustic Emission Tutorial: Acoustic Emission from Boron-Aluminum	S. Sternstein G. Dvorak H. Scarton
Feb 26	Administrative Report General Discussion: Joints in Composites	R. Loewy O. Bauchau R. Loewy
Mar 4	Administrative Report Report on CCMS Open House CVD & Carbon/Carbon Composites	R. Diefendorf S. Sternstein R. Diefendorf
Mar 11	Administrative Report Update on Darpa/ONR HiTASC Program. Failure Mechanism in MMC	R. Diefendorf R. Diefendorf G. Dvorak
Mar 18	Administrative Report General Discussion: Composites and the Space Environment	R. Loewy R. Reeves

Table III-5 (concluded)

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Brown Bag Lunch Schedule

May 1, 1987 through May 1, 1988

DATE	TOPIC	RESP. FACULTY
Mar 25	Administrative Report Progress on RP-3 Modelling Studies in Thermoplastic Matrix Comp's	R. Loewy V. Paedelt M. Shephard S. Sternstein
Apr 1	SPRING BREAK	
Apr 8	Administrative Report Using Thermal Deformations Fatigue in Composites	R. Loewy S. Winckler E. Krempl
Apr 15	Administrative Report Discussion: Applications of Ceramics in High Temp/High Stress Situations	R. Loewy R. Diefendorf G. Dvorak
Apr 22	Administrative Report Failure Mechanisms in MMC Modelling Studies in Thermoplastic Composites	R. Loewy G. Dvorak M. Shephard S. Sternstein
Apr 29	Administrative Report Characterizing Thermoplastics Report on MRS Mtg	R. Loewy S. Sternstein R. Diefendorf

Table III-6

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Short Course: Composite Materials and Structures
Participants and Affiliations

July 27, 1987 through July 31, 1987

Kenneth Bannister
Mechanical Engineer
Ballistics Research Lab.
Aberdeen Proving Ground, MD

Gerd Beckmann
Project Manager
Rensselaer Polytechnic Institute
Troy, NY

Edward Bennett
Mechanical Design Engineer
Mare Island Naval Shipyard
Vallejo, CA

Bernice Brezina
Mechanical Engineer
Naval Ordinance Station
Indianhead, MD

Gregory Curd
Aerospace Engineer
Naval Air Systems Command
Washington, DC

Valery Dunaevsky
Sr. Staff Engineer
American Standard Co.
Westinghouse Airbrake Division
Wilmerding, PA

Mark Hering
Aerospace Engineer
Hill Air Force Base
Ogden, UT

Rick Jensen
Member, Technical Staff
McDonnell Douglas Helicopter Co.
Mesa, AZ

Bill Johnson
Mechanical Engineer
Texas Instruments
Louisville, TX

Courtney Johnson
Mechanical Engineer
Naval Air Test Center
Patuxent River, MD

Allyne Kaizoji
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McDonnell Douglas Helicopter Co.
Mesa, AZ

Walter Krainski
Mechanical Engineer
U. S. Army
Natick R, D & E Center
Natick, MA

Fania Lee
MTS II
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Mesa, AZ

Gisela McClellan
Specialist Engineer
Lockheed Georgia Co.
Marietta, GA

Michael Mohajery
Dir. Technology Marketing Div.
Alcoa
Pittsburgh, PA

Joe Musco
Member, Technical Staff
McDonnell Douglas Helicopter Co.
Mesa, AZ

Table III-6 (concluded)

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Short Course: Composite Materials and Structures
Participants and Affiliations

July 27, 1987 through July 31, 1987

Peter Newmeier
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Burbank, CA

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Kaman Aerospace Corp.
Bloomfield, CT

Philip Rice
Senior Engineer
General Dynamics - Convair
San Diego, CA

Luis Santos
Materials & Process Engineer
Kaman Aerospace Corp.
Bloomfield, CT

Tony Scelsi
Member, Technical Staff
McDonnell Douglas Helicopter Co.
Mesa, AZ

Bruce Snyder
U.S. Air Force
AFWAL/FIBRA
Wright Patterson AFB, OH

Alan Stewart
MTS I
McDonnell Douglas Helicopter Co.
Mesa, AZ

John Waldron
Aerospace Engineer
Warner, Robins Air Logistic Ctr.
Robins AFB, GA

Richard Warnock
Sergeant
Chanute Air Force Base
Chanute AFB, IL

Dan Will
Naval Architect
Mare Island Naval Shipyard
Vallejo, CA

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PART IV

REFERENCES

REFERENCES

[1] Tsai, S.W. & Hahn, H.T., "Introduction to Composite Materials", Technomic Publishing, Westport, CT., 1980.

[2] Krempl, E. and Sutcu, M., "A Simplified Orthotropic Viscoplasticity Theory Based on Overstress", RPI Report MML 87-8, September, 1987, revised April 1988, submitted for publication.

[3] Krempl, E. and Hong, B. Z., "A Simplified Laminate Theory Using The Viscoplasticity Theory Based On Overstress. Part I: In-Plane Stress-Strain Relations For Metal Matrix Composites", RPI Report MML 87-9, September 1987, revised March 1988, submitted for publication.

[4] Krempl, E. and Lee, K. D., "Thermal, Viscoplastic Analysis of Composite Laminates", Symposium on High Temperature/High Performance Composites, Materials Research Society, to appear in the Proceedings (1988).

[5] Krempl, E. and Hong, B. Z., "A Simplified Laminate Theory Using The Viscoplasticity Theory Based On Overstress. Part II: General Stress-Strain Relations For Metal Matrix Composites", RPI Report MML 88-5, August 1988.

[6] Kreider, K. G. and Prewo, K. M., "Boron-Reinforced Aluminum", Composite Materials, Vol. 4, Brautman, L. J. and Krock, R. H., editors, Academic Press, 399-471, 1974.

[7] Shetty, H. R. and Chou, T. W., "Mechanical Properties and Failure Characteristics of FP/Aluminum and W/Aluminum Composites", Metallurgical Transaction A, Vol. 16A, 853-864, May 1985.

[8] Bahei-El-Din, Y. A. and Dvorak, G. J., "Plasticity Analysis of Laminated Composite Plates", Transactions of ASME, J. of Applied Mechanics, Vol. 49, 740-746, December, 1982.

[9] "ABAQUS Theory and User's Manual", Hibbitt, Karlsson and Sorensen, Inc., 100 Medway St., Providence, Rhode Island, 02906-4402, July 1985, Version 4.5(a).

[10] Beahmann, P. L., Wittchen, S. L., Shephard, M. S., Grice, K. R., and Yerry, M. A., "Robust Geometrically Based, Automatic Two-Dimensional Mesh Generation", Int. J. Num. Meth. Engrg., Vol. 24, 1987, pp 1043-1078.

[11] Teply, J. L., "Periodic Hexagonal Array Model for Plasticity analysis of Composite Materials", Ph.D. Dissertation, University of Utah, 1984.

[12] Teply, J. L. and Dvorak, G. J., "Bounds on Overall Instantaneous Properties of Elastic-Plastic Composites", J. Mech. Phys. Solids, to appear in 1988.

[13] Bankert, R. J., Sternstein, S.S. and Shephard, M. S., unpublished research, Rensselaer Polytechnic Institute, Troy, N.Y., 1986.

[14] Bankert, R. J., Lambropoulos, N. D., Shephard, M. S. and Sternstein, S. S., "Thermoplastic Matrix Composites: Finite Element Analysis of Mode I and Mode II Failure Specimens", ASTM Symposium on Advances in Thermoplastic Matrix Composite Materials, 1987.

PART V

PERSONNEL, AUTHOR INDEX

PERSONNEL

Co-Principal Investigators

Loewy, Robert G., Ph.D.	Institute Professor
Wiberley, Stephen E., Ph.D.	Professor and Chairman of Chemistry

Senior Investigators

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

Research Staff

Technical Manager, Composites Laboratory
Paedelt, Volker

Post Doc
Rex Chen, Ph.D.
Donald Radford, Ph.D.

Research Associate
Gilles Pijaudier-Cabot

Graduate Students

Barlow, S.	Majors, P.
Buhrmaster, C.	Martine, E.
Chen, T.	Ngo, D.
Hall, R.	Palmer, M.
Henderson, L.	Shah, R.
Hill, S.	Srinivasan, K.
Hong, A. B.Z.	VanBuskirk, C.
Kaveh-Ahangar, A.	Wu, J. F.
Lambropoulos, N.	Wung, E.
LaraCurero, E.	Zarzour, J.

* Fields of Specialty
† Member of Budget Committee together with Co-Principal Investigators

AUTHOR INDEX

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Loewy, R. G. - Editor

Appendix A-1

Site Visit

NASA/AFOSR Composite Materials and
Structures Program

Room 3117 JEC, RPI, Troy, N.Y.

Agenda

Oct. 6, 1987

8:30	Welcome and Introduction	R. Loewy
9:15	Carbon/Carbon Constituent Research	R. Diefendorf
10:15	Break	
10:30	Matrix Dominated Failure in Thermoplastic Matrix Composites: Mode I & Mode II Studies	S. Sternstein
11:30	Finite Element Modeling of Composite Behavior	M. Shephard N. Lambropoulos*
12:30	Lunch (Sage Dining Hall - Center Mtg. Rm)	
1:15	Plasticity and Fatigue Damage in MMC	
2:15	Viscoplasticity of Fiber Reinforced Metal Matrix Laminates	E. Krempl
3:15	Break	
3:30	Aeroelastic Tailoring of Composite Beam Structures	O. Bauchau
4:30	General Discussion	
5:00	Adjourn	
5:30	Cocktails	Sage Dining Hall - Center Mtg. Rm
6:30	Dinner	Sage Dining Hall - Center Mtg. Rm

* Graduate Student

Oct. 7, 1987

8:30	Student Presentations of Associated Topics	
	1) Development of Fiber Coatings for Producing Stable Intermetallic Matric Composites	D. Larkin*
	2) Ceramic Matrix Composites	R. Boisvert*
	3) High Temperature Creep in Composites	E. Lara-Curzio*
9:30	Overview of the Center for Composite Materials & Structures	S. Sternstein
10:15	Break & Walking Tour of New Facilities	
10:45	Summary	
11:15	Evaluative Session (working lunch) (JEC 3012)	- NASA/AFOSR Representatives
11:15	Advisory Panel Meeting (working lunch) (JEC 3117)	- Industry Representatives
12:30	Executive Session -	NASA/AFOSR Representatives and RPI Budget Advisory Committee
1:30	Adjourn	

* Graduate Student

Site Visit

ATTENDEES

NASA/AFOSR Composite Materials and
Structures Program

Rensselaer Polytechnic Institute

October 6-7, 1987

Daniel Mulville (Technical Monitor)	NASA - Headquarters
Christos Chamis	NASA - Lewis
Michael Nemeth	NASA - Langley
Lester Nichols	NASA - Lewis
Darryl Tenney	NASA - Langley

Industrial Technical Advisory Panel

I. Grant Hedrick	Grumman Aerospace
Ron Johnson	Boeing Military
Bob Riley	McDonnell Douglas
James Whiteside	Grumman Aerospace