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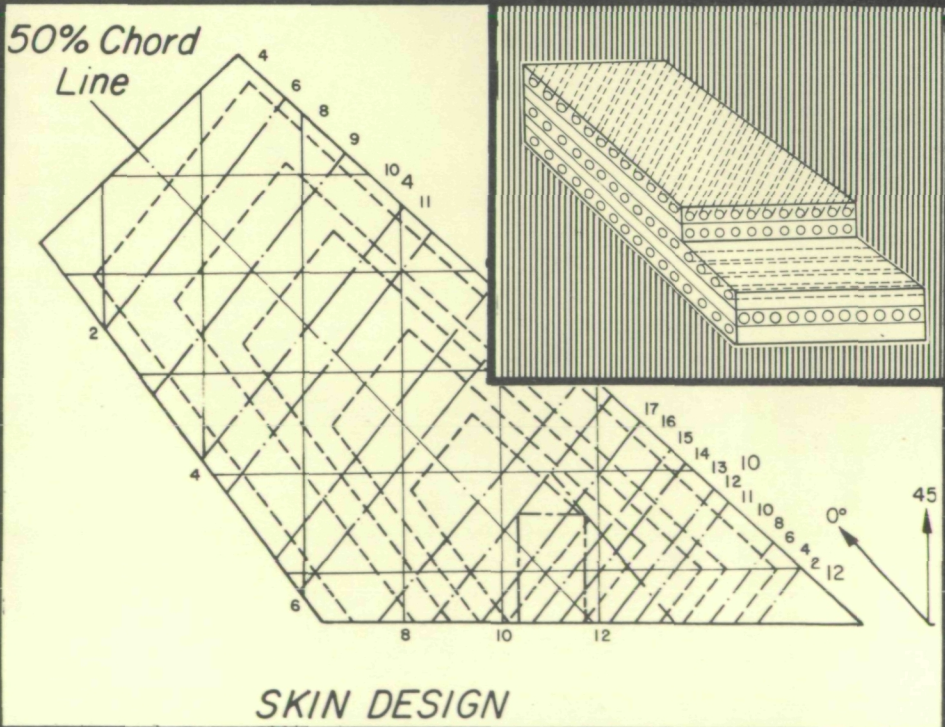
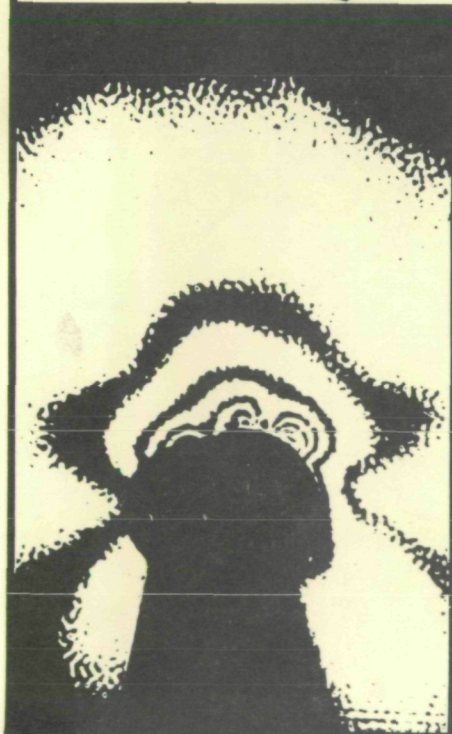
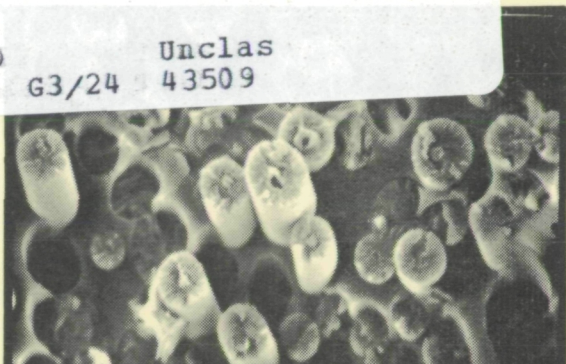
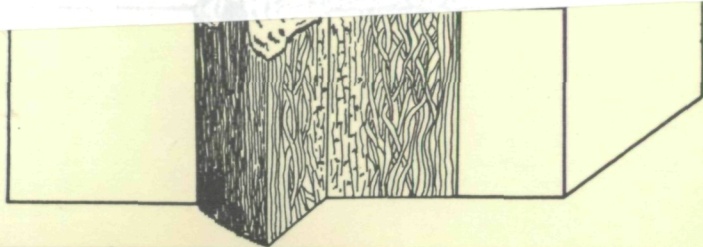
Materials and Structures Program

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May 1, 1985 through April 30, 1986

COMPOSITE STRUCTURAL MATERIALS

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PART I
INTRODUCTION

INTRODUCTION

Widespread materials and structures research activity and application developments are underway as the aerospace community enters what may be considered the second generation of filamentary composite materials advances. The promise of substantially improved performance and potentially lower costs provided the driving force behind research into fiber reinforced composite materials for application in aerospace hardware at the beginning of the composites era more than twenty years ago. Although increased strength and stiffness to weight ratios were paramount, not the least of such advantages was the new practicality of components with continuously variable properties, known to give better performance but prohibitively expensive using even the latest metal forming techniques.

Much progress has been achieved since the initial developments in the mid 1960's. Applications to secondary structure are now extensive, and applications to primary structure continue to increase on operational vehicles, the latter mainly on military aircraft, the former on both military and commercial vehicles. Most utilization is still largely in a material substitution mode, and only a handful of designs represent departure from metal structure design practice of the kind which fully exploit the nature of these new materials. More extensive experiments - including (a) those remaining from NASA's influential ACEE program, currently underway on large airplanes in commercial passenger operation; (b) the US Army's All Composite Aircraft (helicopter) Program, ACAP; (c) specialized applications to spacecraft; and (d) in a few military developments, such as the AV-8B and the X-29 - have accumulated only limited flight experience.

The strong technology base needed to realize the full promise of composites in sophisticated aerospace structures is only just beginning to be put in place. NASA and AFOSR have supported expanding and strengthening the technology base through programs which advance fundamental knowledge and the means by which it can be successfully applied in design and manufacture. The purpose of the RPI program as funded by NASA and AFOSR has been to develop critical advanced technology in the areas of physical properties, structural concepts and analysis, manufacturing, reliability and life prediction. Specific goals within the RPI program have

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shifted as the state of composite materials and structures art has developed. Major efforts in arriving at new structural design concepts, for example, have given way to the pressing need to deal with the problems of higher operating temperatures.

Our approach to accomplishing such goals is through an interdisciplinary program, unusual in several important aspects for a university. First, the nature of the research is comprehensive. Specific projects deal with fiber and matrix constituent properties, the integration of constituents into composite materials and their characterization, the behavior of composites as they are used in generic structural components, their non-destructive and proof testing and, where the state of the art will be advanced by doing so, extending the research effort into simulated service use so that the composite structure's long-term integrity under conditions pertinent to such use can be assessed.

Inherent in the RPI program is the motivation which basic research into the structural aspects provides for research at the materials level, and vice versa.

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

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

A third aspect is increasing the interaction between appropriate members of NASA's staff of Research Center scientists and engineers and those active in the program at RPI. This has required, first, identification of individual researchers within NASA centers whose areas of interest, specialization and active investigation are in some way related to those of RPI faculty

supported under the subject grant. Second, a program of active interchange has been encouraged and the means by which such interaction can be fostered is sought. Benefits expected as a result of 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.

Overall program emphasis is on basic, long-term research in the following categories: (a) constituent materials, (b) composite materials, (c) generic structural elements, (d) processing science technology and (e) maintaining long-term structural integrity. Depending on the status of composite materials and structures research objectives, emphasis can be expected to continue to shift, from one time period to another, among these areas. Progress in the program will be reported in the following pages under these headings. Those computer methodology developments are also undertaken which both support Rensselaer projects in composite materials and structures research in the areas listed above and which also represent research with the potential of widely useful results in their own right.

In short, the NASA/AFOSR Composites Aircraft Program is a multi-faceted program planned and managed so that scientists and engineers in a number of pertinent disciplines at RPI will interact, both among themselves and with counterpart NASA Center researchers, to achieve its goals. Research in basic composition, characteristics and processing science of composite materials and their constituents is balanced against the mechanics, conceptual design, fabrication and testing of generic structural elements typical of aerospace vehicles so as to encourage the discovery of unusual solutions to present and future problems. In the following sections, more detailed descriptions of the progress achieved in the various component parts of this comprehensive program are presented.

PART II
CONSTITUENT MATERIALS

II-A MECHANICAL PROPERTIES OF HIGH PERFORMANCE CARBON FIBERS

II-A-1 COMPLETION OF EARLIER PROJECTS

II-A-2 CHEMICAL VAPOR DEPOSITION

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II-A-1 Completion of Earlier Projects

Senior Investigator: R. J. Diefendorf

The following projects under this general heading, are now considered complete, as described in the previous progress report.

- Ordered Polymers as Matrices for Composite Materials
- The Influence of Carbon Fiber-Epoxy Interface Bond on the Fracture of Composites
- Residual Stress in High Modulus and High Strength Carbon Fibers

II-A-2 Chemical Vapor Deposition

Senior Investigator: R. J. Diefendorf

1. Introduction

The objective of this project is to obtain a better understanding of the mechanisms involved in the Chemical Vapor Deposition (CVD) of carbon. Through a more exact understanding of the carbon deposition process, we anticipate being able to realize advantages both in the production economics of high temperature carbon/carbon composites and in the mechanical properties achieved for the graphite fibers produced by this means.

2. Status

CVD was one of the earliest methods of advanced filament fabrication; Boron CVD onto a Tungsten substrate, for example, in the early to mid 1960's. Little is known about the process for carbon, however, despite its use in making carbon-carbon composites. RPI's approach is to give insight through studies of simple but representative carbon CVD configurations.

3. Progress During Reporting Period

Work is being done in two major areas. The first employs graphite capillary tubes as a model of the pore structure of a 3-dimensional carbon weave preform. The intent is to investigate CVD mechanisms on basal plane and edge surfaces. Methane is used as the source gas in the CVD apparatus whose schematic is shown in Fig. II-A-1. Furnace temperatures ranging from 1300° to 1600° C, pressures from 2 to 5 torr, and gas flow held constant at

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270 cm³/sec cover the conditions used in these investigations. Good penetration, in terms of a uniform deposit throughout the length of the tube, was observed at the lower temperatures and pressures (Fig. II-A-2a and b). The structure of the depositions were mainly columnar in nature and all were very similar. Additional studies using feed gases with higher molecular weight are needed to define the actual deposition mechanisms which occur.

The second area of effort concentrates on CVD of carbon on graphite fibers. A pitch based fiber is used as a substrate for deposition of a very fine coating of carbon (Fig. II-A-3). Deposition is accomplished using the same furnace as employed in the capillary studies, but temperatures were held at 1000° C, pressures at 2 torr and gas flows at 50 cm³/sec. Fibers processed in this manner showed that the coating resulting from a three hour duration showed an increase in the fiber elastic modulus of approximately 67% while decreasing the strength by only 10% (Table II-A-1). Although fiber diameter growth of 10% could be measured, the coating is barely observable under SEM examination, suggesting that the region of change in fiber structure is very thin. One possible explanation for these results is that the carbon coating penetrates the fiber and thus increases its modulus relative to the untreated substrate fiber. More work is necessary to properly identify the character of the coating.

The carbon skin also appears to alter the fiber-epoxy interfacial bond. Several composite specimens fabricated using the CVD-coated fibers were produced and subsequently tested to failure to analyze the fiber fracture surfaces. While the fracture appearance of the fibers was similar to that of uncoated fiber specimens, differences did appear in the adherence of epoxy to the fiber surface and in fiber pull-out length.

4. Plans for Upcoming Period

We anticipate making use of higher molecular weight precursor gases to observe their deposition character. Some runs will be made with a hydrogen diluent as well, since it is known to retard deposition, although the mechanism is not yet clear. The data from these studies, in conjunction with that taken during the lower molecular weight experiments already performed, may provide the insight needed to formulate a plausible deposition mechanism theory. Other work towards that end will deal with a "species trap" scheme in which only certain molecular weight species will be allowed to deposit. By

observing the variations in deposits we should be able to speculate more knowledgably as to a model of deposition.

More work will be done coating fibers using CVD to determine if the same effects obtained in low-temperature furnace runs can be observed using higher temperatures. The higher temperature runs will more accurately simulate the heat treatment procedures followed during actual fiber production. This anticipates the possibility of incorporating CVD into existing production scenarios.

Finally, for the upcoming period, we intend to complete characterization of the effects of coating carbon fibers on the mechanical properties of carbon-epoxy laminates and on the fiber-epoxy interface.

5. Current Publications or Presentations by Professor Diefendorf on this Subject

"Carbon Fibers"

Presented at Fiber Conference, Strosk'e Plaso, Czch., May 1985.

"Evolution or Revolution in Materials"

Presented at NSF Innovation Meeting, Albany, NY, May 1985.

"The Physical Chemistry of the Carbon Fiber/Epoxy Resin Interface", with C. E. Uzoh

"The Chemical Vapor Deposition in Open-Ended Capillary Tubes", with Y. Sohda

"A Theoretical Calculation of Residual Stresses in Carbon Fibers", with K. J. Chen

"The Effect of Heat Treatment on the Structure and Properties of Mesophase Precursor Carbon Fibers", with G. D. D'Abate

"The Strength Distribution of Etched Carbon Fibers", with K. J. Chen

Presented at the 17th Carbon Conference and published in the Proceedings of the 17th Carbon Conference, Lexington, KY, June 1985.

"Structure and Properties of Carbon Fibers"

Presented at Wright Patterson Materials Laboratory, Dayton, OH, August 1985.

"Mesophase Formation in Polynuclear Aromatics"

Presented at US Steel, Monrovia, PA, November 1985.

5. Current Publications or Presentations by Professor Diefendorf on this Subject (continued)

"Carbon Fibers"

Published in *Chem. V. Lakna*, [35], 154, 1985.

"The Relationships Between Structure and Properties in Carbon Fibers"

Presented at duPont Company, Wilmington, DE, February 1986.

"Ceramic Matrix Composites"

Presented to Kaiser Aerotech Corp. at RPI, Troy, NY, March 1986.

"Carbon Fibers From Mesophase Pitch Precursors"

Presented at 3rd Annual Materials Technology Center Conference and Distinguished Lecture, Southern Illinois Univ., Carbondale, IL, April 1986.

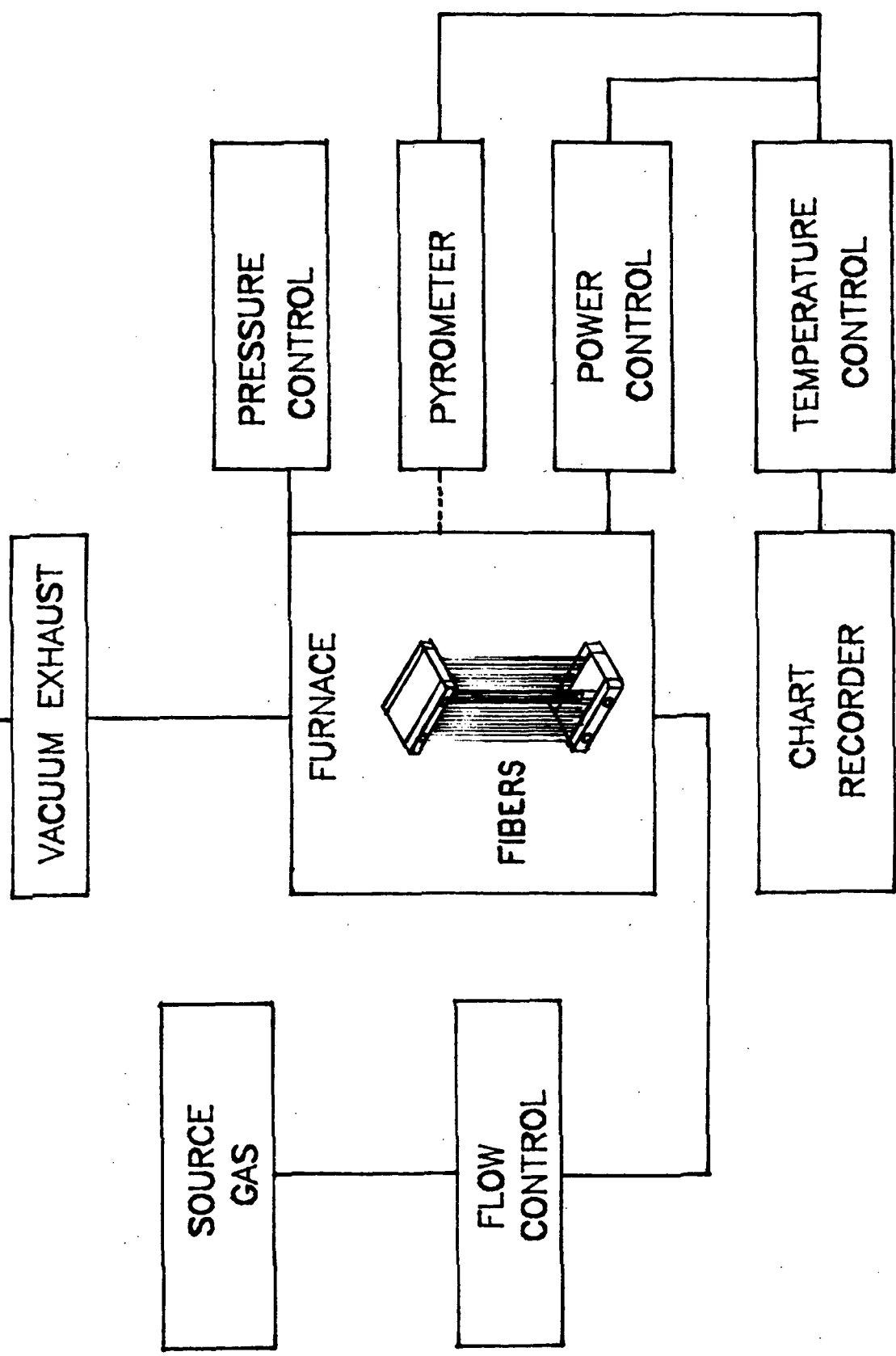


Figure II-A-1
CVD APPARATUS SCHEMATIC DIAGRAM

TEMPERATURE EFFECT

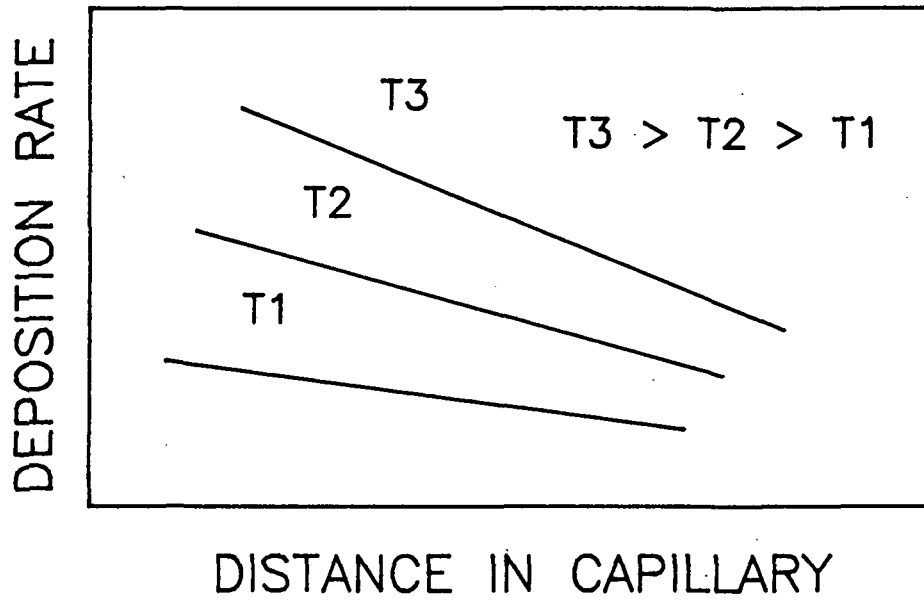


Figure II-A-2a
TEMPERATURE EFFECT ON DEPOSITION RATE
AS A FUNCTION OF DISTANCE IN CAPILLARY

PRESSURE EFFECT

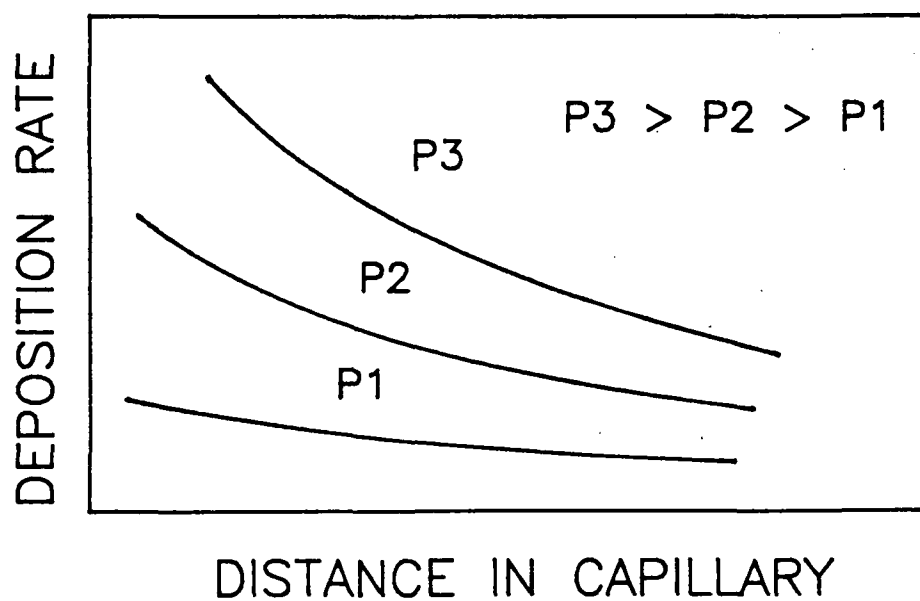


Figure II-A-2b
PRESSURE EFFECT ON DEPOSITION RATE
AS A FUNCTION OF DISTANCE IN CAPILLARY

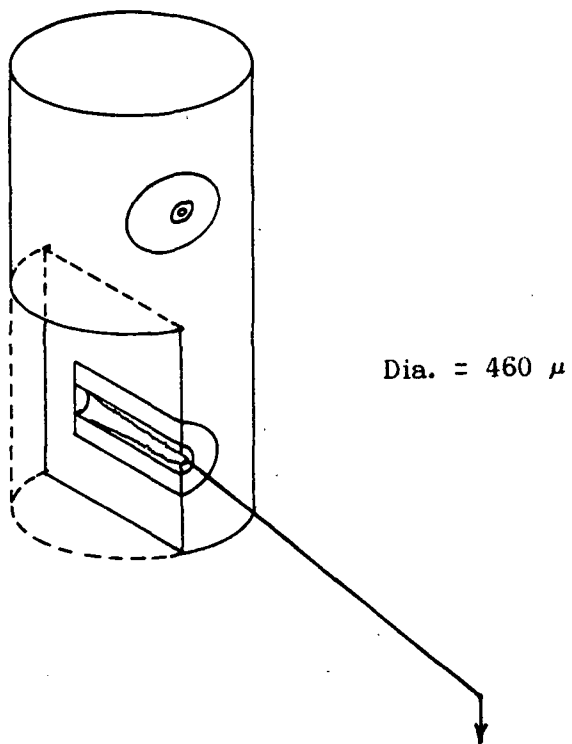


Figure II-A-3
CAPILLARY TEST BLOCK SHOWING CARBON DEPOSIT

CVD / FIBER EXPERIMENTAL RESULTS

FURNACE PARAMETERS:

T = 1000 °C FLOW = 50 SCCM CH4

P = 2 TORR

<u>TIME (Hrs)</u>	<u>FIBER DIA. (μ)</u>	<u>STRENGTH (ksi)</u>	<u>MODULUS (msi)</u>
0	10.29 + 0.15	280 + 29	30.3 + 3.0
1	10.05 + 0.47	309 + 46	29.4 + 2.3
2	11.13 + 0.35	322 + 43	30.9 + 1.95
3	11.39 + 2.1	252 + 66	50.8 + 4.9

Table II-A-1
CVD/FIBER EXPERIMENTAL RESULTS

PART III

COMPOSITE MATERIALS

- III-A FATIGUE IN COMPOSITE MATERIALS
- III-B MECHANICAL PROPERTIES OF HIGH PERFORMANCE POLYMERIC
MATRIX COMPOSITE LAMINATES
- III-C NUMERICAL INVESTIGATION OF THE MICROMECHANICS OF COMPOSITE
FRACTURE
- III-D DELAMINATION IN GRAPHITE/EPOXY LAMINATES

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III-A Fatigue in Composite Materials

Senior Investigator: E. Krempl

1. Introduction

The deformation and failure behavior of graphite/epoxy tubes under biaxial (axial tension and torsion) loading is being investigated. The aim of this research is to increase basic understanding of and provide design information for the biaxial response of graphite/epoxy composites.

2. Status

In Reference [1]* an existing phenomenological damage accumulation law was extended to multiaxial conditions and a fatigue limit was introduced in the differential equation. In this report period further progress was made in studying the nature of the phenomenological damage accumulation laws and how they relate to residual strength and residual life. An experimental investigation into the influence of interlaminar normal stresses on the fatigue life - initiated in response to questions which arose regarding tests of tubes being configuration-specific - was completed. This phase of the research has been conducted by PhD candidate Deukman An and will be completed during the fall of 1986. A 10-kW induction heating unit and an MTS biaxial high-temperature extensometer were delivered and installation of these systems begun during the reporting period in preparation for future testing at elevated temperatures (to 1000°C).

3. Progress During Report Period

a) Concept of Time-Discontinuity of Damage at Failure

To illustrate the idea of discontinuity of damage at failure, consider the example of constant creep loading with applied stress level, σ_{CP} . During this creep loading, as shown in Figure III-A-1, the ratio of residual to ultimate strength, R_S , decreases from one, at time=0, to a lower residual strength, $R_S(\sigma_{CP})$, which corresponds to the applied stress level, σ_{CP} . As the specimen breaks, the residual strength drops to zero resulting in a discontinuity of residual strength at the time of failure, t_f . Using the usual notation for a discontinuity in a real function, the residual strength immediately before and

* References in this section are given on page 27.

after the failure at time t_f may be expressed as

$$\begin{aligned} R_S^- &= R_S(\sigma_{cp}) & \text{and} \\ R_S^+ &= 0 \end{aligned} \quad (1)$$

where superscripts "-" and "+" denote approaching t_f (before failure) and leaving t_f (after failure), respectively.

Figure III-A-1 shows the discontinuity of residual strength at the time of failure. By conceptually equating a discontinuity in residual strength with damage, we also have discontinuity in damage at failure, t_f .

As a second example of time-discontinuity of damage, consider the single-edge, slotted specimen of Figure III-A-2 which has constant stress amplitude ($0 \sim \sigma$) fatigue loading. If the slot is viewed as a straight crack, we can define another kind of damage, D'' , in the form

$$D'' = \frac{a}{2b} \quad (2)$$

where a is the crack length and $2b$ is the width of the specimen.

Considering the crack length as variable, there is a relationship between crack length, a , and damage, D'' as follows:

$$\begin{aligned} a = 0 &\leftrightarrow D'' = 0 & \text{and} \\ a = 2b &\leftrightarrow D'' = 1 \end{aligned} \quad (3)$$

The definition of damage, D , given in Reference [1] can be recovered from the expression for damage in equation (2) by setting

$$D'' = 1 - \frac{1}{D + 1} \quad (4)$$

From linear elastic fracture mechanics [2], the specimen has a critical crack length, a_c , for a given loading, σ . If the crack length exceeds a_c , failure of the specimen occurs; so discontinuity of damage at failure may be expressed in the form

$$\begin{aligned} D''^- &= \frac{a_c}{2b} & \text{and} \\ D''^+ &= 1 \end{aligned} \quad (5)$$

In summary, the definition of failure by an approach from time after failure (i.e., the "right-hand approach") defines damage at failure in terms of zero residual strength, but an approach from time before failure (i.e., the "left-hand approach") defines damage at failure in terms of the the loading conditions on the critical cross-section. In general, these definitions will lead to different results. Miner [3], Hashin and Rotem [4], Subramanyan [5],

Bui-Quoc [6], Chaboche [7], and Ostergren and Krempl [8], etc., used the left-hand approach, whereas Broatman and Sahu [9], Yang and Liu [10], and Yang and Jones [11], etc. used the right-hand approach. To our knowledge, the concept of time-discontinuity of damage at the failure has not been explored elsewhere. Figure III-A-3 shows the results of the two different approaches of failure definition on a typical S-N curve.

b) Sequence Effects in Fatigue

Based on the above definitions of failure by the right-hand and left-hand approaches, the loading sequence effects may be examined applying the particular differential evolution law of damage used by Ostergren and Krempl [8], Yang and Liu [10], Yang and Jones [11], etc. This equation is given by

$$\frac{dD}{d\eta} = g(D) f(\dot{\phi}), \frac{d\phi}{d\eta} \quad (6)$$

where

D = dimensionless damage,
 $\dot{\phi}$ = dimensionless forcing function, and
 η = dimensionless time.

If the effect of the forcing function rate is neglected, equation (6) can be written as

$$\frac{dD}{dN} = g(D) f(\tilde{\phi}) \quad (7)$$

where N is the number of cycles and $\tilde{\phi}$ the appropriate forcing variable. If the loading is controlled, then $\tilde{\phi}$ may be chosen as the maximum stress during the cycle. Miner's coefficient in two-block, stress-controlled loading, as shown in Figure III-A-4, is defined as

$$M = \frac{n_1}{N_1} + \frac{n_2}{N_2}$$

where n_i and N_i ($i = 1, 2$) are the number of cycles and the fatigue life at the stress level σ_i , respectively. From the equations in Reference [1], equation (7) can be rewritten as

$$\frac{dR_S}{dn} = \tilde{g}(R_S) f(\tilde{\phi}) \quad (8)$$

where

$$\tilde{g}(R_S) = g\{D(R_S)\}$$

The functions $g(D)$, $\tilde{g}(R_S)$ and $f(\tilde{\phi})$ are always positive, and $f(\tilde{\phi})$ is only zero

when its argument is zero. As shown in Figure III-A-5, if the frequency of loading is faster, relatively, than the rate of decrease of the residual strength, then the residual strength immediately before failure is determined by the maximum stress in a cycle. The residual strength at failure is, therefore, given by

$$R_S = R_S(\sigma) \quad \text{by the left-hand approach}$$

and

$$R_S = 0 \quad \text{by the right-hand approach.}$$

The Right-hand Approach

Suppose we calculate Miner's coefficient by the right-hand approach for the two-stage loading shown in Figure III-A-4. Knowing that the residual strength at failure equals zero and by integrating from $N = 0$ to $N = n_1 + n_2$, equation (8) yields:

$$-\int_1^0 \frac{dR_S}{g(R_S)} = \int_0^{n_1 + n_2} f(\tilde{\phi}) dN \quad (9)$$

During each block of n_1 and n_2 load cycling there are no changes in forcing variables. Therefore, equation (9) becomes,

$$n_1 f(\tilde{\phi}_1) + n_2 f(\tilde{\phi}_2) = \int_0^1 \frac{dR_S}{\tilde{g}(R_S)} \quad (10)$$

where $\tilde{\phi}_1$ and $\tilde{\phi}_2$ are appropriate forcing variables in each block loading. The fatigue lives, N_1 and N_2 , are computed from (10) as:

$$N_1 \triangleq \frac{1}{f(\tilde{\phi}_1)} \int_0^1 \frac{dR_S}{\tilde{g}(R_S)} \quad (11)$$

$$N_2 \triangleq \frac{1}{f(\tilde{\phi}_2)} \int_0^1 \frac{dR_S}{\tilde{g}(R_S)} \quad (12)$$

Using equation (7), the remaining life, n_2 , after n_1 cycles (under the first block loading) is

$$n_2 = \frac{1}{f(\tilde{\phi}_2)} \int_0^1 \frac{dR_S}{\tilde{g}(R_S)} - n_1 \frac{f(\tilde{\phi}_1)}{f(\tilde{\phi}_2)} \quad (13)$$

Miner's coefficient, M, becomes

$$M = \frac{n_1}{N_1} + \frac{n_2}{N_2}$$

where

$$\frac{n_2}{N_2} = \frac{f(\tilde{\phi}_2)}{\int_0^1 \frac{dR_S}{\tilde{g}(R_S)}} \cdot \frac{1}{f(\tilde{\phi}_2)} \int_0^1 \frac{dR_S}{\tilde{g}(R_S)} - \frac{n_1}{N_2} \frac{f(\tilde{\phi}_1)}{f(\tilde{\phi}_2)} = 1 - \frac{n_1}{N_1}$$

Therefore, $M = 1$ and there are no sequence effects in the damage evolution equation (7) with failure defined by the right-hand approach.

The Left-hand Approach

The definition of failure using the left-hand approach yields the cycles-to-failure N_1 and N_2 as follows:

$$N_1 = \frac{1}{f(\tilde{\phi}_1)} \int_{R_S(\sigma_1)}^1 \frac{dR_S}{\tilde{g}(R_S)} \quad (14)$$

and

$$N_2 = \frac{1}{f(\tilde{\phi}_2)} \int_{R_S(\sigma_2)}^1 \frac{dR_S}{\tilde{g}(R_S)} \quad (15)$$

where $R_S(\sigma_1)$ and $R_S(\sigma_2)$ are the residual strength corresponding to stress level σ_1 and σ_2 , respectively. For two-stage loading, the equivalent expression to (10) is

$$n_1 f(\tilde{\phi}_1) + n_2 f(\tilde{\phi}_2) = \int_{R_S(\sigma_2)}^1 \frac{dR_S}{\tilde{g}(R_S)} \quad (16)$$

using (14) - (16)

$$\frac{n_2}{N_2} = 1 - \frac{n_1}{N_2} \frac{f(\tilde{\phi}_1)}{f(\tilde{\phi}_2)} \quad (17)$$

and Miner's coefficient becomes

$$M = 1 + \frac{n_1}{N_1} \left[1 - \frac{\int_{R_S(\sigma_1)}^1 \frac{dR_S}{\tilde{g}(R_S)}}{\int_{R_S(\sigma_2)}^1 \frac{dR_S}{\tilde{g}(R_S)}} \right] \quad (18)$$

If $\sigma_1 > \sigma_2$, then $R_S(\sigma_1) > R_S(\sigma_2)$ and by making an assumption as to the positiveness of the function $\tilde{g}(R_S)$ then

$$\int_{R_S(\sigma_1)}^1 \frac{dR_S}{\tilde{g}(R_S)} < \int_{R_S(\sigma_2)}^1 \frac{dR_S}{\tilde{g}(R_S)} \quad (17)$$

Therefore, in this case, the value of Miner's coefficient was found to be greater than one. If the low amplitude stage were applied first, the value for Miner's coefficient would be less than one.

Ostergren and Krempl [8] show sequence independence of the damage evolution equation, (7). Yang and Jones [11] demonstrate that the damage evolution equation shows sequence dependence. None of the previous publications include the concept of discontinuity of damage, which reconciles this apparent discrepancy.

c) Effect of Interlaminar Normal Stresses on the Uniaxial Zero-to-Tension Fatigue Behavior of Graphite/Epoxy Tubes

Tests using internal pressure, in addition to axial loading, lead to the conclusion that interlaminar normal stresses between plies, which may develop during tensile loading, do not affect fatigue performance for $R = 0$ and the combinations of tube configuration and materials tested [12].

4. Plans for the Upcoming Period

Based on the evolution law of damage studied during this last period, the sequence effects of $[\pm 45^\circ]_S$ tubular specimens will be examined experimentally in order to correlate theory with experimental data. Particular emphasis will be given to the two-step loading conditions. These studies will be continued without sponsorship under the subject grant.

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6. Current Publications or Presentations by Professor Krempl on this Subject

"The Effect of Biaxial In-phase Cycling on the Residual Strength of ($\pm 45^\circ$)_S Graphite/Epoxy Thin-walled Tubes"

Presented at the Second International Conference on Biaxial/Multiaxial Fatigue, Sheffield, UK, December 1985.

6. Current Publications or Presentations by Professor Kreml on this Subject
(continued)

"The Effect of Interlaminar Normal Stresses on the Uniaxial Zero-to-Tension Fatigue Behavior of Graphite/Epoxy Tubes", with D. An

Published as R.P.I. Report 86-1, 1986.

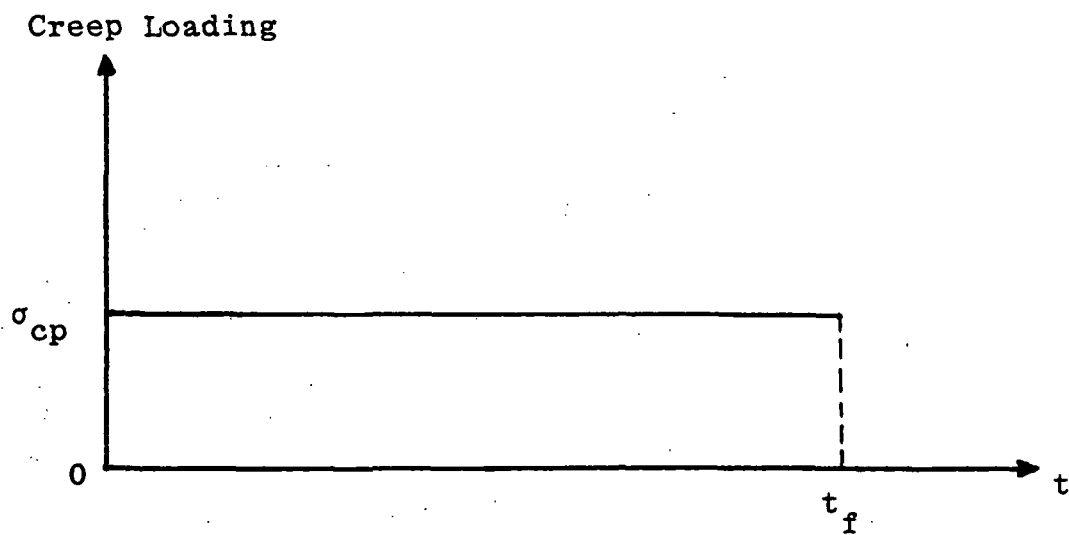
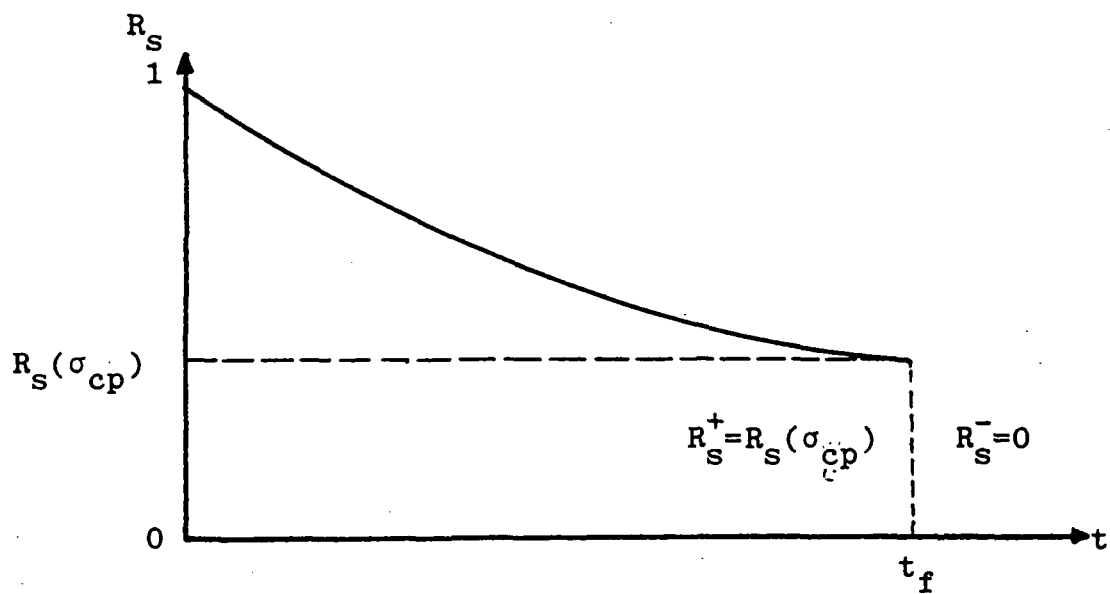
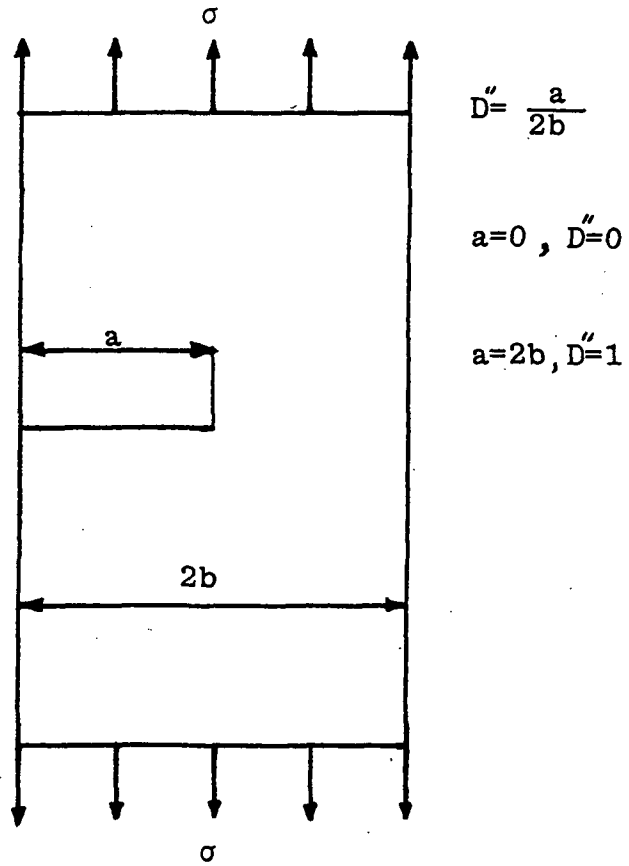


Figure III-A-1
RESIDUAL STRENGTH DEGRADATION IN A CREEP LOADING



AT FAILURE

$$D'' = \frac{a_c}{2b} \quad \text{BY LEFT APPROACH}$$

$$D'' = 1 \quad \text{BY RIGHT APPROACH}$$

Figure III-A-2
A SINGLE-EDGE NOTCHED SPECIMEN

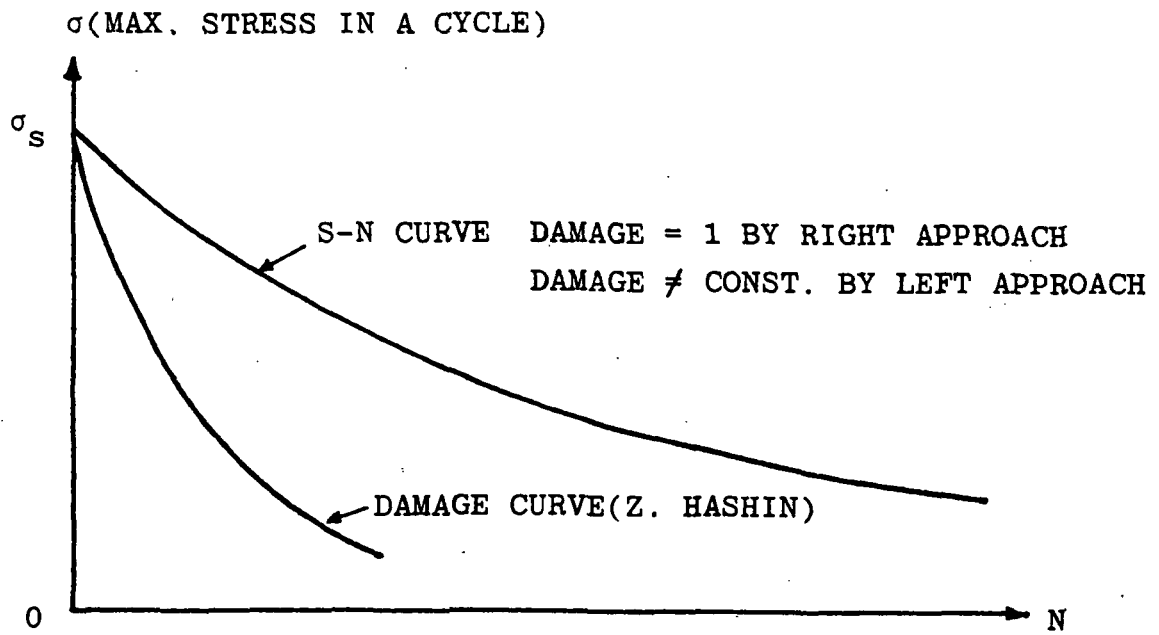


Figure III-A-3
S-N CURVE WITH THE RIGHT-HAND AND
LEFT-HAND APPROACH OF FAILURE DEFINITION

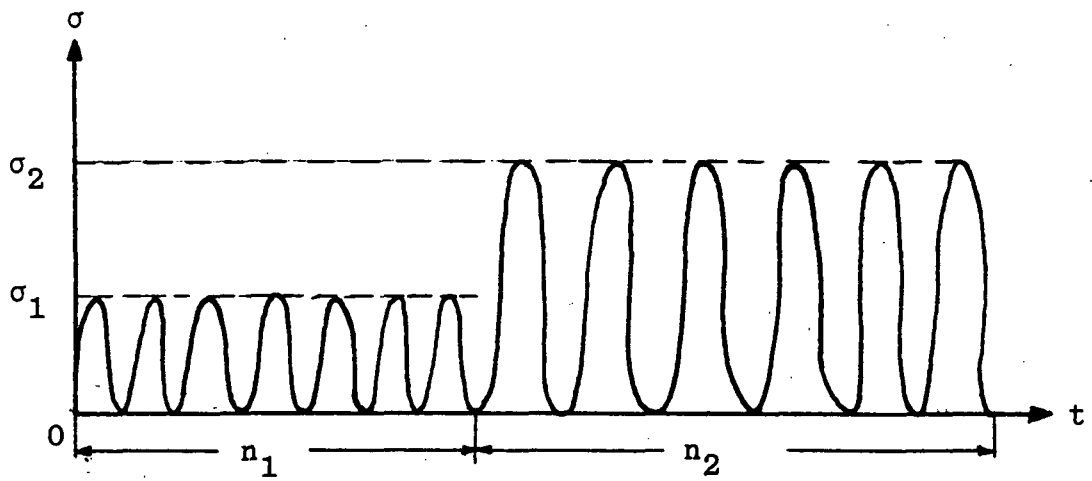


Figure III-A-4
TWO-STEP LOADING FATIGUE

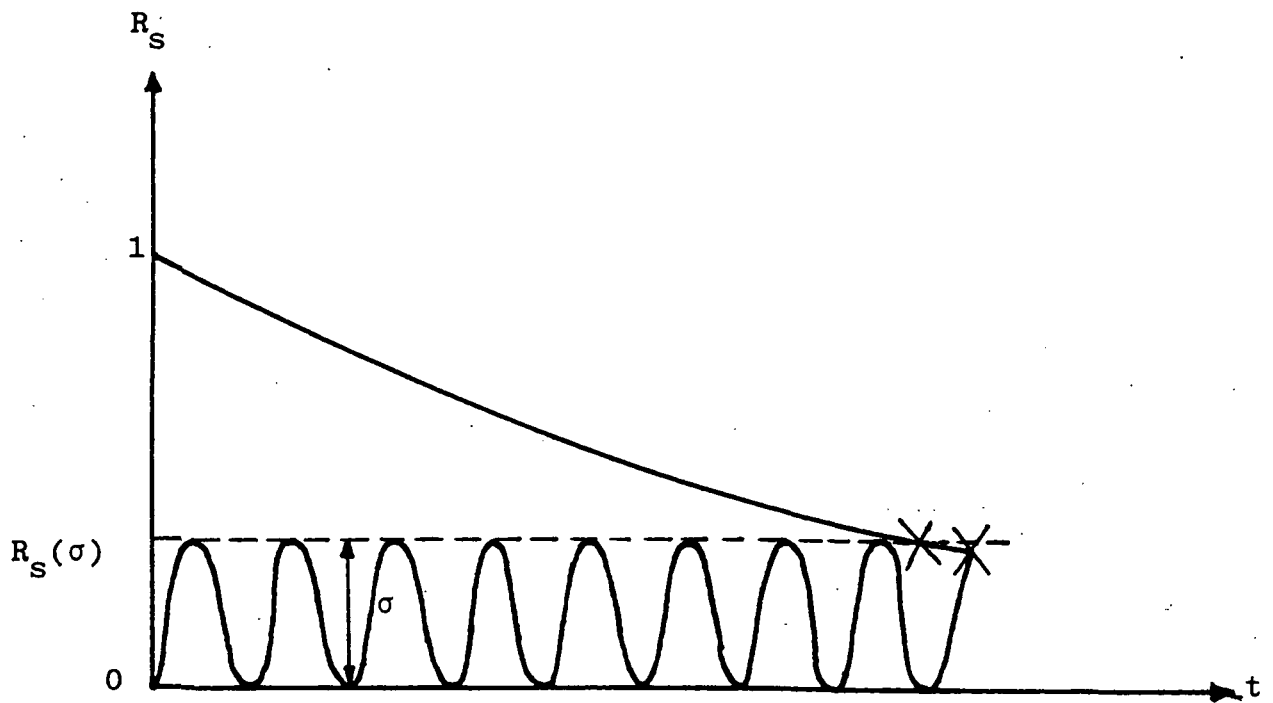


Figure III-A-5
FREQUENCY EFFECT IN RESIDUAL STRENGTH DEGRADATION

III-B Mechanical Properties of High Performance Polymeric Matrix Composite Laminates

Senior Investigator: S. S. Sternstein

1. Introduction

Delamination fracture toughness and damage tolerance are major objectives in the development of new matrix materials for high performance composites. Thermoplastic matrix materials offer the potential for major improvements in these properties, albeit at the expense of other properties such as solvent resistance, creep and compression strength.

2. Status

Thermoplastics have much greater strain to failure than typical rigid epoxy systems. Consequently, the role of the ply structure, e.g., fiber distribution, interface thickness and fiber volume fraction represent unknown parameters in many engineering properties determinations. For example, it remains to be established as to what role the interface thickness between plies plays in the evaluation of delamination fracture toughness by the double cantilever beam method, what role the fiber waviness and fiber distribution play in compression strength, and what role the fiber-matrix interface plays in the stiffness and toughness of thermoplastic matrix composites.

3. Progress During Report Period

During the reporting period we have begun research designed to address some of the unknown relationships noted above. Work has been initiated to examine the properties of all zero degree laminates in directions both parallel to and perpendicular to the layup direction.

If a unidirectional layup sample which has a square cross-section (i.e., the thickness is equal to the width) with the fiber direction perpendicular to this square section has uniform fiber distribution and matrix properties in all directions perpendicular to the fibers, then the bending modulus of the square cross-section beam should be the same when measured in either plane (i.e., when the sample is rotated 90° about the fiber axis). However, if the interface planes are of finite thickness or if the fiber distribution in the plane of the plies is different than perpendicular to the plies, the bending modulus will be different. If, in fact, the laminate planes are perpendicular

to the applied load (the bending deflection), a lower modulus should result.

Samples of Ryton PPS, F185 and PEEK-APC2 were obtained from NASA-Langley and carefully ground to a square cross-section rectangular beam. The dimensions of the square section were held to plus or minus one mil, while the length of the beam was held as closely parallel to the fiber axis as possible. Some degree of misalignment was inevitable due to fiber waviness. All samples were tested in three point bending using a Dynastat Mechanical Spectrometer in both the transient and dynamic modes. Bending tests were performed on all four faces of the beam, i.e., the sample was tested with a given face in four different positions with respect to the load, each 90° from the last position.

The bending modulus was found to be significantly different when tested in each of the four bending directions. Clearly, faces 1 and 3 should give the same result and similarly, 2 and 4. Lack of agreement suggests that the beams are not symmetric or balanced about the neutral plane. Comparison of faces 1 and 2 is more difficult since the lamination planes (which tend to be resin rich) will be oriented differently with respect to the bending deflection. We are pursuing the analysis of the data and are currently investigating the microstructure of the samples for corroborative evidence of the bending modulus results.

These results and similar experiments which we plan to do are aimed at elucidating the role which ply microstructure plays in mechanical properties of composites, especially as regards delamination failure and other matrix dominated properties.

Additional studies aimed at investigating the role of fiber-matrix adhesion on delamination fracture toughness have been conducted. Samples of 8-ply, unidirectional composites were obtained from NASA-Langley and tested for tensile modulus in the transverse direction. It is our belief that samples with better fiber-matrix adhesion will have a higher transverse modulus due to the constraint of matrix contraction on the fibers. The results are summarized in Table III-B-1 below.

Table III-B-1
Polycarbonate Matrix-Carbon Fiber
Unidirectional Composites

<u>Figure</u>	<u>Sample</u>	<u>Fiber</u>	<u>Fiber Treatment</u>	<u>Transverse Modulus (MPa)</u>
III-B-1	395	AS4	Surface Treated, unsized	4048
III-B-2	522	XAS	Surface Treated, N size	3874
III-B-3	529	AS4	Surface Treated, epoxy size	3711
III-B-4	543	XAS	Untreated, unsized	3679
III-B-5	524	XAS	Surface Treated, unsized	3563
III-B-6	525	XAS	Surface Treated, epoxy size	3174

The modulus results gave no consistent trend with fiber surface treatment. Accordingly, we have examined the microstructure of these samples in detail as shown in Figures III-B-1 to III-B-6. A qualitative evaluation of these micrographs suggests that the transverse moduli are in the same ordering as fiber volume fraction, with Figure III-B-1 having the highest fiber fraction. However, the clearly visible differences in fiber distribution uniformity (i.e., clustering) precludes the simple reevaluation of the moduli by proportionality to fiber volume fraction. In summary, the gross differences in morphology among these samples masks any dependence on the fiber surface treatment.

It should also be noted that the samples shown in Figures III-B-1 through III-B-6 demonstrate the absence of isotropy in planes transverse to the fiber axes. This bears directly on the points made earlier with respect to the square beam bending moduli.

We believe that the experiments discussed above clearly demonstrate the need for caution in the interpretation of trends in mechanical properties with variables such as fiber-matrix bonding, as well as the need for coordinated

studies which include microstructural analysis and data. The need for better control of prepreg quality is also evident.

4. Plans for Upcoming Period

We propose to continue studies of fiber distribution, fiber waviness and matrix tension-compression asymmetry and how they affect a useful compression failure model. Similarly, the effects of interphase thickness, processing history and stacking sequence on interlaminar shear behavior will be investigated. These experiments are anticipated as including thermoplastic, thermoset and toughened thermoset matrix materials.

5. Current Publications or Presentations by Professor Sternstein on this Subject

"Matrix Dominated Deformation of Composites"

Presented at and published in the Proceedings of the ACS 189th National Meeting, Miami Beach, FL, Apr 28-May 3, 1985.

"Deformation of Composites"

Presented at a Colloquium, University of Massachusetts, Amherst, MA, November 1985.

"Viscoelastic Effects in Composites"

Presented at the Gordon Conference on Composites, Santa Barbara, CA, January 1986.

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Figure III-B-1
MICROGRAPH OF SAMPLE 395 WITH
AS4 FIBER, SURFACE TREATED, UNSIZED



Figure III-B-2
MICROGRAPH OF SAMPLE 522 WITH
XAS FIBER, SURFACE TREATED, N SIZE

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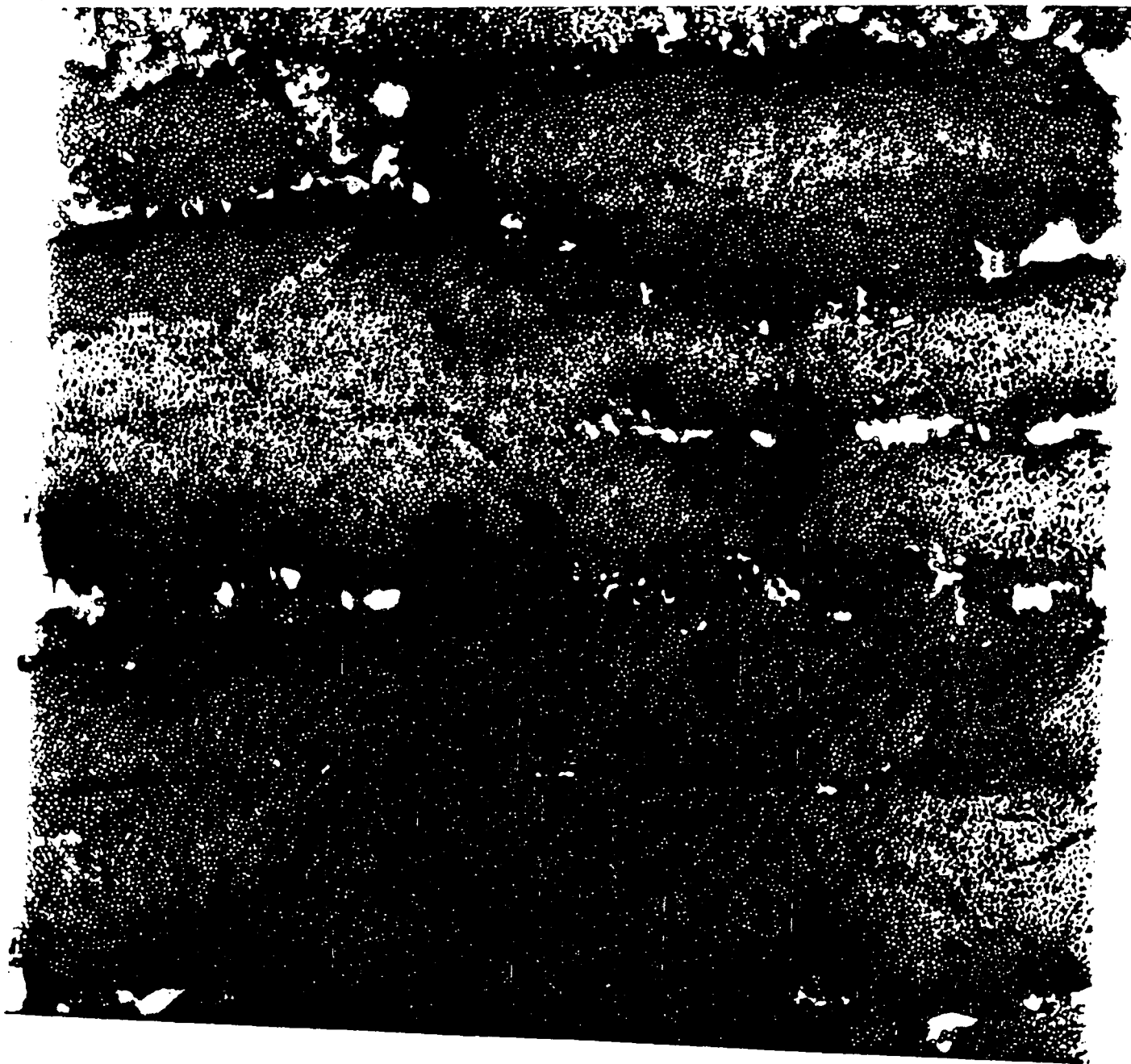


Figure III-B-3
MICROGRAPH OF SAMPLE 529 WITH
AS4 FIBER, SURFACE TREATED, EPOXY SIZE

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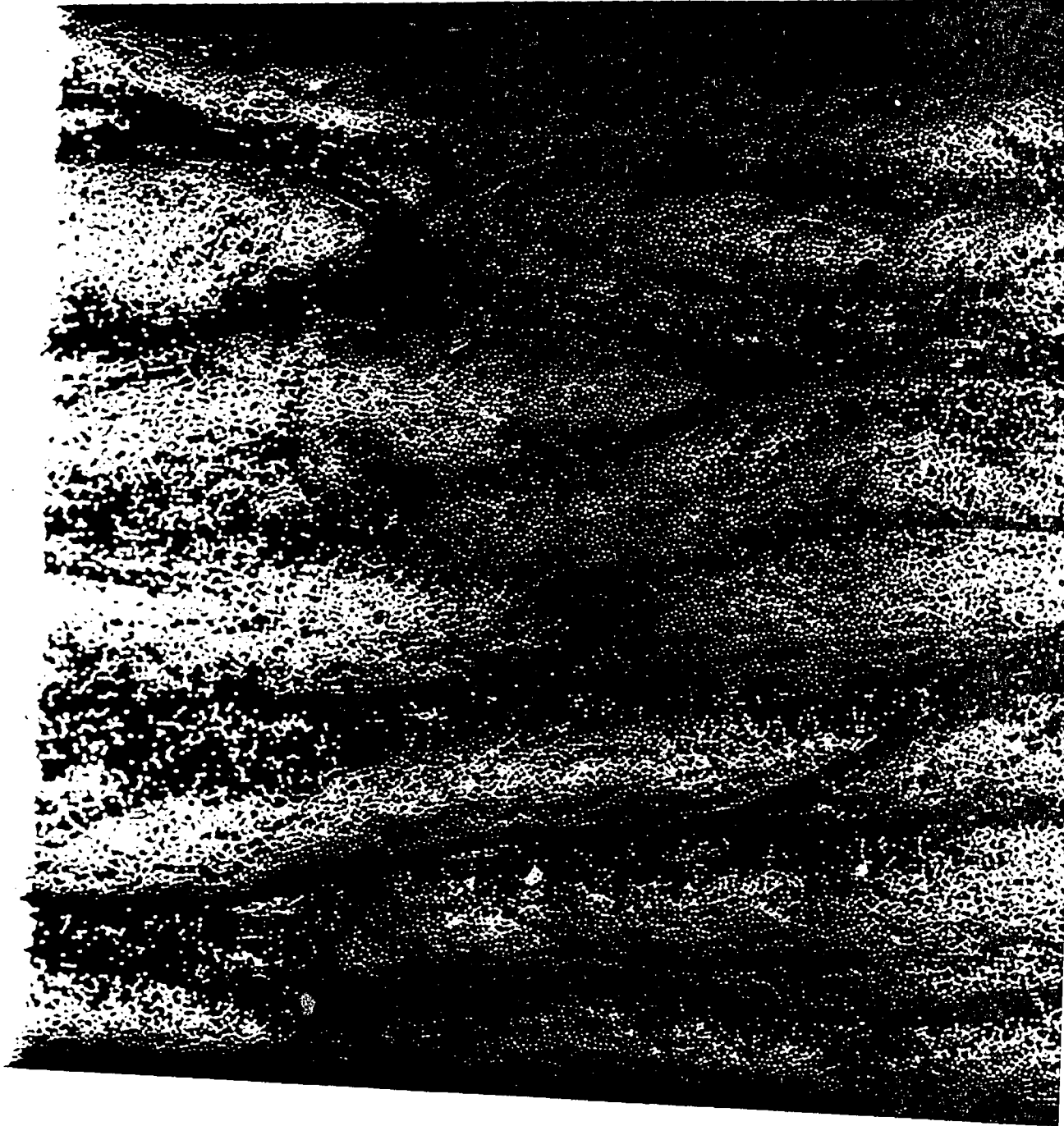


Figure III-B-4
MICROGRAPH OF SAMPLE 543 WITH
XAS FIBER, UNTREATED, UNSIZED

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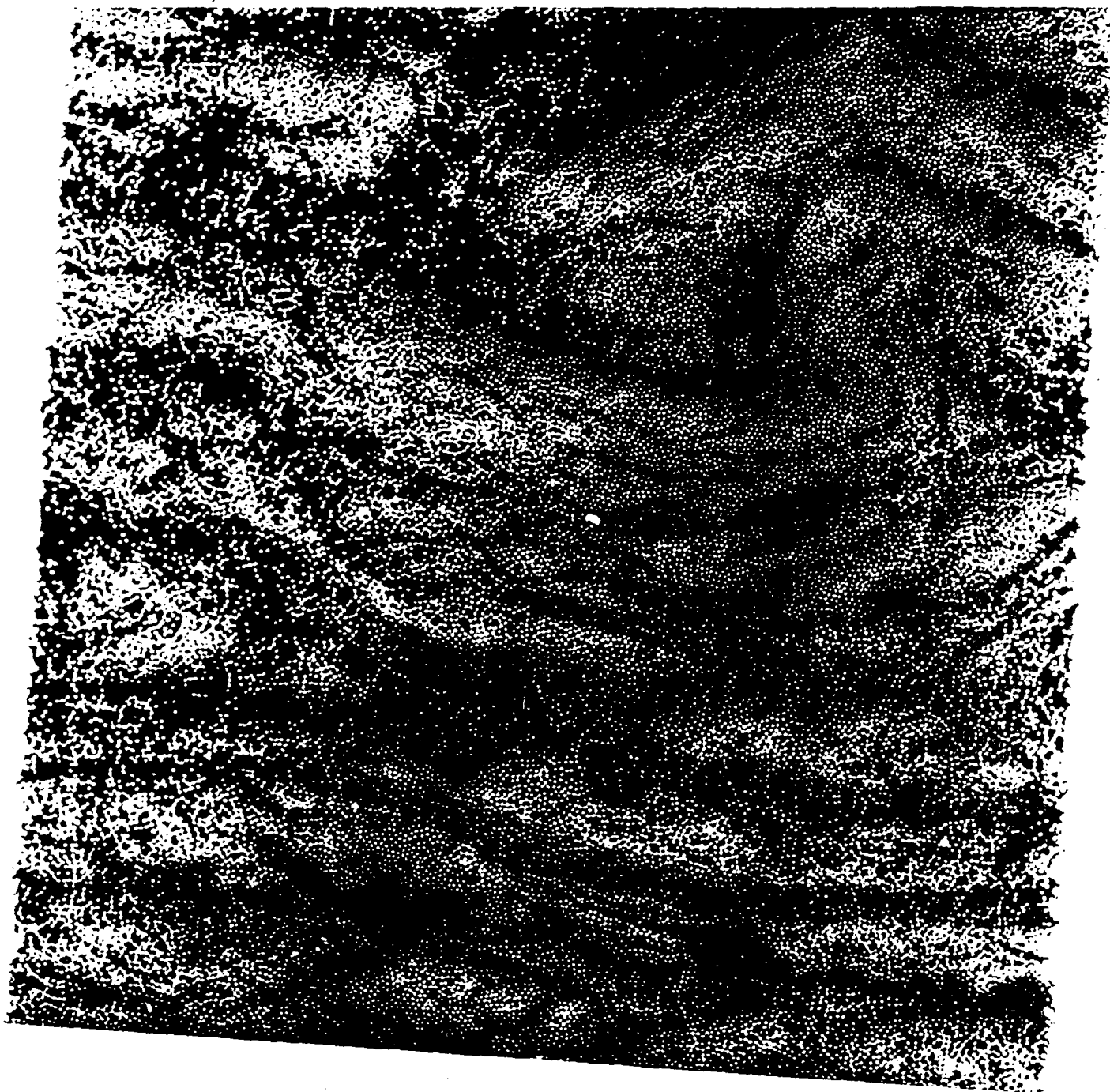


Figure III-B-5
MICROGRAPH OF SAMPLE 524 WITH
XAS FIBER, SURFACE TREATED, UNSIZED



Figure III-B-6
MICROGRAPH OF SAMPLE 525 WITH
XAS FIBER, SURFACE TREATED, EPOXY SIZE

III-C Numerical Investigation of the Micromechanics of Composite Fracture

Senior Investigator: M. S. Shephard

1. Introduction

An understanding of the behavior of and failure mechanisms in composite materials can be aided by appropriate use of analytic/numerical analyses used in conjunction with an experimental program. The goal of this work is to provide nonlinear finite element analysis capabilities, initially at the micromechanical level, which - coupled with an experimental program - will yield an increased understanding of composite behavior. Initial efforts consist of modeling thermoplastic composites, concentrating on the development of nonlinear time-dependent constitutive relations and their incorporation into an existing nonlinear finite element program that has the capability of adding new material models. Professor S. Sternstein is providing the technical expertise required to develop constitutive equations that can realistically model the measured material behavior.

2. Status and Progress During Report Period

Efforts since initiating this project during the reporting period have concentrated on two aspects. The first is an evaluation of available general purpose finite element codes as a means to deal with general time-dependent, nonlinear material properties; and the second is the development of appropriate constitutive relations that are capable of capturing the desired forms of behavior and fitting within the context of a nonlinear finite element analysis code.

The analysis code currently under specific consideration is ABAQUS, which has been specifically designed for nonlinear finite element analysis through combined incremental and iterative techniques. Although none of the available finite element codes have available material models of the desired type, ABAQUS allows for the inclusion of user-defined material models which must be programmed and integrated into the system. As long as the constitutive equation can be cast into an appropriate basic form and is stable enough, the nonlinear algebraic equations resulting from the finite element discretization in space and finite difference stepping in time can be solved with the algorithms available for this purpose in ABAQUS.

Efforts to arrive at an appropriate constitutive relation began with an

examination of a one-dimensional rheological model previously used by Prof. Sternstein. It was found that including the nonlinear viscous component allowed many of the basic nonlinear features of interest to be modified. The procedure for conducting the one-dimensional investigation employed a simple difference scheme using Newton Iteration to account for nonlinear effects. Progress has also been made in modifying the original expression and extending it to multidimensional stress-strain fields. To this point the constitutive relations used have cast strain rate as a function of stress and stress rate. However, the desired form for finite element implementation employing the user-defineable routine is the change in stress increment due to change in strain increment, plus the ability to update the total stresses. Therefore, it will be desirable to define stress as a function of strain. It may be advantageous if this can be cast in the form where strain invariant terms are employed in the coefficients of strain and strain rate vectors.

3. Plans for Upcoming Period

The primary task to be addressed is the development of the required multiaxial constitutive relation. Consideration must be given to both the hydrostatic and deviatoric stress components if the onset of the nonlinear range and behavior in it is to be successfully predicted. Professor Sternstein is providing the fundamental input to the definition of this relationship.

Once an acceptable constitutive equation is available, efforts will turn to its implementation in ABAQUS. This process will be complicated by the fact that the user-defined material routine is not ideally suited for creep-type relations cast directly in terms of stress and strain rates.

Following implementation, the model will be tested and the theoretical results compared to those of experiments. After the model is appropriately tuned, efforts will turn to developing micro- and macro-models of composite materials employing the material model. Initial analysis runs will test the basic behavior of plain thermoplastic specimens. The next set of problems would be simple micromechanical models of thermoplastic composites with a limited number of fibers or layered materials simulating layers of fiber and matrix. The intent of such model development is to produce representations of the internal distributions of stress and strain which can be compared with experimentally observed behavior. From this point more extensive models

would be constructed with the goal of, first, matching the observed behavior of more complex specimens and, then, using the resulting proven analytical tools to reveal the internal influence of critical variables.

4. Current Publications or Presentations by Professor Shephard on this Subject

"On the Effect of Quarter-Point Element Size", with N. A. B. Yehia

Published in *Int. J. Num. Meth. Engng.*, Vol 21, pp.1911-1924, 1985.

"The N-Criterion for Predicting Crack Growth Increment"

To be Published in *Eng. Frac. Mech.*, 1986.

III-D Delamination in Graphite/Epoxy and Boron/Aluminum Laminates

Senior Investigator: T. L. Sham

1. Introduction

We summarize in this report a *new* finite element procedure for the computation of weight functions in anisotropic, cracked structures. The weight function theory allows the stress intensity factors, and hence the energy release rates in all fracture modes, to be computed in a concise manner. It also provides a convenient methodology for investigating environmental interaction problems, for example, the influence of moisture and temperature on the stress intensity levels.

2. Status

We are completing the work on fracture in graphite-epoxy laminates at the conclusion of this reporting period and initiating a new research program on the fracture of metal matrix composites.

3. Progress During Report Period

The following theory for studying delamination in composites has been formulated.

a. Finite Element Method for Determining Weight Functions in Finite Bodies

We consider a two-dimensional, cracked body containing a single or a system of cracks. The body is linear, elastic and homogeneous but arbitrary anisotropy is permitted. The extension of the theory to piecewise homogeneous cracked structures is straight-forward, provided that the crack tips do not terminate at the material interfaces. Let P be the specific crack tip at which we wish to determine the stress intensity factors. Generalized plane deformation is assumed so that the stresses and strains are functions of the in-plane coordinates only. The stress intensity factors for an anisotropic solid can be defined in terms of the traction vector acting on the plane directly ahead of the crack front, $\sigma_{i2}(x_1, 0)$, as follows:

$$K_i = \lim_{r \rightarrow 0} \sqrt{2\pi r} \sigma_{i2}(x_1, 0) \quad (1)$$

where K_1 , K_2 , K_3 are the mode II (in-plane shear mode), mode I (in-plane opening mode) and mode III (out-of-plane shear mode) stress intensity

factors, respectively, r is the distance from the crack tip, and roman subscripts have the range 1 to 3. The weight functions corresponding to the crack tip P will be denoted as $h_i(x;P)$. Under mixed boundary conditions and body force loading, the stress intensity factors K_i of P can be computed by

$$K_i = \int_{S_T} T \cdot h_i \, dA + \int_{S_U} t_i \cdot U \, dA + \int_V F \cdot h_i \, dV \quad (2)$$

where T and U are the prescribed surface tractions and boundary displacements on the boundary S_T and S_U , respectively; F is the prescribed body force field in the body with volume V ; and t_i are the tractions generated by the weight functions h_i on the boundary S_U .

The weight functions h_i are universal functions for the given crack configuration, body geometry and material properties and are independent of loading systems. Thus, when they are known, one can compute the level of stress intensities induced by any external loading systems by means of equation (2). Also, because of the presence of the body force term in the integral of equation (2), we can investigate environmental interaction problems by treating the associated stress-free transformation strains, for example, swelling strains and/or thermal strains, as sources which induce fictitious body forces, and calculate the stress intensity factors directly through the same set of weight functions.

The energy release rate, G , for the anisotropic solid can be expressed in terms of the stress intensity factors as

$$G = K_i \Lambda_{ij} K_j \quad (3)$$

where Λ is symmetric and positive definite; it depends only on the elastic constants; and it can be related to the pre-logarithm energy factor of a straight dislocation line in an uncracked solid, lying parallel to the crack front in the cracked body. The energy release rate, G , can also be decomposed additively into three components, G_i , according to Irwin's concept of virtual crack extension as

$$G_i = \lim_{\delta a \rightarrow 0} \frac{\delta a}{2} \int_0^{\delta a} \sigma_{i2}(x_1, 0) \left[u_i(x_1 - \delta a, 0_+) - u_i(x_1 - \delta a, 0_-) \right] dx_1 \quad (\text{no sum on } i)$$

where $\sigma_{i2}(x_1, 0)$ is the traction acting on the e_2 -plane ahead of the crack tip

and $u_i(x_1 - \delta a, 0_+)$ and $u_i(x_1 - \delta a, 0_-)$ are the displacements on the upper and lower crack face, respectively. It is customary to refer to G_1 , G_2 and G_3 respectively as mode II, mode I and mode III energy release rates, respectively. Thus for an anisotropic body, G_i can be related to the stress intensity factors via

$$G_i = \sum_{j=1}^3 K_i \Lambda_{ij} K_j \quad (\text{no sum on } i)$$

For an isotropic body, Λ is diagonal and equation (3) reduces to the familiar Irwin relation

$$G = \frac{1 - \nu^2}{E} (K_1^2 + K_2^2) + \frac{1 - \nu}{E} K_3^2 \quad (4)$$

under plane strain conditions. Here, ν is the Poisson's ratio and E is the Young's modulus.

b. New Variational Principle

The computation of weight functions is very difficult from the numerical point of view because they lead to an unbounded elastic strain energy in a finite region of the body surrounding the crack tip. Thus, a standard finite element method which relies on the minimization of an energy functional would fail. We have resolved this difficulty by properly regularizing the problem through a new variational principle which involves a bounded functional.

To fix ideas, let S_{int} be a suitably small bounding surface in the body which isolates the crack tip P from the rest of the body. The part of the body inside the surface S_{int} is referred to as region B and the remaining part of the body is denoted as region A . The unit outward normal to the bounding surface of region B is n . In region B , the weight functions h_i are decomposed into modified singular displacements \tilde{u}^s_i and modified regular displacements \tilde{u}^r_i , viz

$$h_i = \tilde{u}^s_i + \tilde{u}^r_i \quad (5)$$

The highly singular term \tilde{u}^s_i in this *local* decomposition is taken to be known from analytical expressions and the remaining term \tilde{u}^r_i , which behaves quite well, can be computed by means of the newly developed finite element method.

This finite element method is based on the following minimum principle. Define a functional H as

$$\begin{aligned}
H[\mathbf{h}_i, \tilde{\mathbf{u}}^r_i] = & \int_A w(\boldsymbol{\varepsilon}_i) dV + \int_B w(\tilde{\boldsymbol{\varepsilon}}^r_i) dV - \int_B (-\tilde{\mathbf{f}}^s_i) \cdot \tilde{\mathbf{u}}^r_i dV \\
& - \int_{S_{int}} (-\tilde{\boldsymbol{\sigma}}^r_i \mathbf{n}) \cdot \tilde{\mathbf{u}}^r_i dA \quad (\text{no sum on } i) \quad (6)
\end{aligned}$$

where w is the elastic strain energy density and $\boldsymbol{\varepsilon}$'s are the strains.

The functional H is bounded and it is a functional of \mathbf{h}_i in the region A and $\tilde{\mathbf{u}}^r_i$ in region B . It has been proven that among all possible fields \mathbf{h}_i in region A and $\tilde{\mathbf{u}}^r_i$ in region B which

- (i) satisfy the strain-displacement relations; and
- (ii) make \mathbf{h}_i zero on the external boundary S_u and equal to the sum of $\tilde{\mathbf{u}}^s_i$ and $\tilde{\mathbf{u}}^r_i$ on the internal boundary S_{int} , where $\tilde{\mathbf{u}}^s_i$ are considered to be given;

the true fields $(\mathbf{h}_i)^*$ in region A and $(\tilde{\mathbf{u}}^r_i)^*$ in region B minimize the functional H .

This variational principle, implemented within the context of a displacement-based finite element method, can be incorporated into a standard linear elastic finite element program without undue programming effort. The procedure is very similar to that of a standard finite element method, and it involves prescribing

- (i) nodal body forces in region B corresponding to body forces $-\tilde{\mathbf{f}}^s_i$;
- (ii) nodal forces corresponding to the tractions $-\tilde{\boldsymbol{\sigma}}^s_i \mathbf{n}$ on the internal boundary S_{int} ;
- (iii) some nodal "effective" body forces for the elements in region A which are adjacent to the internal boundary S_{int} , and
- (iv) zero tractions and displacements on the external boundaries S_T and S_u respectively.

The nodes inside region B , including those on S_{int} , are interpreted as nodal unknowns for the modified regular displacements $\tilde{\mathbf{u}}^r_i$ and the remaining nodes represent the nodal values of the weight functions \mathbf{h}_i .

As we have indicated above, in order to employ this finite element procedure, we have to prescribe the highly singular term $\tilde{\mathbf{u}}^s_i$. The local decomposition of the weight functions which we employed are such that only one set of $\tilde{\mathbf{u}}^s_i$ is needed for the computation of the weight functions in anisotropic solids for all crack configurations, and we have successfully obtained such a set of $\tilde{\mathbf{u}}^s_i$.

c. Fracture Mechanics of Boron/Aluminum Composites

The newly initiated research work on the fracture behavior of boron/aluminum composites is underway. We are in the process of performing a finite element micro-mechanical calculation for a center-cracked boron/aluminum unidirectional laminate; namely; treating fiber and matrix as discrete entities. As a first approximation, we are using small strain, incremental plasticity (elastic-ideally plastic) to model the mechanical behavior of the aluminum matrix, and the boron fibers are modeled as linear elastic. The goal of this work is to investigate the load transfer for different crack plane orientations.

4. Plans for Upcoming Period

The modified singular displacements, \tilde{u}_i^s , obtained in the course of developing the weight function theory for application to graphite/epoxy laminates during the reporting period will be incorporated into an existing finite element program for computing weight functions in anisotropic bodies. The finite element micro-mechanical calculations for boron/aluminum composites will be continued. Neither project is expected to be supported by the subject grant during the upcoming period.

5. Current Publications or Presentations by Professor Sham on this Subject

"Mechanics of Composites"

Presented in a seminar at NASA Langley Research Center, Hampton, VA, January 1986.

"Computation of Weight Functions in Two-Dimensional Anisotropic Bodies"

In preparation.

PART IV

GENERIC STRUCTURAL ELEMENTS

IV-A IMPROVED BEAM THEORY FOR ANISOTROPIC MATERIALS

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IV-A Improved Beam Theory for Anisotropic Materials

Senior Investigator: O. Bauchau

1. Introduction

Many aeronautical structures such as wing boxes and fuselages are composed of flat or curved panels reinforced by stiffeners. A wide variety of stiffener shape and design is possible. Both buckling and post-buckling analyses of such built-up shell structures under in-plane compressive and/or shearing loads pose a major challenge to the designer. When dealing with composite structure, the analysis is further complicated by the existence of a large number of failure modes and their possible interaction.

The analysis of such structures is usually performed with general purpose finite element codes using shell elements, or with specialized code developed specifically for reinforced panel analysis. In the first case, a large scale non-linear analysis is required to study the post-buckling behavior of the structure. This type of analysis is not practical in an initial stage, as it is very complex and costly. On the other hand, specialized codes are based on simplifying assumptions that often render their accuracy questionable, especially for composite structures.

2. Status

The goal of this research is to develop an alternative analysis methodology for reinforced structures. A numerical model has been proposed, which would be formulated in two steps. First, the cross-section of the structure would be analyzed, yielding a set of "Eigen deformation" modes. In the second step, the solution of the problem would be found as a series expansion in terms of the eigenmodes.

3. Progress During Report Period

The first step of the analysis procedure was developed during this period. The kinematics of the deformation are derived from the general theory of shells undergoing arbitrarily large deflections and rotations. This level of generality is necessary as ability to deal with post-buckling behavior (i.e., non-linear analysis) is a goal of this study. Shearing deformations are important in composite shells and are also included on the analysis, as are such classic coupling effects as bending-twisting and extension-twisting.

The general expressions for linear and non-linear strain components are used to evaluate the strain energy in the structure, which is reduced to a quadratic expression by means of a quasi-linearization technique. The resulting expression is the basis for a finite element analysis of the cross-section of the structure and leads to a quadratic eigenvalue problem for the "eigen deformation" modes. The numerical aspects of this problem are presently being worked out.

4. Plans for Upcoming Period

Future work will concentrate on the interpretation of the physical implications of these eigenmodes. We believe they should provide valuable information about the behavior of composite structures. The second step of the analysis procedure, i.e. the buckling and post-buckling analysis, will then be undertaken.

5. Current Publications or Presentations by Professor Bauchau on this Subject

"A Beam Theory for Anisotropic Materials"

Published in the *Journal of Applied Mechanics*, Vol. 52, No. 2, pp. 416-422, June 1985.

"Composite Box Beam Analysis: Theory and Experiments"

To be published in *Journal of Reinforced Plastics and Composites*, January 1987.

PART V

PROCESSING SCIENCE AND TECHNOLOGY

- V-A THERMAL ANALYSIS OF COMPOSITE MATERIALS
- V-B NUMERICAL ANALYSIS OF COMPOSITE PROCESSING
- V-C HEAT TREATMENT OF METAL MATRIX COMPOSITES
- V-D EXPERIMENTS IN INNOVATIVE MANUFACTURING PROCESSES FOR LIGHTLY LOADED STRUCTURES - INITIAL SAILPLANE PROJECT: THE RP-1
- V-E EXPERIMENTS IN INNOVATIVE MANUFACTURING PROCESSES FOR LIGHTLY LOADED STRUCTURES - SECOND SAILPLANE PROJECT: THE RP-2

V-A Thermal Analysis of Composite Materials

Senior Investigator: B. Wunderlich

1. Introduction

This is the final report of our effort on thermal analysis of composite materials. Its goal has been to develop means for identifying variations in the structural properties of thick laminates such as might occur due to non-uniformities in the cure process.

2. Status

This work was terminated on May 1, 1986 by the project's Budget Advisory Committee as a result of reduced support and a reorientation of the research to higher temperature materials. With this report all but one scientific paper (#13 in the list of references*) are written and submitted for publication. Three papers have been published, five have been accepted for publication. The work was brought to a close at the point where actual thermoplastic matrices were to be studied in situ. In case these studies were to be reactivated, it would involve training of a new student to take over the project. The senior investigator will be on sabbatical leave during 1986/87 to add solid state NMR to the techniques to be used for characterization of polymeric solids, including composite matrix materials. Outside support is being sought for this work.

3. Progress During Report Period

During the first year of this research the variation of resin properties through the thickness of the cured sample was investigated [1,4] on the examples of epoxy cross-linked materials. An extensive preliminary report on this work is given in Reference 4. It led to the discovery of the following changes during curing:

- (i) A broadening of the glass transition with beginning cure (an indication of inhomogeneity on a scale of 1-5 nm);
- (ii) A decrease in the change in heat capacity at the glass transition (an indication of increasing immobile regions);
- (iii) A loss of hysteresis (connected with the time-dependence of the glass

* References for this section appear on page 63.

transition), and

- (iv) In some epoxies, a renewed sharpening of the glass transition as the fully cured state is reached.

A report summarizing this work is presently in progress [13]. It is also part of the thesis of Dr. Judovits.

It was quickly observed that higher precision in heat capacity was necessary for measurement of the samples in situ [2]. This was achieved by developing a new technique of heat capacity measurement. In favorable cases it is now possible to measure to $\pm 1\%$ instead of the usual $\pm 3\%$ precision [2,3].

To understand the basic behavior of cross-linked materials, it was next decided to analyze a series of well characterized poly(styrene-co-divinyl benzene) copolymers [5]. This work led to a full characterization of the polymers and permitted the evaluation of all thermal functions [6,7]. Much of this work was discussed in a series of lectures and review articles written by the senior investigator [7,10].

The final topic, and perhaps most promising for the future, was the analysis of composites with thermoplastic matrices [5]. Especially if partial crystallization of the matrix is expected, a clear handle is provided for the materials characterization. A melting can be discovered with approximately 10 times greater sensitivity than the glass transition. All presently considered polymers, polycarbonates, poly(ethylene terephthalate), poly(phenylene oxide)s, poly(phenylene sulfide)s and PEEK were analyzed as to their heat capacity [9,11]. A detailed study of PEEK was completed [11].

From the heat capacity contributions of the various groups of the macromolecules it is possible to predict the thermal behavior of any homopolymer, copolymer, or blends [14]. The special transition behavior can thus be separated from normal increase of thermal energy on heating. For PEEK, for example, an extremely wide (over 100 K) melting, annealing and recrystallization range was discovered [12]. In addition, it was found that a large amount of the amorphous material in semicrystalline PEEK may be strained, so that it remains rigid above the glass transition temperature [12]. Also, the glass transition temperature itself was found to be dependent on the thermal history of the sample [12]. All of these observations lead one to predict that careful manufacturing and quality control conditions must be established to achieve reproducible composite production.

4. Plans for Upcoming Period

This work must be considered complete, with the exception of the final form of Reference 13. Most of the information to be contained therein, however, is also available through reference 4.

5. References

- [1] 45th Semi-Annual Composite Materials and Structures Report; R.P.I., December 1983.
- [2] 46th Semi-Annual Composite Materials and Structures Report; R.P.I., August 1984.
- [3] H. Suzuki and B. Wunderlich, "The Measurement of High Quality Heat Capacity by Differential Scanning Calorimetry", *J. Thermal Analysis*, 29, 1369, 1984.
- [4] 47th Semi-Annual Composite Materials and Structures Report; R.P.I., December 1984.
- [5] 48th Semi-Annual Composite Materials and Structures Report; R.P.I., August 1985.
- [6] D. E. Kirkpatrick, L. Judovits, and B. Wunderlich, "The Heat Capacity of Solid Pol(p-xylylene) and Polystyrene", *J. Polymer Science*, 24, 45, 1986.
- [7] B. Wunderlich, "Quantitative Analysis of Macromolecular Glasses and Crystals", *Thermochemica Acta*, 92, 15, 1985.
- [8] L. H. Judovits, R. C. Bopp, U. Gaur and B. Wunderlich, "The Heat Capacity of Solid and Liquid Polystyrene, p-substituted Polystyrenes and Cross-linked Polystyrenes", *J. Polymer Science, Polymer Phys. Ed.*, accepted for publication, 1986/87.
- [9] S. Z. D. Cheng, S. Lim, L. H. Judovits, and B. Wunderlich, "Heat Capacity of High Melting Polymers Containing Phenylene Groups", *Polymer*, accepted for publication, 1986/87.
- [10] B. Wunderlich and S. Z. D. Cheng, "Thermal Analysis of Linear Macromolecules", *Gazetta Chimica Italiana*, accepted for publication 1986.
- [11] S. Z. D. Cheng and B. Wunderlich, "Heat Capacities and Entropies of Liquid; High Melting Polymers Containing Phenylene Groups (PEEK, PC, and PET)", *J. Polymer Science, Polymer Phys. Ed.*, accepted for publication, 1986/87.
- [12] S. Z. D. Cheng, M.-Y. Cao and B. Wunderlich, "Glass Transition and Melting Behavior of PEEK", *Macromolecules*, accepted for publication, 1986.
- [13] L. Judovits, N. Gjaja and B. Wunderlich, "The Glass Transition as a Function of Crosslinking in Epoxies", *J. Appl. Polymer Science*, to be submitted, 1986.

5. References (continued)

[14] ATHAS, Third Report, 1985, R.P.I., 1985.

6. Current Publications or Presentations by Professor Wunderlich on this Subject

"Thermal Analysis of Liquid and Condensed Crystals"

Presented as the Invited Plenary Lecture at the ACS 189th National Meeting, Miami Beach, FL, Apr 28-03 May, 1985.

"Basic and Future Developments of Thermal Analysis"

Presented at the Gordon Conference on Pyrolysis, Plymouth, NH, July 1985.

"Quantitative Thermal Analysis of Macro-molecular Glasses and Crystals"

Presented as the Plenary Lecture at the International Conference on Thermal Analysis, Bratislava, Czch., August 1985.

"Quantitative Thermal Analysis of Macro-Molecular Glasses"

Published in *Thermochemica Acta*, Vol. 92, pp. 15-26, Sept. 1985.

"Analysis of Linear Macro-molecules by DSC"

Presented at the New England Thermal Forum, Natick, MA, October 1985.

"Confirmational Analysis of Poly-Vinylidene Fluoride"

"Condensed State of Liquid Crystals"

"Thermal Properties of High-melting Polymers Containing Phenylene Groups"

Presented at the American Physical Society Meeting, Las Vegas, NV, March/April 1986.

"Heat Capacity of Elastomers"

Presented as an Invited Poster at the American Chemical Society Meeting, Atlantic City, NJ, April 1986.

"Advanced Thermal Analysis of Linear Polymers Containing Fluorine and Chlorine"

Presented as an Invited Paper at the American Chemical Society Meeting, Atlantic City, NJ, April 1986.

V-B Numerical Analysis of Composite Materials

Senior Investigator: M. S. Shephard

1. Status

This project has been combined with Project III-C and all further reporting on the numerical analysis of composite materials will be found there.

V-C Heat Treatment of Metal Matrix Composites

Senior Investigator: G. Dvorak

1. Introduction

This project is concerned with an experimental and theoretical investigation of the effect of heat treatment on the extent of fatigue damage in laminated fibrous 6061 Al-B plate specimens. Previous work has shown that fatigue damage in these laminates takes place when the matrix experiences cyclic plastic straining during loading. In particular, matrix fatigue cracks grow on planes which are parallel to the fiber axis in each ply, and this process continues until the crack accommodation strain replaces the plastic strain, and a saturation damage state is reached. An overall stiffness reduction, as high as 50%, can be caused by the damage process. The actual magnitude of stiffness loss depends on the amount of cyclic plastic straining of the matrix, which is controlled by the size of the inelastic part of the applied load range. Therefore, for a given load range, a laminate with a higher matrix yield stress should experience less damage than one with a softer matrix.

This hypothesis was examined in an experimental program, and also through modeling of the damage process.

2. Status and Progress During Report Period

The experimental part of the program was designed to supplement and confirm data obtained in 1983-84. Coupon specimens obtained from a $(0/\pm 45/90)_S$ plate were subjected to several different heat treatments described in Table V-C-1. Each specimen was tested under cyclic loading of piecewise constant amplitude which was applied in 50,000 cycle segments. The maximum stress was increased after each segment, while the ratio $R = \sigma_{\min}/\sigma_{\max} = 0.1$ was kept constant. Figure V-C-1 shows the change of the unloading axial Young's modulus of the differently treated laminates. Figure V-C-2 shows a performance comparison of the most (T4) and least (F) damage resistant materials under identical loading conditions.

The results indicate that, in principle, the resistance of B-Al laminates to fatigue-induced damage can be affected quite considerably by heat treatment. However, it is not yet clear why the selected treatments have observed effects, or which treatments are the most or least beneficial. Also,

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the effect of these treatments on endurance limits remains to be determined.

Additional tests were conducted for confirmation of the results. These are still in progress.

In the theoretical part of the program, we have improved an existing modeling procedure for predicting stiffness losses in saturation damage states. It is now possible to make quantitative estimates of overall stiffness changes and of the fiber stress concentration factors in each ply of the damaged laminate. This procedure will be utilized to extend the uniaxial experimental data to general in-plane loading.

3. Plans for Upcoming Period

In the coming year, we plan to continue this program and investigate the effect of heat treatment for a larger range of loading conditions. In particular, the effect of mean stress on fatigue resistance of the heat-treated samples needs to be evaluated, in order to establish the relationship between the damage stress range and mean stress. Also, we would like to examine additional heat treatments to see if further expansion of the damage range is possible. All tests are to be performed on specimens cut from an eight-layer (0/+45/90)_S 6061 aluminum/boron plate.

4. Current Publications or Presentations by Professor Dvorak on this Subject

"Plasticity and Fatigue in Metal Matrix Composites"

Presented at NASA Langley Research Center, Hampton, VA,
February 1986.

"Recent Developments in Plasticity of Composite Materials"

Presented at the University of Wisconsin, Madison, WI, April 1986.

"Damage Mechanics of Composite Materials"

Presented at Michigan State University, East Lansing, MI, April 1986.

Temper	Solution H.T.	Quench	Aging
T4	520°C/20'	W	R.T./7 days
T4+	520°C/20'	W	220°C/2 hrs
T6	520°C/20'	W	200°C/6 hrs
T0	520°C/20'	W	413°C/2hrs//S.C.
O	---	-	413°C/2hrs//S.C.

Table V-C-1
HEAT TREATMENT OF BORON-ALUMINUM SPECIMENS

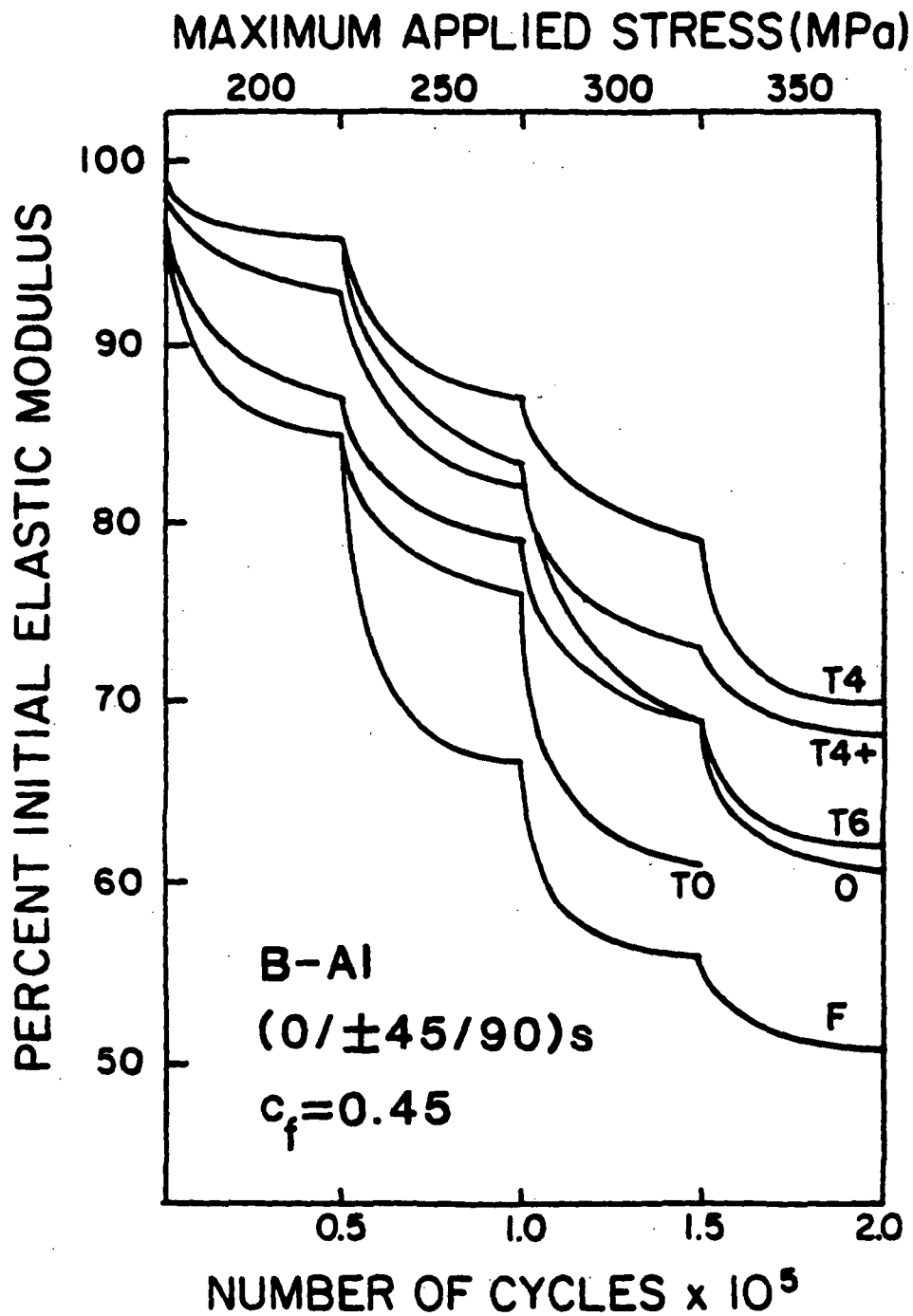


Figure V-C-1
CHANGE IN THE UNLOADING YOUNG'S MODULUS
UNDER PIECEWISE CONSTANT AMPLITUDE LOADING

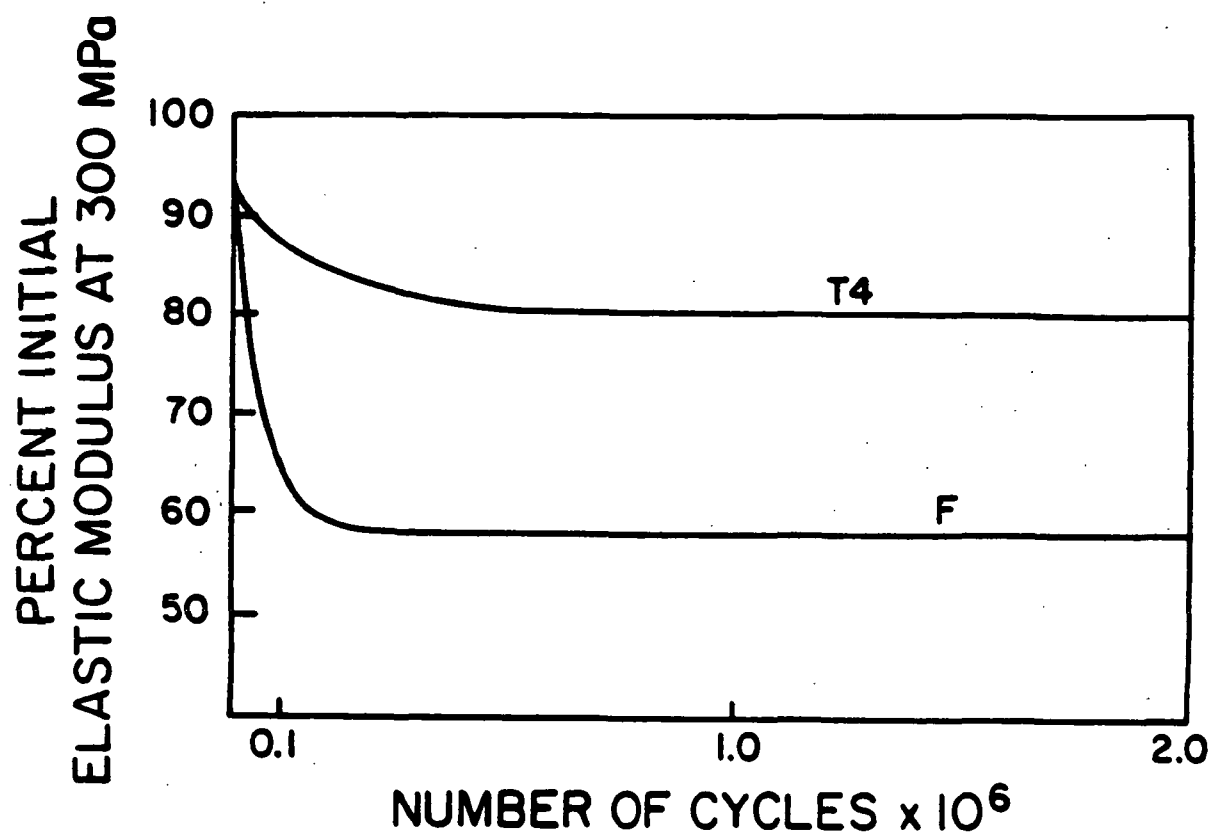


Figure V-C-2
COMPARISON OF FATIGUE DAMAGE RESISTANCE OF THE (0/ \pm 45/90)_S
BORON-ALUMINUM PLATE IN AS FABRICATED CONDITION,
AND AFTER T4 HEAT TREATMENT

V-D Experiments in Innovative Manufacturing Processes for Lightly Loaded Structures - Initial Sailplane Project: The RP-1

Senior Investigators: F. P. Bundy,
R. J. Diefendorf,
H. Hagerup

During this reporting period the RP-1 glider has been disassembled and stored on the balcony of the Composite Materials High Bay Area in the Jonsson Engineering Center. No work or tests have been done on it since the last wing bend-loading test of 15 November 1984 to +4 G's. Except for lack of instruments, which were transferred to the RP-2 glider, the aircraft remains intact structurally and aerodynamically.

V-E Experiments in Innovative Manufacturing Processes for Lightly Loaded Structures - Second Sailplane Project: The RP-2

Senior Investigators: F. P. Bundy,
R. J. Diefendorf,
H. Hagerup

1. Status

At the end of the last reporting period the RP-2 sailplane was nearing completion. During the present reporting period the aircraft has been completed, smoothed and surface-finished, painted, measured for weight and balance, adjusted, and test-flown very successfully. The test flights have included quantitative measurements of its performance characteristics and general assessment of its soaring capabilities. It has proven to be a very capable, efficient sailplane. Only a few minor adjustments are needed to make it completely satisfactory.

2. Progress During Report Period

The aircraft was surface-finished preparatory to painting in the composite materials and structures laboratory. The painting, white with red trim, was done gratis, by a professional vehicle painter, Peter Lofgren, Grangerville, New York.

Weight and balance adjustments were made early in November 1985. Initial flight tests were made at Saratoga Airport on 16, 19 and 23 November 1985. The aircraft was stored over the winter at RPI's Jonsson Engineering Center, part in its trailer and part in the Composite Materials Laboratory

High Bay Area. In early March 1986 the sailplane was exhibited, by invitation, at the National Convention of the Soaring Society of America in Philadelphia, PA, in the "homebuilt" section. On 28, 29 April and 13 May 1986 serious quantitative sink-rate flight tests were conducted in the still air of early morning. On 27 April and 10 May 1986, afternoon thermal soaring flight tests were made, all from Saratoga Airport. To date the sailplane has had 10 flights; 3 by auto-tow, 6 by aero-tow, and 1 by winch-tow for a total flight time of 7 hours, 6 minutes.

3. Results of Tests

The elevator control of pitch and flight speed seems adequate for all flight conditions encountered, including full split-flap deployment. The aileron system seems adequate, but the present throw-setting produces more adverse yaw than is desirable. The rudder authority is not adequate for rough air flight conditions. A larger rudder (and possibly vertical stabilizer) is needed. The split flaps produce very little pitch moment when deployed, and give very good glide path control. Precision landings are readily made with their use.

The weight of the aircraft after painting, and including all instruments, batteries, etc. is 273 pounds. For the initial flight tests, 18 pounds of lead ballast was mounted just ahead of the instrument panel station to place the C.G. of the glider, with its 142 pound pilot, F. P. Bundy, aboard, at 30% chord aft of the leading edge of the wing. In later flight tests this ballast was removed, placing the C.G. at 35% chord aft of the leading edge. It flew very well in both configurations.

The results of the quantitative sink-rate vs. flight speed tests from the early morning, quiet, smooth air flights are summarized in Figures V-E-1 and V-E-2. Figure V-E-1 shows the sink-rate plotted against airspeed for flap positions of 0°, 30° and 60°. The minimum sink rate is about 125 feet per minute at 40 miles per hour. The air conditions for the 29 April 1986 morning flight were ideal, and the data points (circles) are very reliable. Curves for Schweizer sailplanes of the 1950-1955 era (the 1-23A and 1-26A) are shown for comparison, and similar curves for the most advanced German, carbon-fiber, laminar-flow, 15 meter sailplane, the Schempp-Hirth Ventus B15. Figure V-E-2 shows the glide ratios derived from the sink-rate/flight speed data. It is gratifying that the measured performance of the RP-2 slightly

exceeds the 28 to 1 forecast for it theoretically.

In thermal soaring flight, the RP-2 performs very well (except for weak rudder control). Circling at 40 mph in thermals it was not outclimbed by any other gliders at the Saratoga Airport, including the modern, high-performance ones. Cruising at 50 to 55 mph, the 24 to 1 glide ratio enables fairly good cross-country speed. In the two soaring test flights, totalling about 4 hours, altitudes of nearly 6000 feet were reached (cloud base) and about 80 miles of cross-country distance flown (all well within gliding range of the airport). The RP-2 proves to be a very capable machine for serious soaring, such as for FAI badge flights and general recreation. While one would not match it against the most advanced mold-formed, laminar flow airfoil-winged machines for speed racing, it is considered a noteworthy accomplishment that the moldless, "lay-on the skin wing" fabrication technique used to build the RP-2 achieved the theoretical performance.

4. Plans for Upcoming Period

- A. The following sub-projects for the RP-2 sailplane are worthy of serious consideration. These are listed for completeness, although sponsor guidance has led the Faculty Budget Advisory Committee to recommend concluding these experiments with the conclusion of the current period.
- (i) Fabricate and install a larger rudder.
 - (ii) Adjust bellcranks of the aileron linkage for more up-throw and less down-throw.
 - (iii) Build resilience into the tailwheel assembly by soft mount, soft wheel, or both.
 - (iv) Add wedges to the rudder pedals to make foot position more vertical.
 - (v) Provide hand-hole/door access on the right side of the cockpit wall so that the canopy can be latched and unlatched by reaching in from the outside.
 - (vi) Fabricate a soft cloth cover for the aircraft nose and canopy.
- B. Submissions of Spring 1986 RPI student designs as entries in the contest for a follow-on project to the RP-2 will be evaluated and early work initiated.

5. Current Publications or Presentations by Professors Bundy and/or Diefendorf on this Subject

Public Static Exhibit (by invitation), Flight '85 Air Show, Schenectady County Airport, NY, June 1985 (Prof. Bundy).

"The RP Sailplanes: An Undergraduate Design Activity in Composite Materials"

Presented at ASEE, Atlanta, GA, June 1985 (Prof. Diefendorf).

"First Flights of the RP-2, An All-Composite Ultralight Sailplane"

Published in *Soaring*, pp. 18-20, March 1986 (Prof. Bundy).

Public Static Exhibit (by invitation), Soaring Society of America National Convention, Philadelphia, PA, March 1986 (Prof. Bundy).

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Legend:
 O 29 April '86 data
 Δ 13 May '86 data

Figure V-E-1
 SINK RATE
 AS A FUNCTION OF
 AIRSPEED

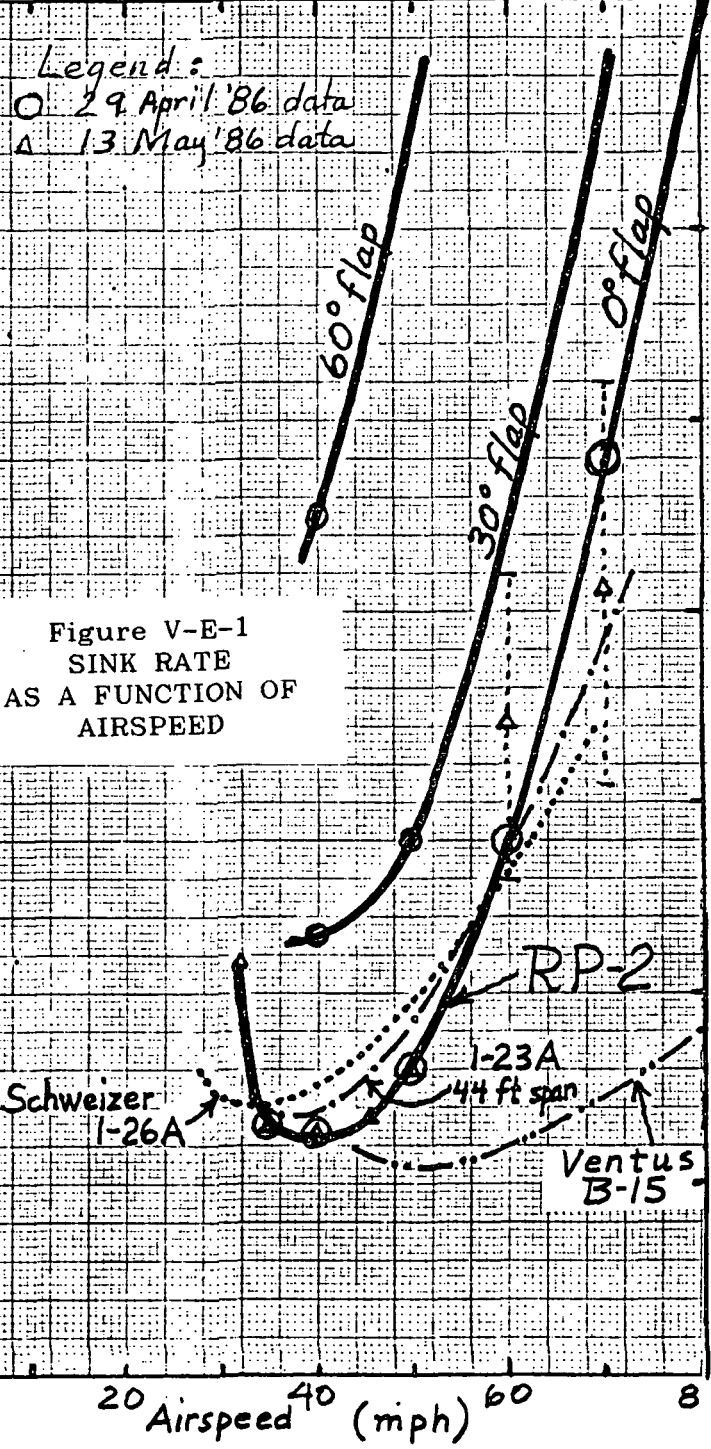
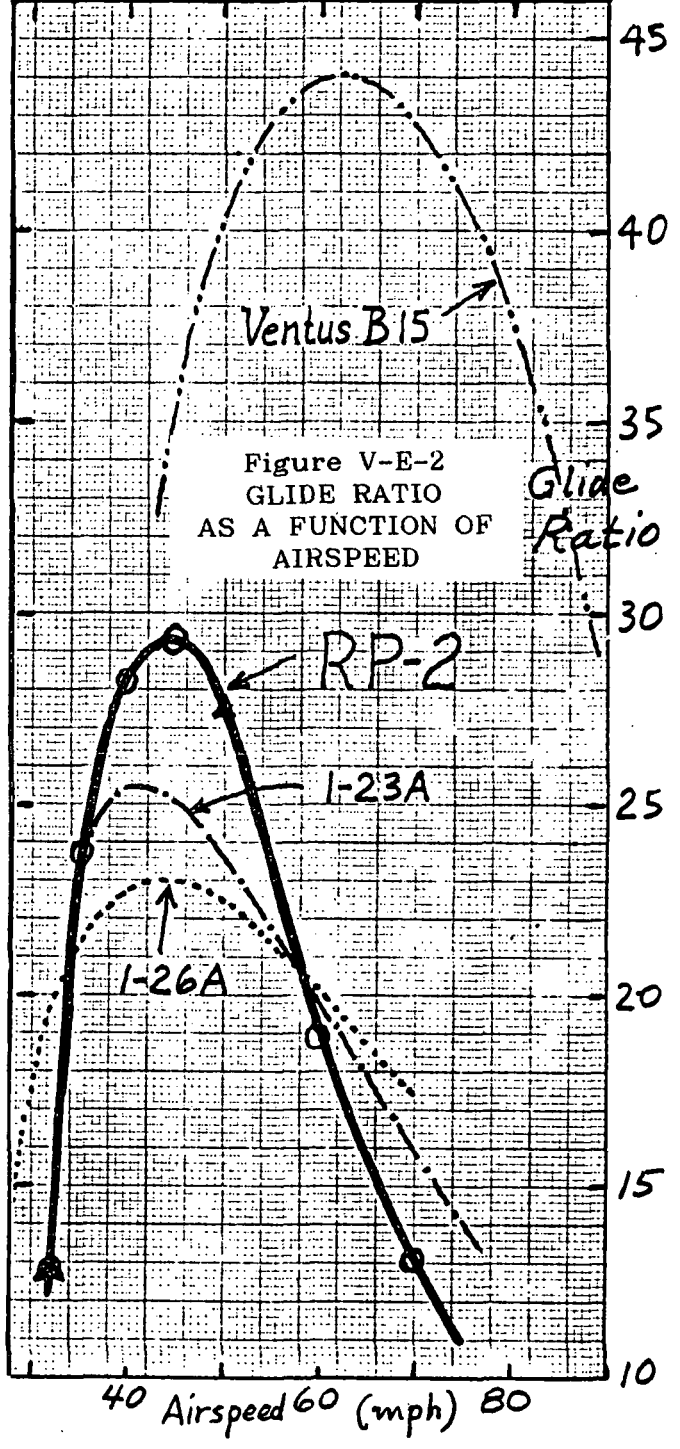


Figure V-E-2
 GLIDE RATIO
 AS A FUNCTION OF
 AIRSPEED



PART VI
TECHNICAL INTERCHANGE

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TECHNICAL INTERCHANGE

Technical meetings, both on- and off-campus, enhance opportunities for the interchange of technical information. In order to assure that a Rensselaer faculty/staff member can participate in such meetings off campus, a central listing of upcoming meetings is compiled, maintained and distributed periodically. The calender for this reporting period is shown in Table VI-1. Table VI-2 shows the meetings attended by RPI composites program faculty/staff/students during the reporting period. Some on-campus meetings, with special speakers particularly relevant to composites, are listed in Table VI-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 VI-4.

The diversity of the research conducted within this program has continued to be wide; indeed, it is seen as one of the strengths of the program. To insure information transfer among groups on campus, a once-a-week luncheon program is conducted. Faculty and graduate students involved (listed in Part VII - Personnel - of this report) attend. These meetings are held during the academic year and are known as "Brown Bag Lunches" (BBL's), since attendees bring their own. Each BBL allows an opportunity for graduate students and faculty to briefly present plans for, problems encountered in and recent results from their individual projects. These seminars also are occasions for brief reports on the content of off-campus meetings attended by any of the faculty/staff participants (as listed in Tables VI-2 and VI-4 of this report) 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 VI-5 lists a calender of internal, oral progress reports as they were given at BBL's during this reporting period.

During the week of July 22-26, 1985, RPI offered, for the sixth time, a special short course in composite materials and structures. A record number of graduate engineers from government and industry enrolled, requiring a rearrangement of the "hands-on" portions of the course to properly handle the increased numbers. The announcement brochure, listing lecturers and the subject matter is attached as an appendix to this report, and the

participants and their organizations are listed in Table VI-6.

As indicated in the Introduction of this report, an initiative is being implemented which has, over this and the previous reporting period, brought about increased communication between NASA researchers and their RPI counterparts. One step in that direction has been taken by the holding of a series of Research Coordination Meetings. Following one such meeting with members of NASA Langley Research Center's Materials Division and a second with members from NASA Lewis Research Center, both at R.P.I., in the previous reporting period, plans as evolved in these earlier meetings were reviewed with Drs. M. Greenfield and L. Vosteen of NASA Headquarters and Langley Research Center, respectively, on July 19, 1985. A formal site visit and review was also held on December 2 & 3, 1985 with scientists/engineers from both NASA and AFOSR, as sponsoring agencies, and members of the Industrial Technical Advisory Panel for the program, as well. A list of these and other interactions which took place during the reporting period is given in Table VI-7.

Table VI-1

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Calendar of Composites-related Events

May 1, 1985 through April 30, 1986

<u>DATES</u>	<u>MEETING</u>	<u>SPONSOR</u>	<u>PLACE</u>
28 Apr- 03 May 85	ACS 189th National Mtg	ACS	Miami Beach, FL
06-08 May 85	NSF Innovation Mtg	NSF	Albany, NY
17-21 Jun 85	17th Biennial Carbon Conference	-	Lexington, KY
24-26 Jun 85	ASME/ASCE Mechanics Conference	ASME/ASCE	Albuquerque, NM
24-27 Jun 85	Nat. Symp. on Fracture Mechanics	ASTM	Boulder, CO
07-12 Jul 85	Gordon Conference on Pyrolysis	-	Plymouth, NH
19-21 Jul 85	AIAA 20th Thermophysics Conference	AIAA	Williamsburg, VA
30-Jul- 01 Aug 85	5th Inter. Conf. on Composite Materials	AIME/ASM/ASTM	San Diego, CA
04-08 Aug 85	Inter. Computers in Engrg Conf. & Exhibition	ASME	Boston, MA
04-07 Aug 85	Nat. Heat Transfer Conf.: Composite Matls Session	AIAA	Denver, CO
19-21 Aug 85	AIAA Atmospheric Flight Mechanics Conference	AIAA	Snomass, CO
19-21 Aug 85	Composite Materials: Mechanics, Experimental Methods, Processing and Quality Assurance	SEM	Dayton, OH
19-22 Aug 85	International Conference on Thermal Analysis	ICTA	Bratislava, Czechoslovakia
20-22 Aug 85	Exper. Mechanics of Fiber Reinforced Comp. Matls	SESA	Dayton, OH
08-13 Sep 85	ACS 190th National Mtg	ACS	Chicago, IL

Table VI-1 (continued)

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Calendar of Composites-related Events

May 1, 1985 through April 30, 1986

<u>DATES</u>	<u>MEETING</u>	<u>SPONSOR</u>	<u>PLACE</u>
08-13 Sep 85	61st Struct. & Matl. Pnl Mtg: Adv Joining of Aero Matls	AGARD	Fed. Rep. of Germany
09-13 Sep 85	Fatigue, Corrosion Crack- ing, Fracture Mech, & Failure Analysis	ASM/ASME/AIME/ AWS/ASTM	Salt Lake City, UT
09-13 Sep 85	Fiber Composites: Devel- oping, Manufacturing, Certifying, and Maintain- ing Composite Structures and Composite Products	CEI	Columbia, MD
10-13 Sep 85	10th Biennial ASME Design Engr. Div. Conf. & Exhibit on Mech. Vibration & Noise	ASME	Cincinnati, OH
16-20 Sep 85	Composite Materials: Pro- cessing, Quality Assurance, and Repair	UCLA	Los Angeles, CA
24-27 Sep 85	1st European Conf. on Composite Materials	EACM/AEMC	Bordeaux, France
01-04 Oct 85	Symposium on Low Cycle Fatigue-Directions for the Future	ASTM/AIME/ ASM	Lake George, NY
05-07 Oct 85	EUROMECH 200 Colloq. on Post-Buckling Behavior of Elastic Structures	EUROMECH	Matrafured, Hungary
08-10 Oct 85	Adv Metallic Struc MMC Review	AFWAL/FIBA	Evendale, OH
13-17 Oct 85	TMS-AIME Fall Meeting	TMS-AIME	Toronto, Canada
14-17 Oct 85	SAE Aerospace Technology Conference	SAE	Long Beach, CA
21-25 Oct 85	11th Annual Inter Symp for Testing & Failure Analysis	ISTFA	Long Beach, CA
22-24 Oct 85	11th Annual Mechanics of Composites Review	ML-AFWAL	Dayton, OH

Table VI-1 (continued)

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Calendar of Composites-related Events

May 1, 1985 through April 30, 1986

<u>DATES</u>	<u>MEETING</u>	<u>SPONSOR</u>	<u>PLACE</u>
22-24 Oct 85	17th Natl Tech Conf on Materials	SAMPE	Kiamesha Lake, NY
22-24 Oct 85	Symp on Shock & Vibration	NRL	Monterey, CA
28-30 Oct 85	SIAM Fall Meeting	SIAM	Tempe, AZ
29 Oct 85	New England Thermal Forum	-	Natick, MA
05-07 Nov 85	1985 11th World Conf. on Nondestructive Testing	ASNT	Las Vegas, NV
12-15 Nov-85	EUROMECH 204 Colloq on Struct & Crack Prop in Brittle Mtrx Comp Matls	EUROMECH	Jablonna, Poland
17-20 Nov 85	SESA Fall Conference on Experimental Mechanics	SESA	Grenelefe, FL
17-22 Nov 85	ASME Winter Annual Mtg	ASME	Miami Beach, FL
18-20 Nov 85	Testing Tech. of Metal Matrix Comp: 1st Symp.	ASTM	Nashville, TN
25-29 Nov 85	16th Annual Manufac. Technology Conf.	DOD	Seattle, WA
02-06 Dec 85	Inter Conf & Exhib on Fatigue, Corrosion Cracking, Fracture Mechanics & Failure Analysis	ASM ⁺	Salt Lake City, UT
02-06 Dec 85	Symp on Defect Properties & Processing of High Tech Nonmetallic Materials	MRS/AmCerS	Boston, MA
16-20 Dec 85	Second International Conference on Biaxial/Multi-axial Fatigue	-	Sheffield, UK
13-16 Jan 86	Composites in Manufacturing 5 Conf. and Exposition	SME	Los Angeles, CA
13-17 Jan 86	Gordon Conf on Composites	-	Santa Barbara, CA

Table VI-1 (continued)

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Calendar of Composites-related Events

May 1, 1985 through April 30, 1986

<u>DATES</u>	<u>MEETING</u>	<u>SPONSOR</u>	<u>PLACE</u>
01-03 Mar 86	Soaring Society of America National Conv	SSA	Philadelphia, PA
02-06 Mar 86	AIME Annual Mtg	TMS-AIME	New Orleans, LA
03-05 Mar 86	Full-Field Techniques for Experimental Stress Analysis	SEM	Ann Arbor, MI
31 Mar- 03 Apr 86	American Physical Society Meeting	APS	Las Vegas, NV
06-11 Apr 86	ACS 191th National Mtg	ACS	Atlantic City, NJ
08 Apr 86	3rd Annual Matls Tech Center Conference	So. Ill. U.	Carbondale, IL
11 Apr 86	Military Standards for Composites Manufacturing	SME	Las Vegas, NV
07-09 Apr 86	Modal Analysis and Seminar	SEM	Kansas City, MO
08-10 Apr 86	31st Natl Symp & Exhib on Matls & Processes	SAMPE	Las Vegas, NV
17-18 Apr 86	13th Southeastern Conf. on Theor. & Appl. Mechanics	USoCarolina	Columbia, SC
28-30 Apr 86	8th ASTM Conference on Composite Materials	ASTM	Hampton, VA

Table VI-2

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Pertinent Professional Meetings Attended

May 1, 1985 through April 30, 1986

<u>DATES</u>	<u>MEETING</u>
28-Apr- 03 May 85	ACS 189th National Mtg (Prof. Sternstein/Prof. Wunderlich), Miami Beach, FL Professor Sternstein presented the paper: "Matrix Dominated Deformation of Composites" Professor Wunderlich presented the Invited Plenary Lecture: "Thermal Analysis of Liquid and Condensed Crystals"
04-06 May 85	Fiber Conference (Prof. Diefendorf), Strosk'e Plaso, Czch. Professor Diefendorf presented the paper: "Carbon Fibers"
06-08 May 85	NSF Innovation Meeting (Prof. Diefendorf), Albany, NY Professor Diefendorf presented the paper: "Evolution or Revolution in Materials"
17-21 Jun 85	17th Biennial Carbon Conference (Prof. Diefendorf), Lexington, KY Professor Diefendorf presented the papers: "The Physical Chemistry of the Carbon Fiber/Epoxy Resin Interface" "The Chemical Vapor Deposition in Open-Ended Capillary Tubes" "A Theoretical Calculation of Residual Stresses in Carbon Fibers" "The Effect of Heat Treatment on the Structure and Properties of Mesophase Precursor /carbon Fibers" "The Strength Distribution of Etched Carbon Fibers"
7-12 Jul 85	Gordon Conference on Pyrolysis (Prof. Wunderlich), Plymouth, NH Professor Wunderlich gave the Lecture: "Basic and Future Developments of Thermal Analysis"
19-22 Aug 85	International Conference on Thermal Analysis (Prof. Wunderlich), Bratislava, Czechoslovakia Professor Wunderlich gave the Plenary Lecture: "Quantitative Thermal Analysis of Macro-molecular Glasses and Crystals"

Table VI-2 (continued)

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Pertinent Professional Meetings Attended

May 1, 1985 through April 30, 1986

<u>DATES</u>	<u>MEETING</u>
29 Oct 85	New England Thermal Forum (Prof. Wunderlich), Natick, MA Professor Wunderlich gave the Lecture: "Analysis of Linear Macro-molecules by DSC"
16-20 Dec 85	Second International Conference on Biaxial/Multi-axial Fatigue (Prof. Krempl), Sheffield, UK Professor Krempl presented the paper: "The Effect of Biaxial In-phase Cycling on the Residual Strength of ($\pm 45^\circ$) _S Graphite /Epoxy Thin-walled Tubes"
13-17 Jan 86	Gordon Conference on Composites (Prof. Sternstein), Santa Barbara, CA Professor Sternstein presented the paper: "Viscoelastic Effects in Composites"
01-03 Mar 86	Soaring Society of America National Convention (Prof. Bundy), Philadelphia, PA
31 Mar- 3 Apr 86	American Physical Society Meeting (Prof. Wunderlich), Las Vegas, NV Professor Wunderlich gave the Papers: "Confirmational Analysis of Poly-Vinylidene Fluoride" "Condensed State of Liquid Crystals" "Thermal Properties of High-melting Polymers Containing Phenylene Groups"
08 Apr 86	3rd Annual Materials Technology Center Conference (Prof. Diefendorf), Carbondale, IL Professor Diefendorf presented the paper: "Carbon Fibers from Mesophase Pitch Precursors"
9-10 Apr 86	American Chemical Society Meeting (Prof. Wunderlich), Atlantic City, NJ Professor Wunderlich gave the Invited Poster: "Heat Capacity of Elastomers"

Table VI-2 (continued)

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Pertinent Professional Meetings Attended

May 1, 1985 through April 30, 1986

DATESMEETING

14-17 Apr 86

American Chemical Society Meeting (Prof. Wunderlich),
Atlantic City, NJProfessor Wunderlich gave the Invited Paper:
"Advanced Thermal Analysis of Linear Polymers Containing
Fluorine and Chlorine"

Table VI-3

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

May 1, 1985 through April 30, 1986

<u>SUBJECT</u>	<u>SPEAKER</u>	<u>DATE</u>
Improving the Strength Prediction for Advanced Composite Material with Stress Concentration	T.-H. Hu Doctoral Dissertation	7/16/85
SHORT COURSE: Advanced Composite Materials and Structures (16 Attendees from Industry & Govt)	Prof. R. Diefendorf Dr. H. G. Helwig, Dornier Systems, GmbH Dr. B. W. Rosen, Materials Sciences Corp. Dr. S. W. Tsai, AFML, WPAFB Mr. Dick Wilkins, General Dynamics Corp.	7/22-26/85
Automatic Adaptive Remeshing in Large Deformation Forming Analysis	Dr. J.-H. Cheng General Electric Co. Schenectady, NY	9/17/85
The Overstress Concept and Its Application to Creep-Fatigue Analysis	Prof. Y. Asada University of Tokyo Tokyo, Japan	10/8/85
Large Deflection Analysis of Elasto-Plastic Structures	Dr. M. P. Bieniek Columbia University New York, NY	10/29/85
An Orthotropic Formulation of the Viscoplasticity Theory based on Overstress	M. Sutcu Doctoral Dissertation	11/25/86
Pathological Cases in Elastic-Plastic Response to Short Pulse Loading	Prof. P. S. Symonds Brown University Providence, RI	12/10/86
Some Size Effects in the Mechanical Behavior of Materials	Prof. I. Finnie University of California Berkeley, CA	3/28/86

Table VI-3 (continued)

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

May 1, 1985 through April 30, 1986

<u>SUBJECT</u>	<u>SPEAKER</u>	<u>DATE</u>
Fluid Flow & Heat Transfer in Materials Processing	Prof. M. M. Chen University of Illinois Urbana-Champaign	4/15/86
The Theory of Finite Elastic-Plastic Deformation with Induced Anisotropy Modelled as Combined Isotropic- Kinematic Hardening	A. Agah-Tehrani Doctoral Dissertation	4/29/86

Table VI-4

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

May 1, 1985 through April 30, 1986

<u>Faculty Member</u>	<u>Purpose of Visit</u>	<u>Location</u>	<u>Date(s)</u>
B. Wunderlich	Presented Seminar: "Thermal Analysis of Linear Macro-molecules"	Oak Ridge National Labora- tory, Oak Ridge, TN	5/29/85
R. Diefendorf	Presented Lecture: "The RP Sailplanes: An Undergraduate Design Activity in Composite Materials"	ASEE Mtg Atlanta, GA	6/18/85
S. Sternstein	Member of Site Review Committee for High Temperature Resin Research	NASA Lewis RC Cleveland, OH	7/15-16/85
R. Diefendorf	Presented Lecture: "Structure and Prop- erties of Carbon Fibers"	Wright Patterson Materials Lab Dayton, OH	8/8/85
R. Loewy	Mtg with Mr. Hugo Kreusi to discuss possible interactions with RPI	US Composites Corporation at RPI Troy, NY	8/15/86
R. Loewy	Presented Review: "Transatmospheric Vehicle" Rpt of the US SAB	SDI Panel at Space Applications International Washington, DC	10/7/85
R. Loewy	Presented Lecture: "Tests and Analyses of Pin-Loaded Holes in Composites"	Beijing Inst. of Aero. & Astro. Beijing, PRC	10/28/85
R. Loewy	Presented Report: "Transatmospheric Vehicle" Rpt of the US SAB	US Scientific Advisory Board Meeting Washington, DC	10/23/85
R. Loewy	Presented Lecture: "Tests and Analyses of Pin-Loaded Holes in Composites"	Northwest Poly- technic Univ. Xi'an, PRC	11/1/85

Table VI-4 (continued)

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

May 1, 1985 through April 30, 1986

<u>Faculty Member</u>	<u>Purpose of Visit</u>	<u>Location</u>	<u>Date(s)</u>
S. Sternstein	Presented Lecture: "Deformation of Composites"	U. of Mass. Amherst, MA	11/1/85
R. Diefendorf	Presented Review: "Mesophase Formation in Polynuclear Aromatics"	US Steel Monrovia, PA	11/7/85
S. Sternstein	Presented Review & Seminar: "Matrix Dominated Mechanical Properties of Composites"	NASA Langley RC Hampton, VA	11/12/85
R. Diefendorf	Presented Seminar: "Filament Winding of Complex Composite Parts"	General Motors Troy, NY	11/21/85
S. Sham	Presented seminar: "Mechanics of Comp- osites"	NASA Langley	1/16/86
S. Sham	Attended Seminar: "A Unified Finite Element Method for Determining Weight Functions"	National Bureau of Standards, Gaithersburg, MD	1/17/86
S. Sternstein	Presented Lecture: "Matrix Dominated Mechanical Properties of Composites"	Air Force Thermo- plastics Comp- osites Review San Diego, CA	2/4-6/86
S. Sternstein	Presented Lecture: "Deformation of Composites"	IBM Reseach Cntr San Jose, CA	2/7/86
R. Diefendorf O. Bauchau	Gave Short Course: "Composite Materials and Structures"	Sikorsky Aircraft Stratford, CT	2/7-21/86

Table VI-4 (continued)

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

May 1, 1985 through April 30, 1986

<u>Faculty Member</u>	<u>Purpose of Visit</u>	<u>Location</u>	<u>Date(s)</u>
B. Wunderlich	Colloquium: "Thermal Analysis of Linear Macro-molecules"	Penn State University, State College, PA	2/13/86
R. Diefendorf	Presented Lecture: "The Relationship Between Structure and Properties in Carbon Fibers"	duPont Corp. Wilmington, DE	2/14/86
G. Dvorak	Presented Seminar: "Plasticity & Fatigue in MMC"	NASA Langley Hampton, VA	2/18/86
R. Diefendorf A. Falcone B. Tung S. Yurgartis S. Cheng S. Winckler	Presented Seminar: "Advanced Composites - RPI/GE Overview"	General Electric Plastics Div., Pittsfield, MA	3/12/86
R. Diefendorf	Presented Review: "Filament Winding of Complex Parts"	General Motors at RPI Troy, NY	3/14/86
R. Loewy	Presented Seminar: "Composites and Manuf. Productivity Reseach at RPI"	U of Delaware Dr. Dick Wilkins	3/18/86
R. Diefendorf	Presented Review: "Ceramic Matrix Composites"	Kaiser Aerotech at RPI Troy, NY	3/20/86
R. Loewy	Mtg with Gen. R. Rankine to discuss Aerospace-plane research requirements	Pentagon Washington, DC	3/21/86
G. Dvorak	Presented Seminar: "Recent Developments in Plasticity of Composite Materials"	U. of Wisconsin, Madison, WI	4/10/86

Table VI-4 (continued)

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

May 1, 1985 through April 30, 1986

<u>Faculty Member</u>	<u>Purpose of Visit</u>	<u>Location</u>	<u>Date(s)</u>
G. Dvorak	Presented Seminar: "Recent Developments in Plasticity of Composite Materials"	Michigan State U. East Lansing, MI	4/29/86
R. Diefendorf	Presented Review: "Filament Winding of Complex Shapes"	General Motors at RPI Troy, NY	4/30/86

Table VI-5

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Brown Bag Lunch Schedule

May 1, 1985 through April 30, 1986

<u>DATE</u>	<u>TOPIC</u>	<u>RESP. FACULTY</u>
03-May	Administrative Report Ordered Polymers Beams with Warping	Loewy Diefendorf Bauchau
06-Sep	Administrative Report Fracture Considerations in Ceramic/Ceramic Composites Beams with Warping	Wiberley Diefendorf Bauchau
13-Sep	General Discussion - "What Improvements can be made Toward Development of the Next Generation of Composite Materials"	Diefendorf
20-Sep	Administrative Report Cumulative Damage Law Resin Matrix Characterization	Loewy Krempf Sternstein
27-Sep	General Discussion - The Role of the Matrix	Sternstein
04-Oct	Administrative Report Composite Shafting Edge Failures	Wiberley Darlow Sham
11-Oct	General Discussion - Report on 5th International Conf. on Com- posite Materials	Diefendorf
18-Oct	Administrative Report Numerical Analysis of Comp. Processing Fabrication Technology	Loewy Shephard Bundy/Hagerup/Paedelt
25-Oct	General Discussion - Gas-Dynamic/Material-Surface Interactions at High Temperature	Nagamatsu
01-Nov	Administrative Report Ordered Polymers Beams with Warping	Diefendorf Diefendorf Bauchau
08-Nov	General Discussion - Planning for the Future (Rpt on National SAMPE Mtg)	Diefendorf

Table VI-5 (continued)

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Brown Bag Lunch Schedule

May 1, 1985 through April 30, 1986

<u>DATE</u>	<u>TOPIC</u>	<u>RESP. FACULTY</u>
15-Nov	Administrative Report Failure in Metal Matrix Composites Composites Fatigue	Diefendorf Dvorak Krempf
22-Nov	General Discussion - Thermo- Mechanical Field Effects in Composites	Bauchau
29-Nov	Thanksgiving Recess (No Meeting)	
06-Dec	Administrative Report Completely-Reversed Bending Fatigue	Wiberley Sternstein
13-Dec	General Discussion - Problems in Composites Manufacturing	Diefendorf
17-Jan	Administrative Report Ordered Polymers Beams with Warping	Loewy Diefendorf Bauchau
24-Jan	General Discussion Topic - Successor Projects to the RP-2	Loewy
31-Jan	Administrative Report Composites Fatigue Resin Matrix Characterization	Loewy Krempf Sternstein
07-Feb	Administrative Report General Discussion Topic - Effect of Residual Stress on Part Strength	Wiberley Shephard
14-Feb	Administrative Report Curing Uniformity Edge Failures	Wiberley Wunderlich Sham
21-Feb	Administrative Report General Discussion Topic - New Composite Materials	Wiberley Diefendorf
	<u>VISITORS:</u> Dr. Sheldon Roberts, Private Consultant Dr. Frank Tarzanin, Boeing Vertol	

Table VI-5 (continued)

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Brown Bag Lunch Schedule

May 1, 1985 through April 30, 1986

<u>DATE</u>	<u>TOPIC</u>	<u>RESP. FACULTY</u>
28-Feb	Administrative Report Failure in Metal Matrix Composites Ordered Polymers	Loewy Dvorak Diefendorf
07-Mar	Administrative Report General Discussion Topic - Construction of RP-1 & RP-2 Aircraft	Wiberley Paedelt
14-Mar	Administrative Report Aeroelastic Tailoring of BV Comp Blade Health and Safety with Composites Rpt on Trip to GE Plastics Div	Loewy Bauchau Paedelt Falcone/Winckler
21-Mar	Spring Recess (No Meeting)	
28-Mar	General Discussion Topic - Mechanics of Damage in Composites	Sternstein
04-Apr	Administrative Report Beams with Warping Composites Fatigue	Loewy Bauchau Krempf
11-Apr	Administrative Report General Discussion Topic - Num. Analysis Tools for Composites	Loewy Shephard
18-Apr	Administrative Report Resin Matrix Characterization Curing Uniformity	Wiberley Sternstein Wunderlich
25-Apr	Administrative Report General Discussion Topic - Failure in Metal Matrix Composites	Loewy Dvorak

Table VI-6

COMPOSITE MATERIALS AND STRUCTURES PROGRAM

Short Course: Composite Materials and Structures
Participants and Affiliations

July 22, 1985 through July 26, 1985

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Table VI-6 (continued)

COMPOSITE MATERIALS AND STRUCTURES PROGRAM

Short Course: Composite Materials and Structures
Participants and Affiliations

July 22, 1985 through July 26, 1985

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Table VI-7

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Review of Research Center Interactions

May 1, 1985 through April 30, 1986

<u>Faculty Member(s)</u>	<u>Purpose</u>	<u>Nature of Interchange</u>	<u>Date(s)</u>
S. Sternstein	Member of Site Review Committee for High Temperature Resin Research	NASA Lewis Research Center	7/15-16/85
R. Loewy R. Diefendorf H. Nagamatsu S. Sternstein S. Wiberley	Visit to RPI to Discuss Program Direction	with Dr. M. Greenfield, NASA HQ and Dr. L. Vosteen, NASA Langley	7/19/85
R. Loewy R. Diefendorf S. Sternstein G. Dvorak O. Bauchau S. Sham M. Shephard E. Krempf S. Wiberley F. Bundy B. Wunderlich N. Stoloff	Annual Site Visit and Program Review at RPI	with <i>from sponsoring agencies:</i> N. Pagano, AFOSR T. Serafini, NASA Langley J. Hinckley, NASA Langley M. Nemeth, NASA Langley L. Vosteen, NASA Langley <i>from Industrial Technical Advisory Committee:</i> I. G. Hedrick, Grumman Aerospace J. R. Huebner, McDonnell Douglas J. Jaeb, Boeing Commercial Airplane Co M. Waddoups, General Dynamics J. Whiteside, Grumman Aerospace	12/2-3/85
S. Sham	Presented paper "Mechanics of Composites"	NASA Langley Seminar	1/16/86
G. Dvorak	Discussion on Finite Element Calculations for Non-Linear Problems in MMC	NASA Langley with W. Steve Johnson	2/18/86
E. Krempf	Letter discussing the Effect of Behavior Graphite/Epoxy Tubes	Correspondence, with Dr. Wolf Elber, Langley RC	3/17/86 EK to WE

Table VI-7 (continued)

COMPOSITE MATERIALS AND STRUCTURES PROGRAM
Review of Research Center Interactions

May 1, 1985 through April 30, 1986

<u>Faculty Member(s)</u>	<u>Purpose</u>	<u>Nature of Interchange</u>	<u>Date(s)</u>
R. Loewy	Review of RPI Plans and Capabilities in High Temperature Composites	NASA HQ with Drs. L. Couch and M. Greenfield	3/21/86
S. Sternstein	Provide RPI with Material Samples, Exchange Test Data	Correspondence & Telephone Convers. with Dr. N. Johnson, NASA Langley	Continually, throughout the Reporting Prd.

PART VII
PERSONNEL, AUTHOR INDEX

PERSONNEL

Co-Principal Investigators

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

Senior Investigators

Bauchau, O., Ph.D. (Structural dynamics, advanced composites)*	Assistant Professor of Aeronautical Engineering
Bundy, F. P., Ph.D. (Physical chemistry, structures testing)*	Research Professor of Materials Engineering
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 of Civil Engineering
Hagerup, H. J., Ph.D. (Aerodynamics, configuration, pilot accomodation, flight testing)*	Associate Professor of Aeronautical Engineering
Krempf, E., Dr.Ing. (Fatigue studies, failure criteria)*	Professor of Mechanics and Director of Cyclic Strain Laboratory
Sham, T.-L., Ph.D. (Fracture mechanics, composites)*	Assistant Professor of Mechanical Engineering
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 of Polymer Engineering
Wunderlich, B., Ph.D. (Processing science, constituent material characteristics)*	Professor of Chemistry

* Fields of Specialty

[†] Member of Budget Committee together with Co-Principal Investigators

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Dawkins, Wilbert

Park, Brian

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Pusateri, Robert

Jacob, Daniel

Rosario, Estrella

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Advanced Composite Materials and Structures

July 22-26, 1985

Rensselaer Polytechnic Institute Announces

Advanced Composite Materials and Structures

July 22-26, 1985

Considered revolutionary only a decade ago, the application of advanced fiber-reinforced materials has now become essential in modern structural applications.

This intensive program deals with key issues in the development of modern structures in aerospace, automotive and other advanced engineering applications. A unique combination of lectures, reinforced by hands-on experience, makes this course unique among offerings of its kind.

Objectives

The participants will gain familiarity with the underlying principles, terminology, and basic design and analysis methodology used in the application of composite materials to modern structures of all kinds. They will hear lectures by some of the leading experts in the field and also learn by doing computer analyses, part fabrication and sample testing with their own hands. The course will be based in part on

Who Should Attend

- Engineers, designers and technical managers involved in or responsible for the analysis and design of modern structures.
- Anyone interested in applications of advanced composite materials.

Materials and Structures Research at RPI

Building on the strength of national and international stature in materials engineering, RPI has established a program of composite materials and structures technology spanning the complete range from material component development through laminate design, structural component conceptual design, fabrication, and proof testing. With instructional programs at the undergraduate and graduate levels, and research sponsored by such agencies as NASA, the US Air Force, NSF, Exxon Corporation, the US Army Research Office, and the Office of Naval Research, the over-all program is unique among institutions of higher education.

Several laboratory facilities are used by participants in this one-week program. These facilities include:

The Center for Interactive Computer Graphics

Located in the Jonsson Engineering Center, this outstanding computational facility is devoted to engineering education design and research. Hardware consists of 36 IMLAC Dynagraphic 6220 refresh graphics

terminals, two dedicated PRIME 750 digital computers with 1.5 megabytes of memory each, three 300 megabyte disk units, two magnetic tape units, a card reader, line printer, versatic electrostatic plotter and several alphanumeric terminals. The 6220 is a smart terminal consisting of two processors, 24K words of memory, a light pen and a cathode ray tube.

Monday

(Morning) Physical description of typical composites. Design philosophy: when and how composites should be used. Fabrication and environmental considerations. (Diefendorf)

(Afternoon) Micromechanical aspects of composites. (Rosen)

(Evening) Social hour and banquet.

Tuesday

(Morning) Laminated Plate Theory: Stiffness and strength of composite laminates. (Tsai)

(Afternoon) Computer Demonstration: Application of laminated plate theory to the analysis and design of beams, tubes, point stress analysis, point design (sizing). The disks are not protected, and are easy for the user to enhance. (Tsai)

Wednesday

(Morning) Introduction to optimization of composites. Application of computer graphics (PRIME-IMLAC Terminals) to the design of a simple part.* (Helwig)¹

(Afternoon) Fabrication and materials handling laboratory. Layup and cure of a simple part.* (Helwig)

Thursday

(Morning) Review of fabrication results. Testing of samples illustrating various effects.* (Helwig)

(Afternoon) Review of test results. Post mortem discussions of the various kinds of failure. (Helwig & Wilkins)

Friday

(Morning) Fatigue and creep in composites. Failure mechanisms. (Wilkins)

(Afternoon) Overview of applications to vehicle structures. Summation. (Diefendorf)

Sessions marked with an asterisk () provide hands-on experience in using programmable calculators or the equipment in Rensselaer's Computer Graphics, Advanced Composites or Testing Laboratories.

¹Programs used in this session show what can be done, but will not be made available to the students.

Composite Materials & Structures Laboratory

Five thousand square feet of modern laboratory space is currently dedicated to composite materials and structures research at RPI. The program includes fundamental studies of the constituent materials (fibers, matrices and their interfaces); composite materials (laminates, hybrid laminates; laminate-foam sandwich); generic structural elements (composite plates, lugs, compression members, stiffeners, etc.); processing science and fabrication methods; and NDE and other means to assess long-term structural integrity including environmental effects. Composites fabrication, testing and analysis facilities include a 75 ton press, pressure furnaces, prepregging apparatus, fiber spinning equipment, MTS tension-torsion servohydraulic cyclic strain test system, Instron 1330 servohydraulic dynamic test system, Instron for dynamic biaxial tension-torsion testing and dynamic mechanical spectrometer.

Register by mailing the attached form or phone the Office of Continuing Studies, 518/266-6442. Because of the "hands-on" nature of the course, only the first 25 registrants can be enrolled. Applicants beyond the first 25 will be kept on a waiting list. (See reverse side for additional program details.)

Course Fee: \$875

The fee includes laboratory and computer usage, the textbook *Introduction to Composite Materials*, by Tsai & Hahn, luncheons, refreshment breaks, and a reception on Monday evening. A special stored program suitable for any one of a variety of computers, will be provided to all participants in this program at no extra charge.

Tax Deduction can be taken for all expenses of continuing education (including registration fees, travel, meals and lodging) undertaken to maintain and improve professional skills (Treas. Reg. 1-162-5 Coughlin vs. Commissioner, 203F 2d307).

RPI admits qualified students without regard to age, race, color, marital status, religion, sex, sexual preference, national or ethnic origin, or handicap.

Structures