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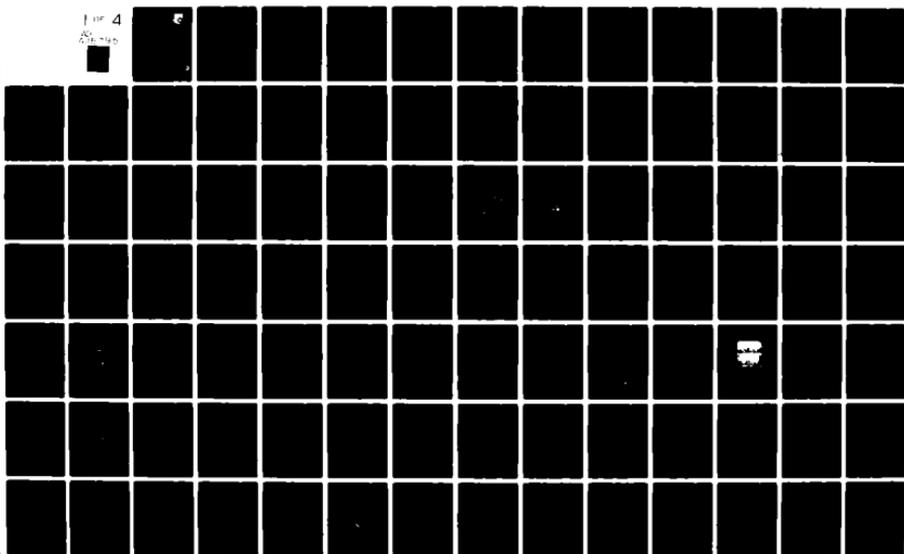
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PROCEEDINGS OF THE SEVENTH ANNUAL MECHANICS OF COMPOSITES REVIEW

Stella D. Gates
Lisa A. Wilson

Mechanics and Surface Interactions Branch
Nonmetallic Materials Division

April 1982

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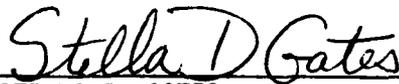
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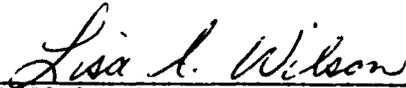
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report contains summaries of the presentations of the <u>Seventh Annual Mechanics of Composites Review</u> sponsored by the Air Force Materials Laboratory. Each paper was prepared by its presenter and is published here unedited. In addition to the presenter's summaries, a listing of both the inhouse and contractual activities of each participating organization is included.		

FOREWORD

This report contains the abstracts and viewgraphs presented at the Seventh Annual Mechanics of Composites Review sponsored by the Materials Laboratory. Each was prepared by its presenter and is published here unedited. In addition, a listing of both the in-house and contractual activities of each participating organization is included.

The Mechanics of Composites Review is designed to present programs covering activities throughout USAF and NASA. Programs not covered in the present review are candidates for presentation at future mechanics of composites reviews. The presentations cover both in-house and contract programs under the sponsorship of the participating organizations.

Since this is a review of on-going programs, much of the information in this report has not been published as yet and is subject to change; but timely dissemination of the rapidly expanding technology of advanced composites is deemed highly desirable. Works in the area of mechanics of composites have long been typified by disciplined approaches. It is hoped that such a high standard of rigor is reflected in the majority, if not all, of the presentations in this report.

Feedback and open critique of the presentations and the review itself are most welcome as suggestions and recommendations from all participants will be considered in the planning of future reviews.

We express our appreciation to the authors for the contribution of their summaries and to the points of contact within the organizations for their effort in supplying the program listings.



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KEYNOTE: 7th ANNUAL MECHANICS OF COMPOSITES REVIEW

DAYTON, OHIO

October 28, 1981

Dr. Robert Loewy, Institute Professor
Rensselaer Polytechnic Institute (RPI)

COMPOSITES: COMING OF AGE

In the early 1960's the aerospace Research and Development (R&D) community was hearing about boron slurries as a new aircraft fuel to get extended range, -- hearing almost as much about them as it was about boron fibers which could be imbedded in plastics and used as a new structural material. In R&D like everything else, you win some and lose some, so here we are -- about 20 years later -- without boron fuels, but with boron fibers, and their companion and perhaps successor fibers, revolutionizing the structural materials business.

It may seem obvious now, and it was obvious to many in the mid-60's, that any material which promised to reduce structural weight by 25 to 40% was worth developing, -- at least for special applications -- even if that material's ultimate cost per pound would be an order of magnitude more than the cost per pound of existing structural materials. But that was not obvious to everyone, and before the Air Force could establish the pioneering programs that largely carried us to our present technological state in composite materials, it was apparently necessary to conduct succession of independent studies. The granddaddy of them all was Project Forecast, concluded in 1964 under the aegis of General Bernard Schriever, usually credited with being the developer of America's first Intercontinental Ballistic Missile (ICBM). Project Forecast covered many subjects, but one major result was to call attention to the unusual properties available in filamentary materials. Project Forecast was followed by three separate studies of composites conducted by the Air Force Scientific Advisory Board, at various strategically selected times; by a lengthy review under the auspices of the National Materials Advisory Board of the National Research Council (NRC)

and subsequently, by Project Recast in 1972. The last of these was established by Al Lovelace, past Chief Scientist and Director of the Air Force Materials Laboratory, Deputy Administrator of NASA and now Corporate Vice President of General Dynamics. There were undoubtedly others, but all these independent studies helped to grease the skids for the herculean efforts on the part of people in the appropriate government offices -- many of whom are in this room, or nearby -- to make aerospace structures using filamentary composites a reality.

Since then, of course, much has happened. The Navy became the first to have advanced composites in the primary structure of a production aircraft, with a boron/epoxy horizontal stabilizer on the F-14. The Army may be considered the first to have employed composites in all lifting surfaces of an aircraft with the fiberglass rotor blades on the CH-47D Chinook helicopter. The Marines could be first with a production composite wing, if their AV-8B goes into service, and NASA, with its ACEE program, has made giant strides in getting composites introduced into the airframes of commercial airplanes, for which ultra-conservatism has been made a fact of life by John Q. Public's view of liability whenever public safety is concerned. What's more, the future promises development of an Air Force composite F-16 wing structure, a composite wing carry-through structure for a commercial air transport under NASA's auspices, a Navy composite F-18 wing structure, and the Army's two exciting (All Composite Aircraft Program) (ACAP) experimental helicopters.

With this much history behind us and such promising prospects immediately ahead, the pace of composites applications to aerospace structures is certainly quickening. But the technology can hardly be said to be mature. To my mind it hasn't even entered its young manhood -- it's more like adolescence.

To be sure, most of the growing pains have been left behind. There are now suppliers whose materials can be used with confidence, if the user knows what he's doing. The properties of useful boron, carbon, glass and aramid fibers and epoxy resins (and some others) are now

rather well known. There is a structural handbook, the "Air Force Advanced Composites Design Guide", (and some fine texts like those of Jones, Christiansen and Tsai and Hahn,) to summarize the considerable theoretical developments and practical experience accumulated to date. Most environmental concerns, like the effects of temperature and moisture, lightning strikes and UV radiation are beginning to be brought to heel. And we've developed repeatable fabrication techniques using prepreg tapes, fabrics and filament winding with well-established cure cycles. Perhaps the most important thing of all is that a stream of new manpower, trained so as to think of composites as more-or-less ordinary structural materials, has begun flowing from our universities. At my university alone, at RPI, over 180 graduates have left the campus in the last 5 years with hands-on experience in designing, fabricating and testing composite structures typical of advanced industry practice. By this time, a significant pool of composite materials and structures talent has been established which can be looked to develop the next generation of aerospace structural designs. Yes, the adolescent is flexing his newly-developed muscles.

But adolescence, for all its new capabilities, can be a time of some trauma, too. Consider composites: from an engineering science viewpoint most of the easy problems have now been solved and the hard ones must be undertaken; from an engineering development point of view we have realized the benefits of doing the simpler things, to make further gains we have to tackle more complicated structures.

The challenges that must be met for composites to enter a healthy technological young manhood are well-stated in the planning documents of the Air Force, Army, Navy and NASA. We need composites with higher strain allowables, durability, damage tolerance, and impact and erosion resistance; we need to know more about failure mechanisms, flaw growth (particularly in thick laminates), and what makes for better fatigue characteristics in subcomponent attachments; we need to know how to design substructures and structural joints with higher integrity and repairability. We need better results from non-autoclave processes, less sensitivity to handling and shelf life, means to produce at higher rates and economically, and improved quality control methods.

I would hardly attempt to second-guess such a list, (which by the way I've distilled from presentations by such spokesmen as George Peterson, Harold Andrews, Richard Carlson and Charles Bersch.) Still, I do have a list of personal favorites among unsolved composites problems and this is a rare opportunity to put four of them before a group with the capabilities assembled here.

First; the idea of softening strips as "crack stoppers" in composites has considerable merit for situations in which fiber breakage is involved in the failure mechanism. But what about delamination stoppers? There are certainly failure modes that begin with delamination and which might be contained with a "delamination stopper."

Second, we've known for some time that the edges of composite plates involve a region of stress concentration, a "boundary layer" so to speak. One of my colleagues at RPI, Judd Diefendorf, recently said "an edge is a terrible thing to do to a composite", and I agree. Perhaps we need to learn how to design and fabricate composite plates which -- from this viewpoint -- have no edges. If this strikes you as a non-problem for some reason, let me remind you that we create edges every time we drill a hole.

Third; we still don't know enough about getting loads into and out of (more or less) constant sections, i.e., our ability to design structural joints is distinctly limited. This problem is bifurcated. In mechanical joints we can't predict the stress distributions around the holes and, therefore, cannot (without costly cut- & -try procedures) approach optimum designs. In bonded joints we have not achieved the level of confidence in manufacturing procedures, quality control and inspection methods to justify their routine use when we join major pieces of primary structure. This despite the fact, first, that bonded joints are usually more efficient than their mechanical counterparts and, second, that in one sense a composite material itself consists of nothing but an infinite array of bonded joints.

And, fourth; to capitalize fully on the manufacturing savings which composites promise we must somehow eliminate the need for separately fabricated panel stiffeners -- stringers in the relatively flat directions, and frames and ribs for highly curved directions. One option is sandwich honeycomb panels. Another is integral stiffeners. Both have been tried, both have some problems. The pay-off of developing either to the point of routine use could be very great.

The role of mechanics in bringing about solutions to my four favorite composites problems - (and all others, for that matter) - is as it has always been. Mechanics is the fundamental discipline underlying the task of applying materials of known properties to useful structures. When advances in the mechanics of composites make clear to us what is wrong with particular designs, applications and manufacturing schemes, we will then know better how to redesign, reapply and manufacture in some other way to avoid the crucial difficulty.

I am very happy to be here, complimented to have been asked to speak and full of anticipation to hear the excellent program our hosts and hostesses have arranged for us.

**EFFECTS OF DEFECTS IN COMPOSITE
STRUCTURES**

BY

G.P. SENDECKYJ

STRUCTURAL INTEGRITY BRANCH

FLIGHT DYNAMICS LABORATORY

AIR FORCE WRIGHT AERONAUTICAL LABORATORIES

WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

DESIGN CRITERIA

FIRST PLY FAILURE

DESIGN ULTIMATE STRAIN (DUS) IS STRAIN FOR FIRST PLY FAILURE

STATE-OF-THE-ART

DUS IS FAILURE STRAIN OF LAMINATE WITH 0.25 INCH HOLE

POSSIBLE

DUS IS FAILURE STRAIN OF LAMINATE WITH LOW ENERGY IMPACT

DAMAGE

BUFFER AND SOFTENING STRIPS USED

UPPER BOUND

DUS IS FAILURE STRAIN OF LAMINATE

STRESS CONCENTRATIONS DESIGNED AROUND

LEAST CONSERVATIVE

PREPREG DEFECTS

HOLLOW FIBERS

EXCESSIVE VARIABILITY IN FIBER PROPERTIES

RESIN-STARVED OR FIBER-STARVED AREAS

WRINKLES, WAVINESS, MISCOLLIMATION

FOREIGN PARTICLES, CONTAMINATION

PILLS AND FUZZ BALLS

NONUNIFORM AGGLOMERATION OF HARDENER

PREPREG OUT OF SPECS.

DEFECTS IN LAMINATES

HOLLOW FIBERS

FIBER BREAKS

EXCESSIVE POROSITY, VOIDS

RESIN-RICH AND RESIN-STARVED AREAS

FIBER WAVINESS, WRINKLES, MISCOLLIMATION

FOREIGN PARTICLES, CONTAMINATION, INCLUSIONS

INCOMPLETE AND/OR VARIABLE CURE

WRONG STACKING SEQUENCE

DENTS, TOOL IMPRESSIONS, SCRATCHES

DELAMINATIONS

PLY GAPS

LAMINATE POROSITY

STUDIED EXTENSIVELY

MATRIX DOMINATED PROPERTIES DEGRADED (DELAMINATION

NOT INCLUDED)

5% STRENGTH REDUCTION FOR 1% POROSITY

50% LIFE REDUCTION FOR 1% POROSITY

FIBER DOMINATED PROPERTIES NOT AFFECTED

DELAMINATION GROWTH AFFECTED - NOT WELL DOCUMENTED

MOISTURE ABSORPTION

EQUILIBRIUM MOISTURE LEVELS INCREASED

AGGRAVATES THERMAL SPIKE PHENOMENON

EFFECT OF PLY GAP DEFECT

REF: AFWAL-TR-79-4128

(0/45/90/-45)_S 2 LAMINATE

- 16.9% STRENGTH REDUCTION FOR GAP(S) IN 90 PLYES

- 8.7% REDUCTION FOR GAP(S) IN 0 PLYES

(0/45/0 /-45/0)_S 2 LAMINATE

- 6.5% STRENGTH REDUCTION FOR GAPS IN 0 PLYES

REF: AFWAL-TR-80-4092

(0/ 45/90)_S 2 LAMINATE

- 12.8% STRENGTH REDUCTION FOR GAPS IN OUTER 45 PLYES

(0/-/45/0)_S 2 LAMINATE

- 6.2% STRENGTH REDUCTION FOR GAPS IN OUTER 45 PLYES

DEFECT CRITICALITY - BENIGN FOR DESIGN ULTIMATE STRAIN 0.7%

EFFECT OF SURFACE NOTCHES

EXPERIMENTAL DATA

STATIC STRENGTH REDUCED UP TO 50%

LOCAL DELAMINATION AT NOTCH

FATIGUE LOADING REDUCES STRESS CONCENTRATION

RESIDUAL STRENGTH HIGHER THAN STATIC STRENGTH

DATA AVAILABLE FOR VARIOUS STACKING SEQUENCES

ANALYSIS

ECCENTRIC BEAM MODEL PREDICTS STRENGTH REDUCTION

STRENGTH REDUCTION IS SMALL FOR SIZES EXPECTED IN SERVICE

DEFECT CRITICALITY

NOT CRITICAL FOR DUS < 0.7

BOLTED ASSEMBLY DEFECTS

OVERTORQUED FASTENERS

IMPROPER FASTENER SEATING

MISSING FASTENERS

FASTENER INSTALLATION DAMAGE

OVERSIZED AND UNDERSIZED FASTENER

BONDING DEFECTS

ADHESIVE POROSITY

MISCURE

ADHESIVE-STARVED AREAS

IMPROPER SURFACE PREPARATION

EFFECT OF PLY WAVINESS DEFECT

REF: AFWAL-TR-80-4044, JUNE 1980

SURFACE 0 PLY WAVINESS IN (0/45/90/-45)₂ LAMINATE

STATIC TENSILE STRENGTH REDUCTION

- 10% FOR SLIGHT WAVINESS
- 25% FOR EXTREME WAVINESS

FATIGUE LIFE REDUCTION

- AT LEAST A FACTOR OF 10
- CONSISTENT WITH STATIC STRENGTH REDUCTION

DEFECT CANNOT BE FOUND BY STANDARD NDE

STRENGTH LOSS CAN BE PREDICTED BY ASSUMING LOSS OF LOAD

CARRYING CAPACITY DUE TO THE WAVINESS

DEFECT CRITICALITY - INSUFFICIENT DATA FOR ACCURATE ASSESSMENT

- SHOULD BE BENIGN FOR DESIGN ULTIMATE STRAINS 0.7%

MACHINING DEFECTS

EDGE DELAMINATIONS	EDGE NOTCHES AND SURFACE NOTCHES
OVERSIZE HOLES	HEAT DAMAGED MACHINED EDGES
UNDERSIZE HOLES	FIBER BREAK-OUT ON HOLE EXIT SIDE
TILTED HOLES	OUT-OF-ROUND HOLES
TILTED COUNTERSINKS	IMPROPER DEPTH OF COUNTERSINKS
	DENTS, FIBER BREAKING FROM IMPACT
	TEARUOT OR PULL-THROUGH IN COUNTERSINKS

AFWAL-TR-82-4007

RESIN SELECTION CRITERIA FOR ENGINE
COMPOSITE STRUCTURES

BY

C. C. CHAMIS AND G. T. SMITH
NASA LEWIS RESEARCH CENTER
CLEVELAND, OH 44135

SEVENTH ANNUAL MECHANICS OF COMPOSITES REVIEW

OCTOBER 28-30, 1981
DAYTON, OHIO

BACKGROUND

IT IS WELL KNOWN THAT RESINS (MATRICES) PROVIDE THE COMPOSITE WITH CAPABILITY TO RESIST LOAD BY KEEPING THE FIBERS IN PLACE. THE CAPABILITY OF THE RESIN TO KEEP THE FIBER IN PLACE IS A COMBINATION OF CHEMICAL, THERMAL AND MECHANICAL INTERACTIONS. THESE COMBINED INTERACTIONS ARE THE IN SITU RESIN PHYSICAL, HYGRAL, THERMAL AND MECHANICAL PROPERTIES WHICH PROVIDE THE COMPOSITE WITH THE REQUISITE STRUCTURAL INTEGRITY.

NEED: A STRUCTURED METHODOLOGY TO IDENTIFY, IN SOME FORMAL WAY, BULK (NEAT) RESIN CHARACTERISTICS WHICH TRANSLATE TO QUANTIFIABLE COMPOSITE BEHAVIOR. THE RESULT OF SUCH STRUCTURED METHODOLOGY IS A SET OF CRITERIA (GUIDELINES) WHICH CAN BE USED A PRIORI TO SCREEN AND/OR SELECT RESINS WITH THE DESIRABLE BULK PROPERTIES WHICH WILL PROVIDE THE SPECIFIED COMPOSITE PROPERTIES.

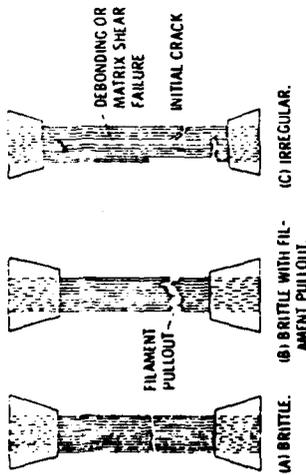
OBJECTIVE: TO DESCRIBE A STRUCTURED METHODOLOGY FOR ASSESSING, EVALUATING, AND IDENTIFYING DESIRABLE BULK RESIN CHARACTERISTICS FOR SPECIFIED COMPOSITE BEHAVIOR.

APPROACH: AN UPWARD INTEGRATED MECHANISTIC METHODOLOGY FORM CONSTITUENT PROPERTIES TO STRUCTURAL RESPONSE - MICROMECHANICS, MACROMECHANICS, LAMINATE THEORY, STRESS AND STRUCTURAL ANALYSIS.

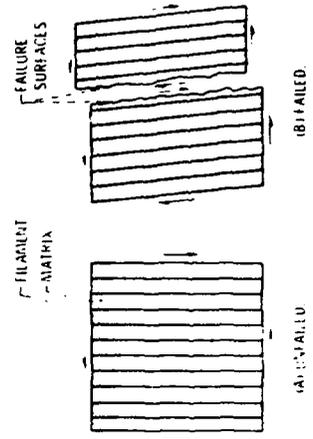
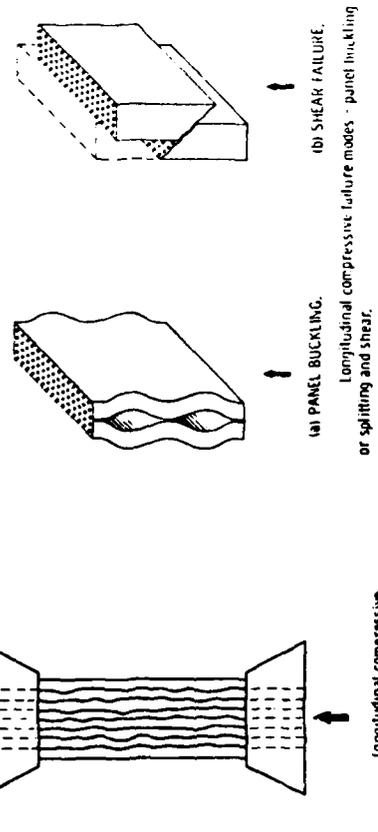
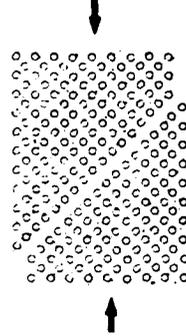
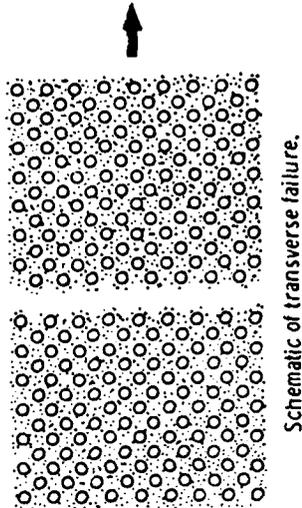
CONCLUSIONS

- o RESIN SELECTION CRITERIA FOR IMPROVED (TOUGHER) COMPOSITE PROPERTIES WERE IDENTIFIED USING AN UPWARD INTEGRATED METHODOLOGY-MICROMECHANICS TO STRUCTURAL ANALYSIS
- o THE CRITERIA ACCOUNT FOR RESIN STRENGTH AND MODULUS, PLY ENERGY DENSITY, LAMINATE FIRST PLY FAILURE, AND ENVIRONMENTAL AND CYCLIC LOAD EFFECTS
- o THE CRITERIA ARE EXPRESSED IN RESIN PROPERTIES BENEFITS REGIONS WHERE THE REGION BOUNDARIES ARE GIVEN BY SIMPLIFIED EQUATIONS OF RESIN STRENGTH AND MODULUS
- o THE PROPOSED CRITERIA CORRELATE WITH MEASURED DATA FOR STRENGTH STIFFNESS, DELAMINATION AND RESISTANCE TO IMPACT AND TO ENVIRONMENTAL EFFECTS
- o THE CRITERIA SELECTION SPACE PROVIDES A FORMALIZED DIRECTION FOR THE DEVELOPMENT OF RESINS FOR "TOUGHER" COMPOSITES

FRACTURE MODES OF UNIDIRECTIONAL FIBER COMPOSITES



Longitudinal tensile failure modes.



Schematic of shear failure modes (inplane, intralaminar).

GOVERNING EQUATIONS: MICROMECHANICS-ELASTIC

$$F_m = \left[\frac{T_{gwr} - T_T}{T_{gro} - T_{ro}} \right]^{1/2}$$

$$E_{l11} = k_f E_{f11} + k_r F_m E_{ro}$$

$$\nu_{l12} = \nu_{l13} = k_f \nu_{f12} + k_r \nu_{ro}$$

$$E_{l33} = E_{l22} = \frac{F_m E_{ro}}{1 - \sqrt{k_f} \left(1 - \frac{F_m E_{ro}}{E_{f22}} \right)}$$

$$G_{l13} = G_{l12} = \frac{F_m G_{ro}}{1 - \sqrt{k_f} \left(1 - F_m G_{ro} / G_{f12} \right)}$$

$$G_{l23} = G_{l32} = \frac{F_m G_{ro}}{1 - \sqrt{k_f} \left(1 - F_m G_{ro} / G_{f23} \right)}$$

$$\nu_{l23} = \left(E_{l22} / 2G_{l23} \right) - 1$$

GOVERNING EQUATIONS: MICROMECHANICS-UNIAXIAL STRENGTHS

LONGITUDINAL TENSION AND COMPRESSION

$$S_{111T} = S_{ft} \left[\beta_{ft} k_f + k_r E_r / E_{f11} \right]$$

$$S_{111C} = \text{MIN} \left\{ S_{fc} (\beta_{fc} k_f + k_r E_r / E_{f11}), S_{rc} \left(k_r + \beta_{fc} k_f E_{f11} / E_r \right) \right.$$

$$\left[\frac{F(k_v) G_r}{(1-k_f) + k_f G_r / G_{f12}} \right], \left. \left. \frac{(\beta_{cs} S_{112S} + S_{rc}) \left(\frac{k_v}{1-k_f} \right) + \left(\frac{k_v}{1-k_f} \right)^2}{1 - 2 \left(\frac{k_v}{1-k_f} \right) + \left(\frac{k_v}{1-k_v} \right)} \right\}$$

$$F(k_v) = \frac{1 - \left(\frac{k_v}{1-k_v} \right)}{1 - 2 \left(\frac{k_v}{1-k_f} \right) + \left(\frac{k_v}{1-k_f} \right)^2}$$

GOVERNING EQUATIONS: MICROMECHANICS-UNIAXIAL STRENGTHS

TRANSVERSE

$$S_{\theta 22T,C} = \frac{1}{\left[1 - \sqrt{k_f} \left(\frac{1 - E_m}{E_{f22}} \right) \right] \left[1 + \varphi_\eta (\varphi_\eta - 1) + \frac{1}{3} (\varphi_\eta - 1)^2 \right]^{1/2}} S_{MT,C}$$

$$\varphi_\eta = \frac{1}{\left(\frac{\pi}{4k_f} \right)^{1/2} - 1} \left[\left(\frac{\pi}{4k_f} \right)^{1/2} - \frac{1}{1 - \sqrt{k_f} \left(\frac{1 - E_m}{E_{f22}} \right)} \right]$$

LOWER BOUND

$$S_{\theta 22T,C} = 1 - \left(\frac{4k_f}{\pi} \right)^{1/2} S_{MT,C}$$

INTRALAMINAR SHEAR: REPLACE E & S_{MT} WITH G & S_{MS}, RESP.

$$\text{VOID EFFECTS: } S_{MV} = \left\{ 1 - \left[\frac{4k_v}{1 - \pi} \right]^{1/2} \right\} S_M$$

PLY STRESS INFLUENCE COEFFICIENTS

$$S_{LX} = \frac{E_{\ell 11}}{E_{cxx} (1 - \nu_{\ell 12} \nu_{\ell 21})} \left[(1 - \nu_{\ell 21} \nu_{cxy}) \cos^2 \theta + (\nu_{\ell 21} - \nu_{cxy}) \sin^2 \theta \right]$$

$$S_{TX} = \frac{E_{\ell 22}}{E_{cxx} (1 - \nu_{\ell 12} \nu_{\ell 21})} \left[(\nu_{\ell 12} - \nu_{cxy}) \cos^2 \theta + (1 - \nu_{cxy}) \sin^2 \theta \right]$$

$$S_{SX} = \frac{G_{\ell 12}}{E_{cxx} (1 - \nu_{\ell 12} \nu_{\ell 21})} \left[(1 + \nu_{cxy}) \sin^2 \theta \right]$$

WHERE

$$\sigma_{\ell 11} = S_{LX} \sigma_{cxx} ; \sigma_{\ell 22} = S_{TX} \sigma_{cxx} ; \sigma_{\ell 12} = S_{SX} \sigma_{cxx}$$

AND AT FAILURE $\sigma_{cxx} = S_{cxx}$

PLY COMBINED STRESS FAILURE CRITERION WITH HYGROTHERMOMECHANICAL EFFECTS

$$\begin{aligned}
 F(\sigma_{\beta}, S_{\beta}, E_{\beta}, \mathcal{F}_{HTM}) = & 1 - \frac{\sigma_{cxy}^2 E_{\beta 11}^2}{E_{cxy}^2} \left\{ \frac{1}{S_{\beta 11}^2 \alpha} \left[(1 - \nu_{\beta 21} \nu_{cxy}) \cos^2 \theta + (\nu_{\beta 21} - \nu_{cxy}) \sin^2 \theta \right]^2 \right. \\
 & + \frac{\mathcal{F}_m^2 E_{\beta 22}^2}{\mathcal{F}_s^2} \frac{1}{HTM E_{\beta 11} S_{\beta 22} \beta} \left[(\nu_{\beta 12} - \nu_{cxy}) \cos^2 \theta + (1 - \nu_{cxy} \nu_{\beta 12}) \sin^2 \theta \right]^2 \\
 & + \frac{\mathcal{F}_m^2 G_{\beta 12}^2}{\mathcal{F}_s^2} \frac{1}{HTM^E \beta 11 S_{\beta 12} s} \left[(1 + \nu_{cxy}) \sin^2 \theta \right]^2 \\
 & - \frac{K_{\beta 12} \mathcal{F}_m E_{\beta 22}}{E_{\beta 11} S_{\beta 11} \mathcal{F}_{HTM} S_{\beta 22} \beta} \left[(1 - \nu_{\beta 12} \nu_{cxy}) \cos^2 \theta + (\nu_{\beta 21} - \nu_{cxy}) \sin^2 \theta \right] \alpha \\
 & \left. \times \left[(\nu_{\beta 12} - \nu_{cxy}) \cos^2 \theta - (1 - \nu_{cxy} \nu_{\beta 12}) \sin^2 \theta \right] \beta \right\}
 \end{aligned}$$

$$\mathcal{F}_m = \left[\frac{T_{gw} - T}{T_{go} - T_0} \right]^{1/2} ; \quad \mathcal{F}_{HTM} = \mathcal{F}_m - B \text{ Log}_{10} N$$

BENEFIT BOUNDS EQUATIONS FOR RESIN PROPERTIES

TRANSVERSE
STRENGTH

$$S_{l22} = (1 - k_f) \bar{f}_{HTM} S_m \approx C_s S_m$$

$$\text{IF } S_m = \lambda_s S_{mo} \quad (\lambda_s > 1)$$

$$S_{l22} \approx C_s \lambda_s S_m$$

TRANSVERSE
MODULUS

$$E_{l22} = \frac{\bar{f}_m E_m}{1 - \sqrt{k_f} \left(1 - \frac{\bar{f}_m E_m}{E_{f22}} \right)} \approx C_m E_m$$

$$E_m = \lambda_m E_{mo} \quad (\lambda_m > 1)$$

$$E_{l22} = C_m \lambda_m E_{mo}$$

ENERGY
DENSITY

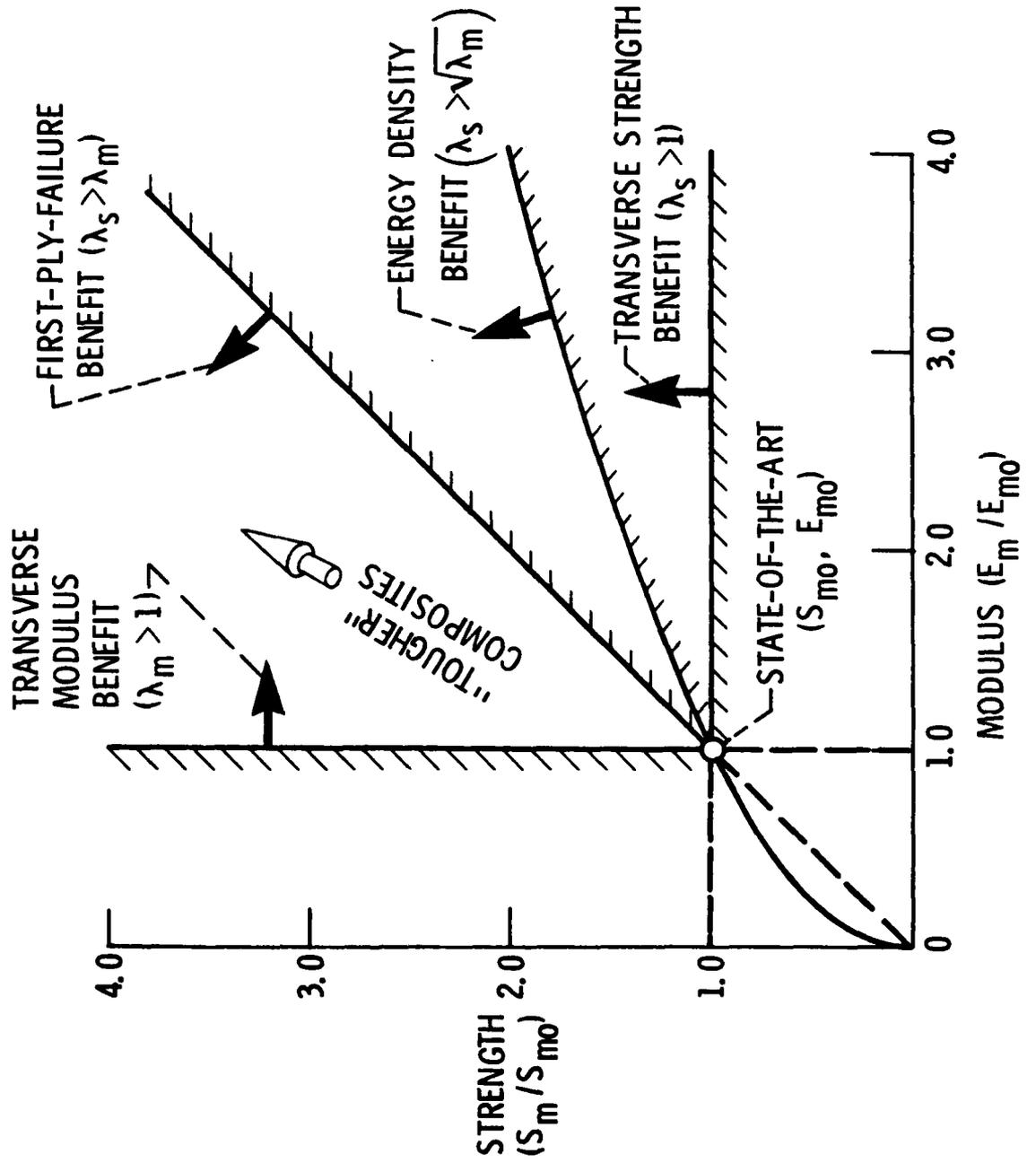
$$U_{l22} = \frac{S_{l22}^2}{2E_{l22}} = \frac{C_s^2 \lambda_s^2 S_{mo}^2}{2 C_m \lambda_m E_{mo}}$$

FIRST PLY
FAILURE

$$S_{cxx} = \left\{ \frac{C_o \bar{f}_m (1 - k_f) \left[1 - \sqrt{k_f} \left(1 - \frac{\bar{f}_m E_m}{E_{f22}} \right) \right]}{\bar{f}_m} \right\} \frac{S_m}{E_m}$$

$$S_{cxx} \approx C \frac{\lambda_s S_{mo}}{\lambda_m E_{mo}}$$

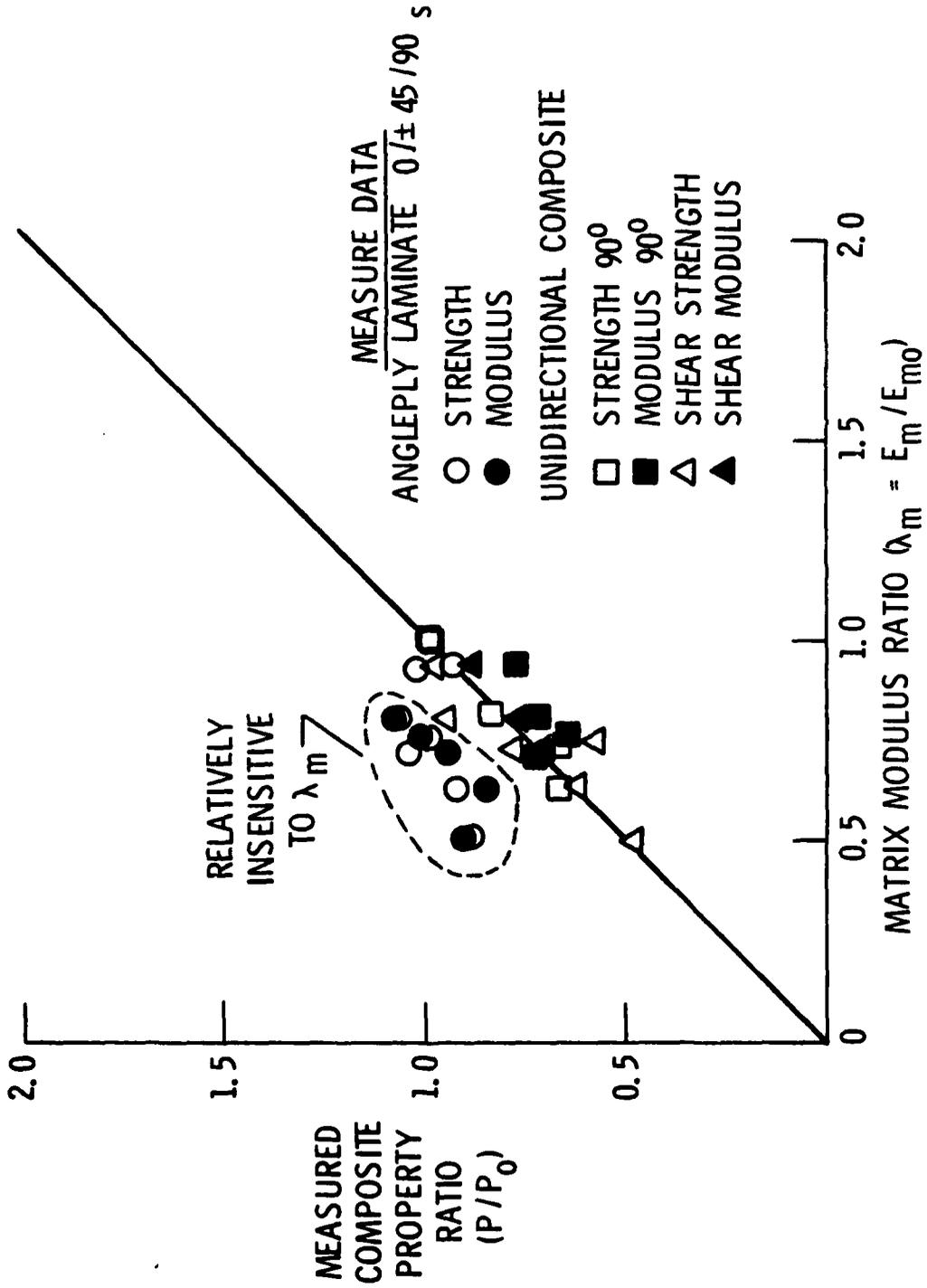
RESIN SELECTION CRITERIA FOR "TOUGHER" COMPOSITES



SELECTION CRITERIA

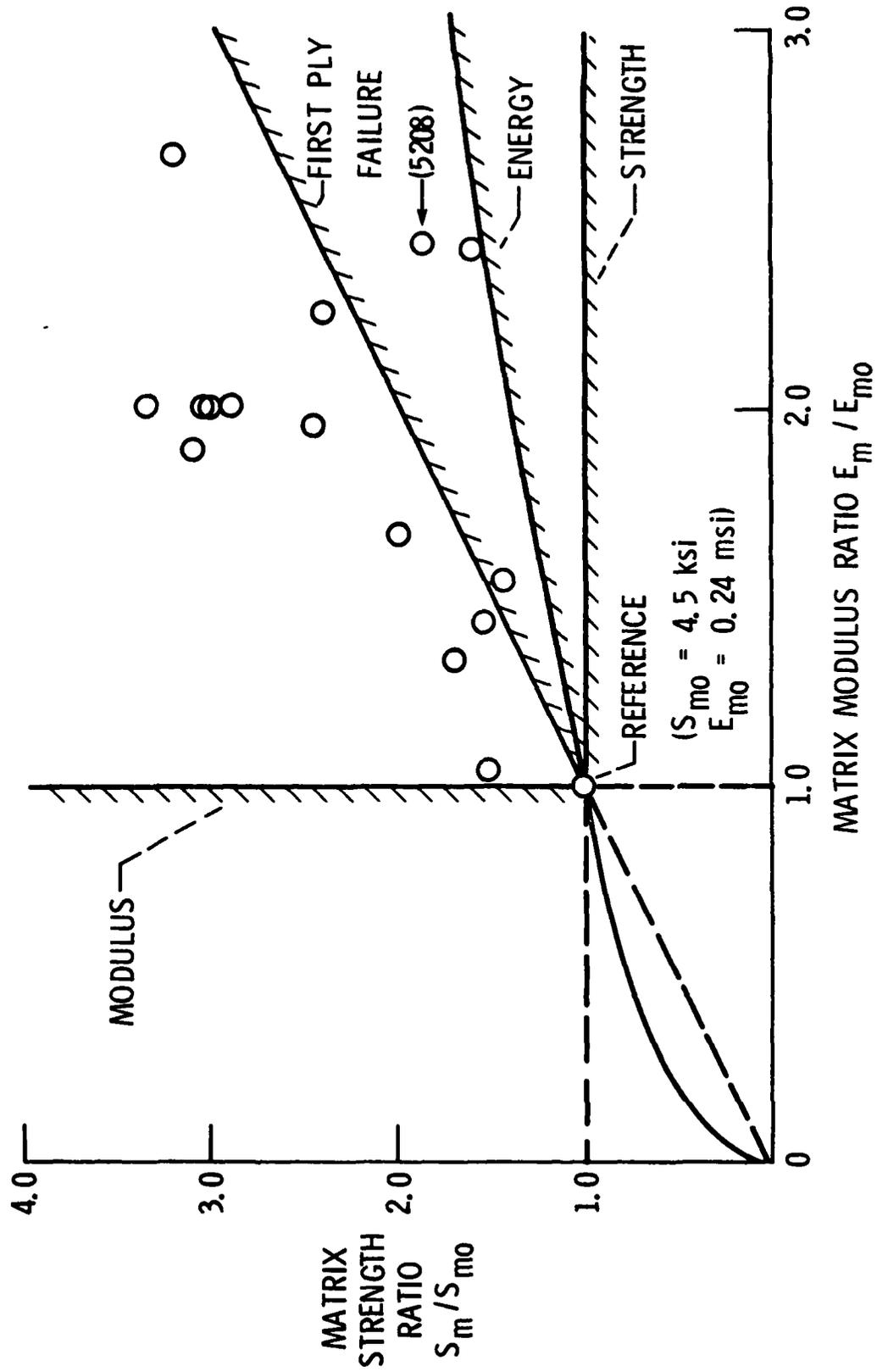
$$\frac{S_m}{E_m} = \frac{\lambda_s S_{m0}}{\lambda_m E_{m0}}$$

PROPOSED RESIN SELECTION CRITERIA CORRELATE WITH MEASURED DATA



NOTE: P_0 AND E_{m0} ARE REFERENCE PROPERTIES

MEASURED RESIN PROPERTIES ON SELECTION CRITERIA SPACE



AFWAL-TR-82-4007

**DAMAGE PROGRESSION IN GRAPHITE-EPOXY
BY A DEPLYING TECHNIQUE**

CONTRACT F33615-80-C3224

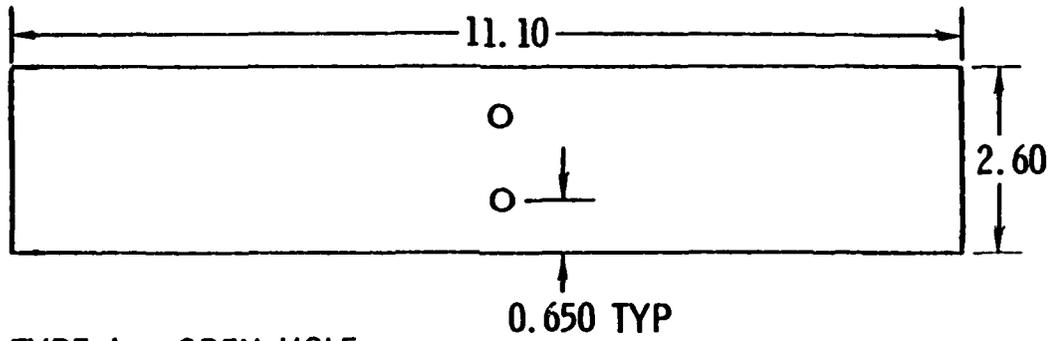
**PROJECT MANAGER - DR. G. P. SENDECKYJ
AFFDL/FBE**

**PROJECT LEADER - S. M. FREEMAN
LOCKHEED-GEORGIA COMPANY**

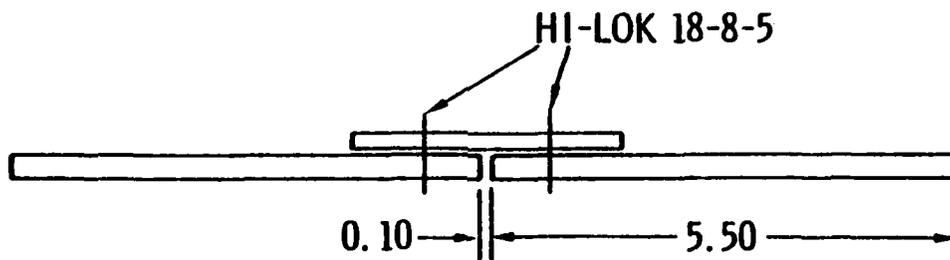
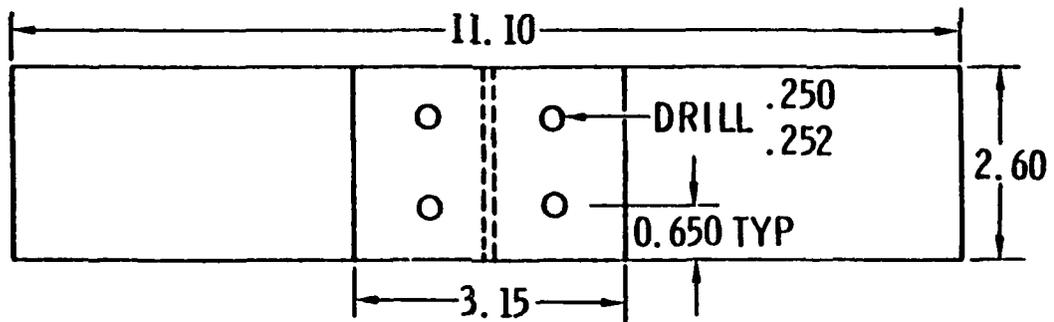
OBJECTIVES

- TO DEMONSTRATE A TECHNIQUE FOR FINDING FIBER FRACTURES AND MATRIX DAMAGE IN GRAPHITE-EPOXY COMPOSITES
- TO USE THIS TECHNIQUE IN CONJUNCTION WITH ACOUSTIC EMISSION AND PENETRANT ENHANCED X-RAY NON DESTRUCTIVE INSPECTION METHODS TO PROVIDE A COMPLETE DESCRIPTION OF DAMAGE PRODUCED AROUND LOADED HOLES IN GRAPHITE-EPOXY COMPOSITES

TEST SPECIMENS



TYPE I - OPEN HOLE



TYPE II - BOLTED JOINT

TEST MATRIX FOR OPEN HOLE SPECIMENS

LOADS	SPECIMENS PER TEST		
	LAMINATE A	LAMINATE B	LAMINATE C
CONTROLS (HOLE QUALITY) NONE	2	2	2
CONTROLS (ULTIMATE) MAXIMUM	5	5	5
LOAD LEVEL 1 DAMAGE INITIATION	5	5	5
LOAD LEVEL 2 INTERMEDIATE	5	5	5
LOAD LEVEL 3 INTERMEDIATE	5	5	5
LOAD LEVEL 4 90% OF MIN. CONTROL	5	5	5
TOTAL	27	27	27

LAMINATE CONFIGURATIONS

A - ($\pm 45^\circ$, 0° , $\mp 45^\circ$, 0° , $\pm 45^\circ$, 0° , $\pm 45^\circ$, 0°)s

B - ($\pm 45^\circ$, $\mp 45^\circ$, $\pm 45^\circ$, 0°)s

C - ($\pm 45^\circ$, 0° , 90° , $\mp 45^\circ$, 0° , 90° , $\pm 45^\circ$, 0° , 90°)s

TEST MATRIX FOR BOLTED JOINT SPECIMENS

LOADS	SPECIMENS PER TEST					
	LAMINATE A ED-2	LAMINATE A ED-3	LAMINATE B ED-2	LAMINATE C ED-2	LAMINATE C ED-3	
CONTROLS (HOLE QUALITY)	2	2	2	2	2	
CONTROLS (ULTIMATE)	5	5	5	5	5	
LOAD LEVEL 1 DAMAGE INITIATION	5	5	5	5	5	
LOAD LEVEL 2 INTERMEDIATE	5	5	5	5	5	
LOAD LEVEL 3 INTERMEDIATE	5	5	5	5	5	
LOAD LEVEL 4 90% OF MIN. ULTIMATE	5	5	5	5	5	
TOTAL	27	27	27	27	27	27

INTRODUCTION OF LOAD INDUCED DAMAGE

- ALL OPEN HOLE AND JOINT TESTS CONDUCTED IN SAME MTS ELECTRO-HYDRAULIC SERVO-CONTROLLED CLOSED-LOOP TEST SYSTEM
- SPECIMENS LOADED IN TENSION APPROXIMATELY 5000 POUNDS PER MINUTE
- ACOUSTIC EMISSION - AE SOURCE LOCATION SYSTEM
REAL TIME DAMAGE MONITORING

OPEN HOLE TESTS
 ULTIMATE TEST VALUES AND SELECTED LOAD LEVELS

SPEC TYPE	LOAD (POUNDS)		PERCENT OF AVERAGE ULTIMATE			
	AVG ULT	MIN ULT	1	2	3	4
IA	24,079	23,473	60	69	79	88
IB	35,065	33,634	41	56	68	86
IC	15,844	15,486	60	73	87	88

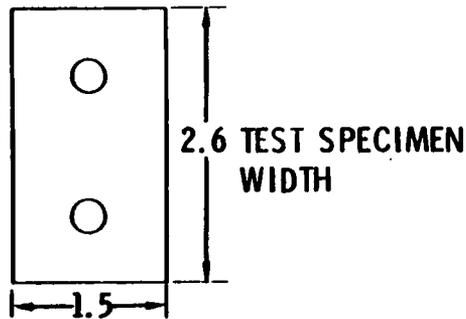
BOLTED JOINT TESTS
 ULTIMATE TEST VALUES AND SELECTED LOAD LEVELS

SPEC TYPE	LOAD (POUNDS)		PERCENT OF AVERAGE ULTIMATE			
	AVG ULT	MIN ULT	1	2	3	4
I1A-A	8240	7821	61	69	77	85
I1A-B	5274	5158	59	69	79	88
I1A-C	9645	9399	62	71	79	88
I1B-A	7797	7582	64	72	80	88
I1B-C	9012	8061	76	78	79	81

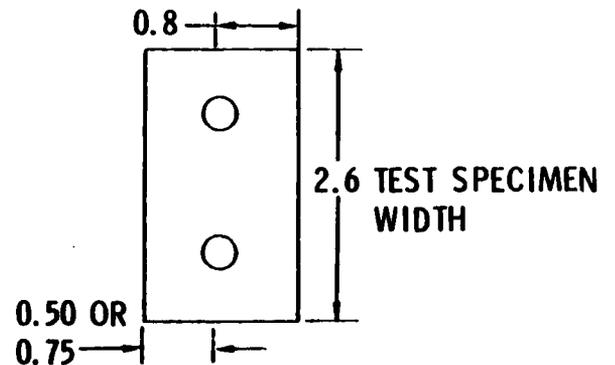
DAMAGE ASSESSMENT TECHNIQUES

- X-RAY RADIOGRAPHY - TBE ENHANCED - CONVENTIONAL AND STEREO
MATRIX CRACKING - DELAMINATION - FIBER BUNDLE FRACTURE
- DESTRUCTIVE PROCEDURE - GOLD PENETRANT AND DEPLY PROCESS
FIBER BUNDLE FRACTURE - DELAMINATION - MATRIX CRACKING
GOLD PENETRANT - GOLD CHLORIDE IN DIETHYL ETHER (9-13% GOLD BY WEIGHT)
DEPLY PROCESS - APPROX. 90 MINUTES AT 785⁰F TO 800⁰F
SEPARATE INTO INDIVIDUAL LAMINAE
- DEPLY SPECIMENS

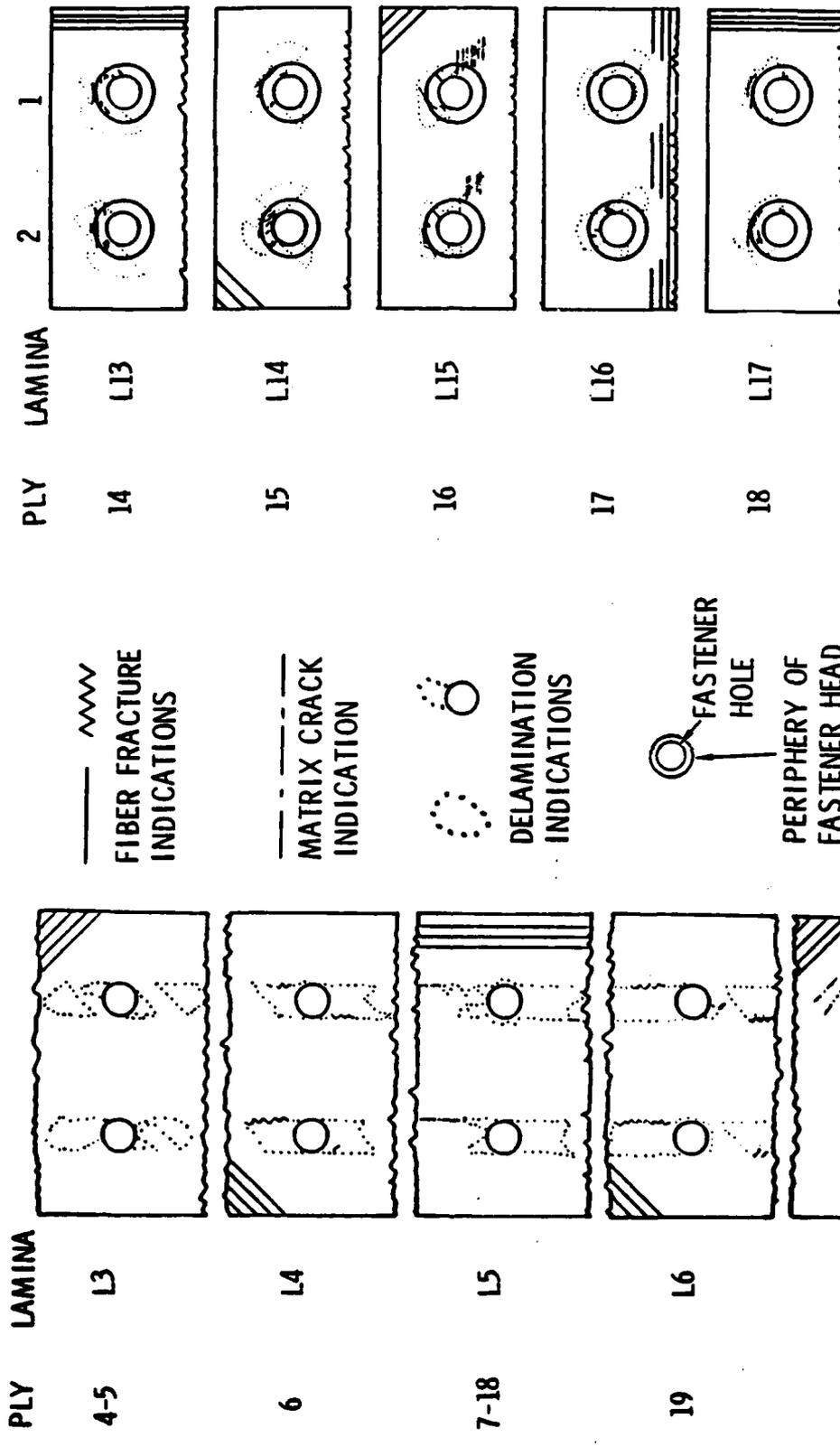
OPEN HOLE DEPLY SPECIMEN



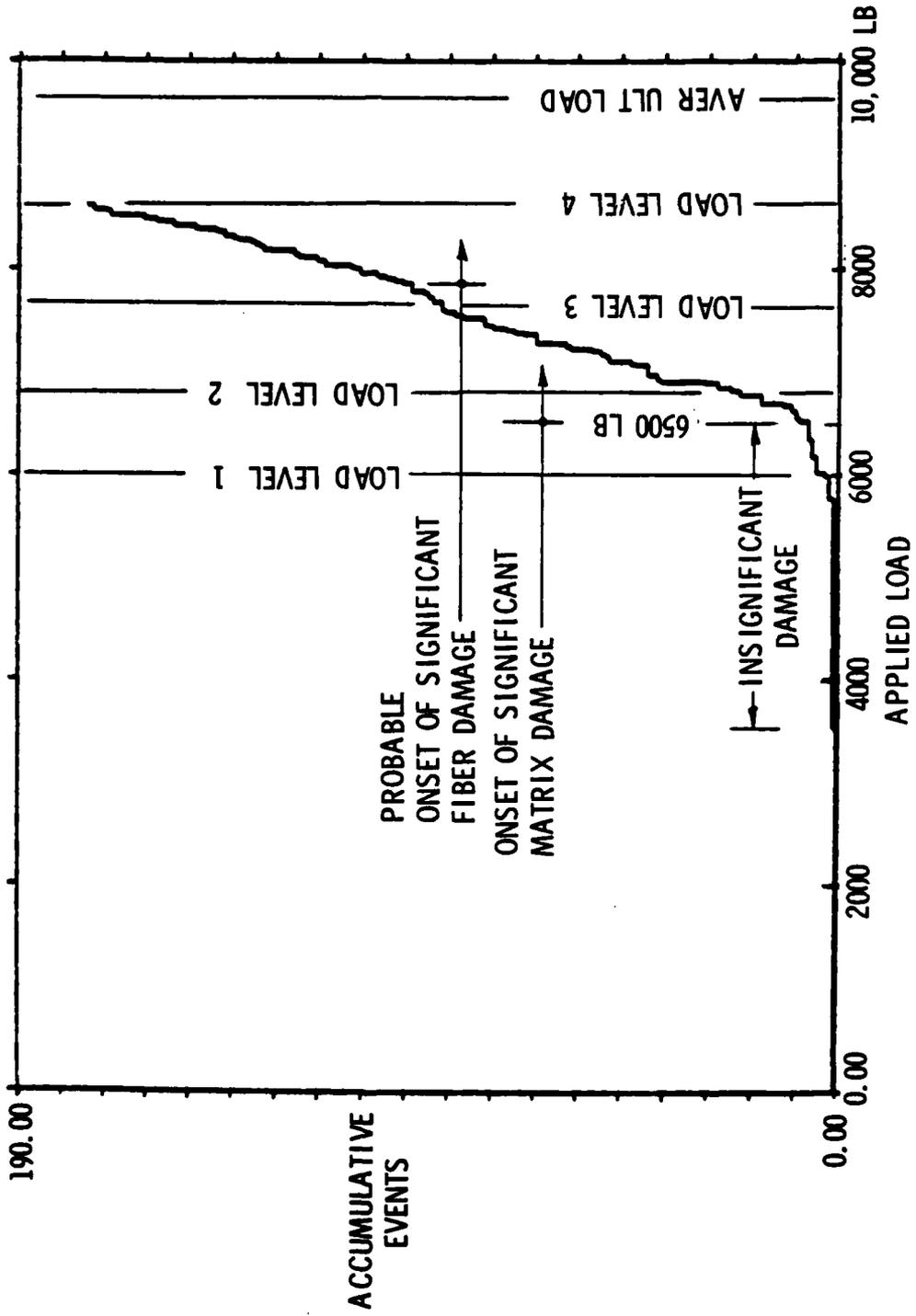
JOINT DEPLY SPECIMEN



EXAMPLES OF CHARTED DAMAGE ON SURFACES OF LAMINATE



CUMULATIVE AE EVENTS VERSUS APPLIED LOAD PLOT
FOR BOLTED JOINT SPECIMEN



CONCLUSIONS

- DEPLY TECHNIQUE
 - PRECISE LAMINA LOCATION OF DELAMINATIONS, MATRIX CRACKS AND FIBER BUNDLE FRACTURES CAN BE FOUND WITH GOLD PENETRANT IN COMBINATION WITH THE DEPLY TECHNIQUE.
- ACOUSTIC EMISSION MONITORING
 - AE DETECTS DAMAGE INITIATION AND MONITORS DAMAGE PROGRESSION IN REAL TIME.
 - CHANGES IN EXTENT OF DAMAGE ARE EVIDENCED BY CHANGES IN SLOPE OF AE VERSUS LOAD CURVES.
- PENETRANT ENHANCED X-RAY RADIOGRAPHY
 - DELAMINATIONS AND MATRIX CRACKS ARE EASILY IDENTIFIED.
 - STAIR STEP FIBER FRACTURES ARE EASILY IDENTIFIED.
 - OVERLAPPING DELAMINATIONS CAN OBSCURE CONFIGURATION DETAILS, MATRIX CRACKS AND SMALL FIBER FRACTURES.

AFWAL-TR-82-4007

FRACTURE THEORY AND DAMAGE TOLERANCE
OF COMPOSITE LAMINATES

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O B J E C T I V E S

FRACTURE THEORY: TO PREDICT STRENGTHS OF DAMAGED LAMINATES FROM FIBER AND MATRIX PROPERTIES. TO DETERMINE WHAT MAKES COMPOSITES TOUGH.

DAMAGE TOLERANCE: TO MEASURE ABILITY OF BUFFER STRIPS AND BONDED STRINGERS TO INCREASE STRENGTH OF DAMAGED PANELS. TO PREDICT STRENGTHS IN TERMS OF CONFIGURATION AND DAMAGE SIZE.

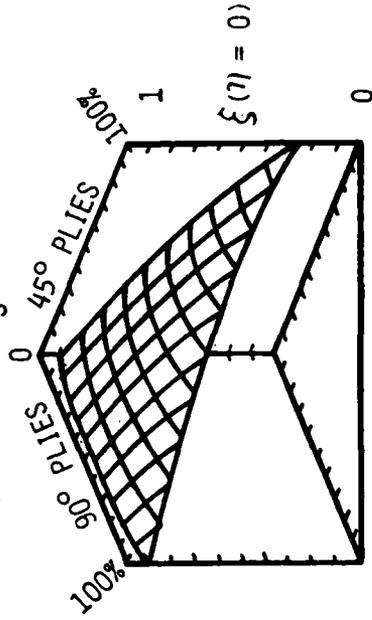
C O N C L U S I O N S

FRACTURE THEORY: STRENGTHS OF DAMAGED LAMINATES CAN BE PREDICTED IN TERMS OF LAMINA PROPERTIES WITH THE GENERAL FRACTURE TOUGHNESS PARAMETER Q_c IF CRACK-TIP DAMAGE IS SMALL.

DAMAGE TOLERANCE: BUFFER STRIPS AND STRINGERS INCREASE STRENGTH OF DAMAGED PANELS CONSIDERABLY.

STRAIN CRITERION FOR FRACTURE OF
COMPOSITE LAMINATES

$$[0_1/\pm 45]_k / 90_k]_S \text{ GR/EP}$$

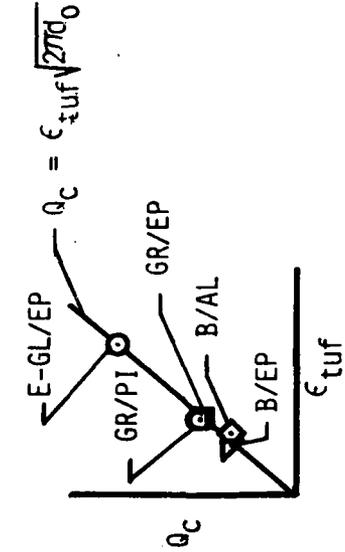
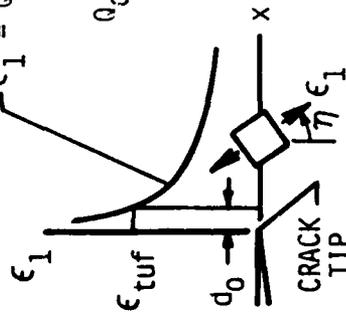


$$\xi = (1 - \nu_{yx} \sqrt{E_x/E_y}) (\sqrt{E_y/E_x} \sin^2 \eta + \cos^2 \eta)$$

$$\epsilon_1 = \alpha_c / \sqrt{2\pi x} + H(0)$$

WHERE

$$\alpha_c = K_Q \xi / E_y$$



FOR LONG CRACKS,

$$S_c \approx E_y \alpha_c / (\xi \sqrt{\pi a})$$

AND FOR $E_y = \epsilon_{tuf} / F_{tuf}$

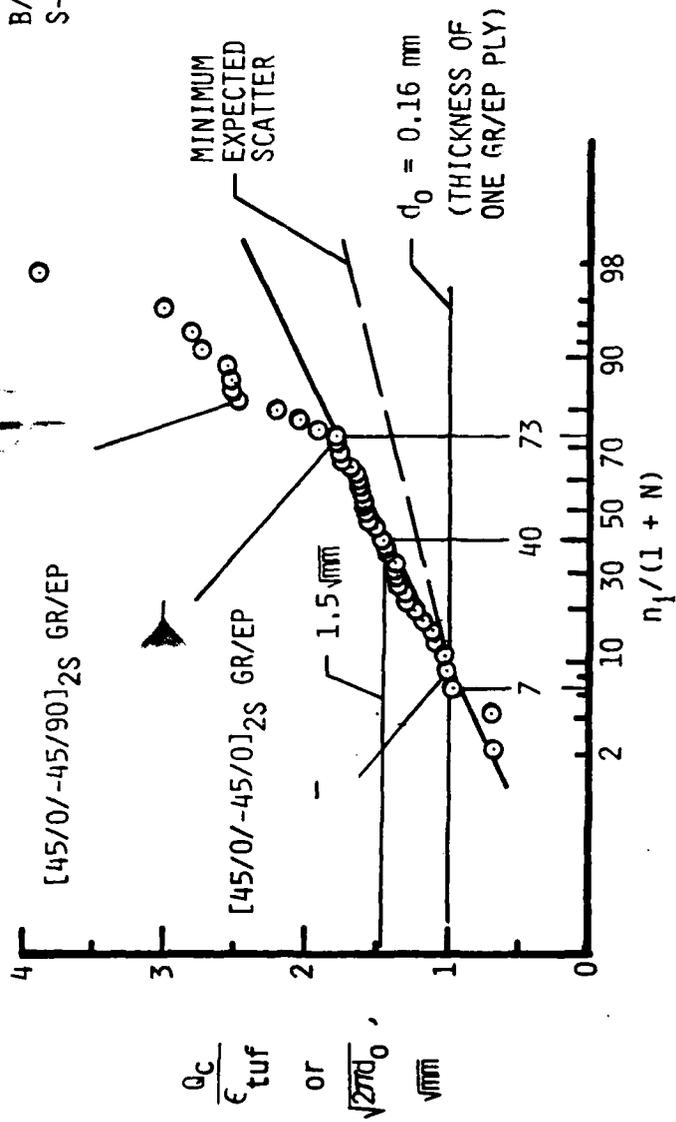
$$S_c / F_{tuf} \approx \sqrt{2d_0/a} / \xi$$

Q_c/ϵ_{tuf} VALUES FOR $[0_1/\pm 45_J/90_k]$ LAMINATES

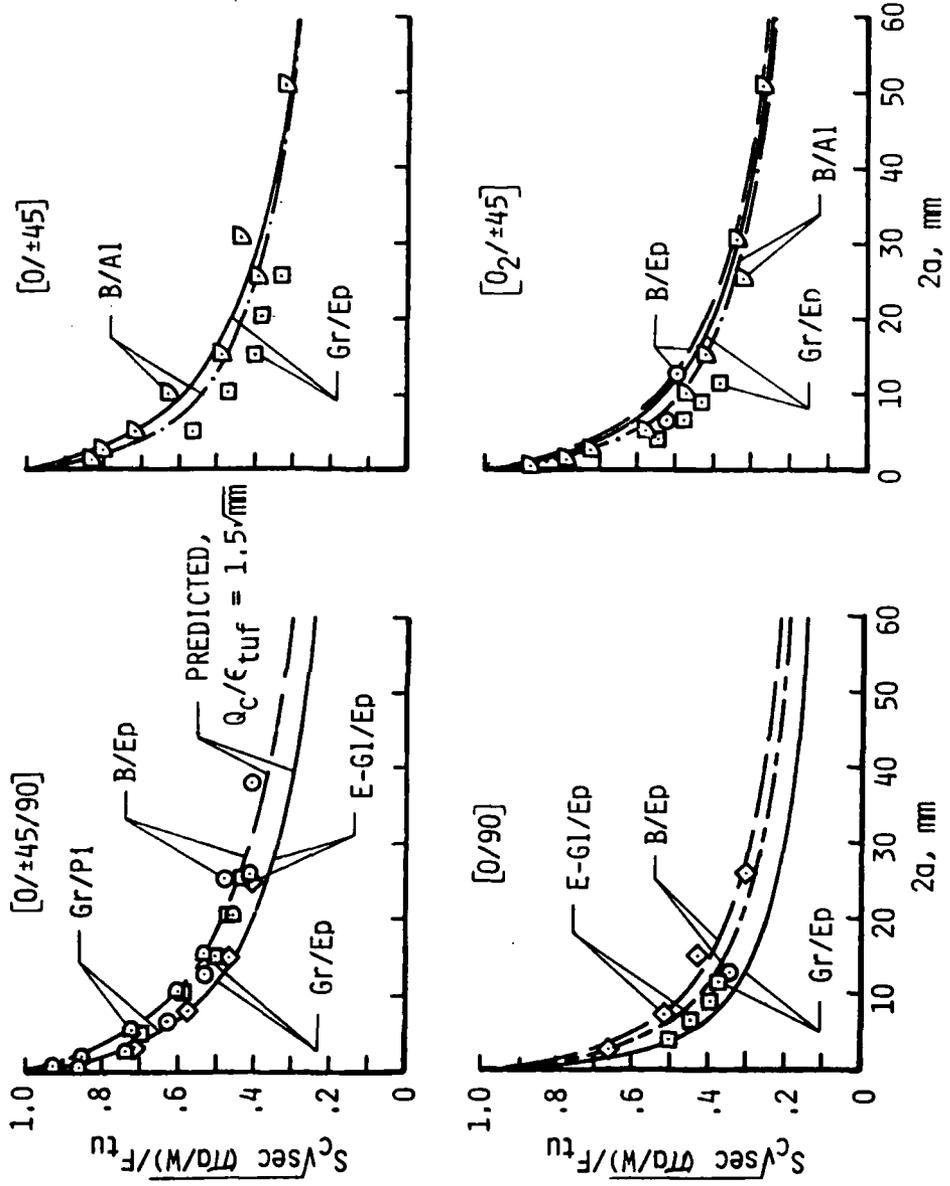
$[0_{2G1}/\pm 45_{Gr}]_S$ S-GLASS-GR/EP HYBRID

MATERIALS REPRESENTED:

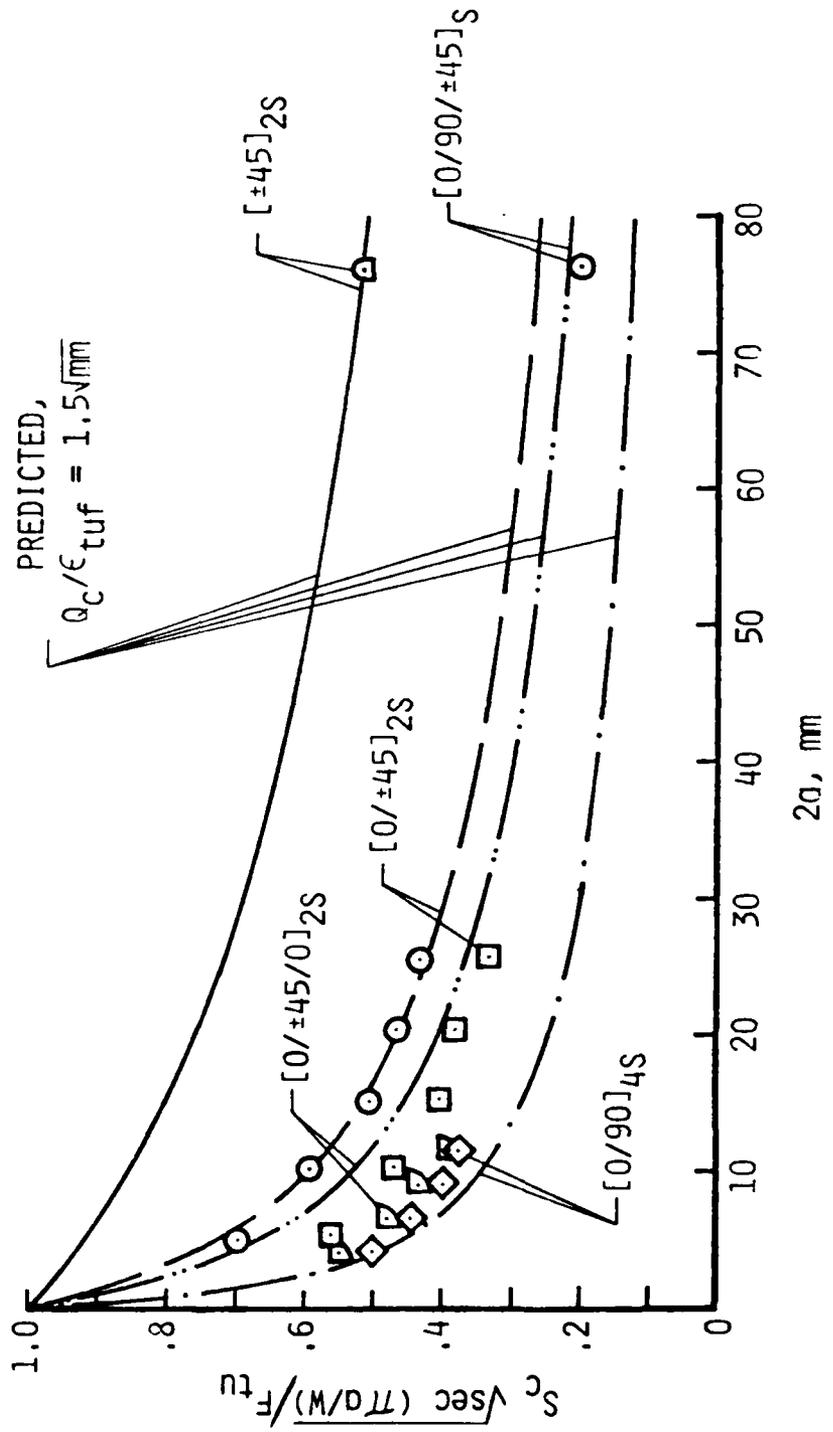
- GR/EP
- GR/PI
- E-GLASS/EP
- B/EP
- B/AL
- S-GLASS-GR/EP



PREDICTED AND MEASURED STRENGTHS OF SPECIMENS
WITH DIFFERENT MATERIALS

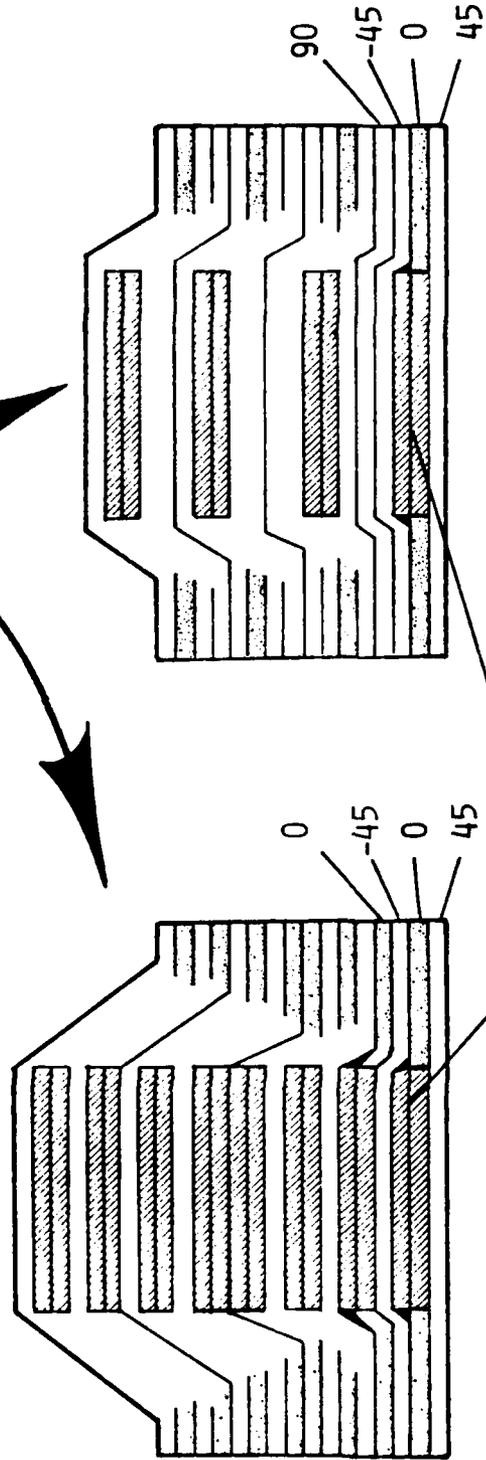
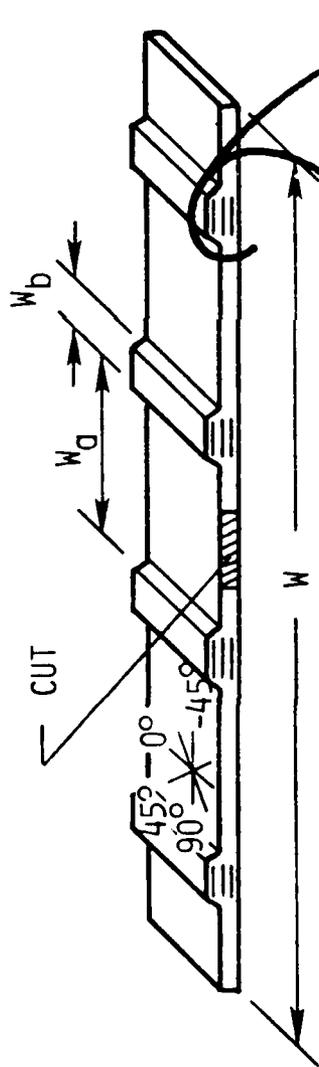


PREDICTED AND MEASURED STRENGTHS OF GR/EP
SPECIMENS WITH DIFFERENT LAYUPS



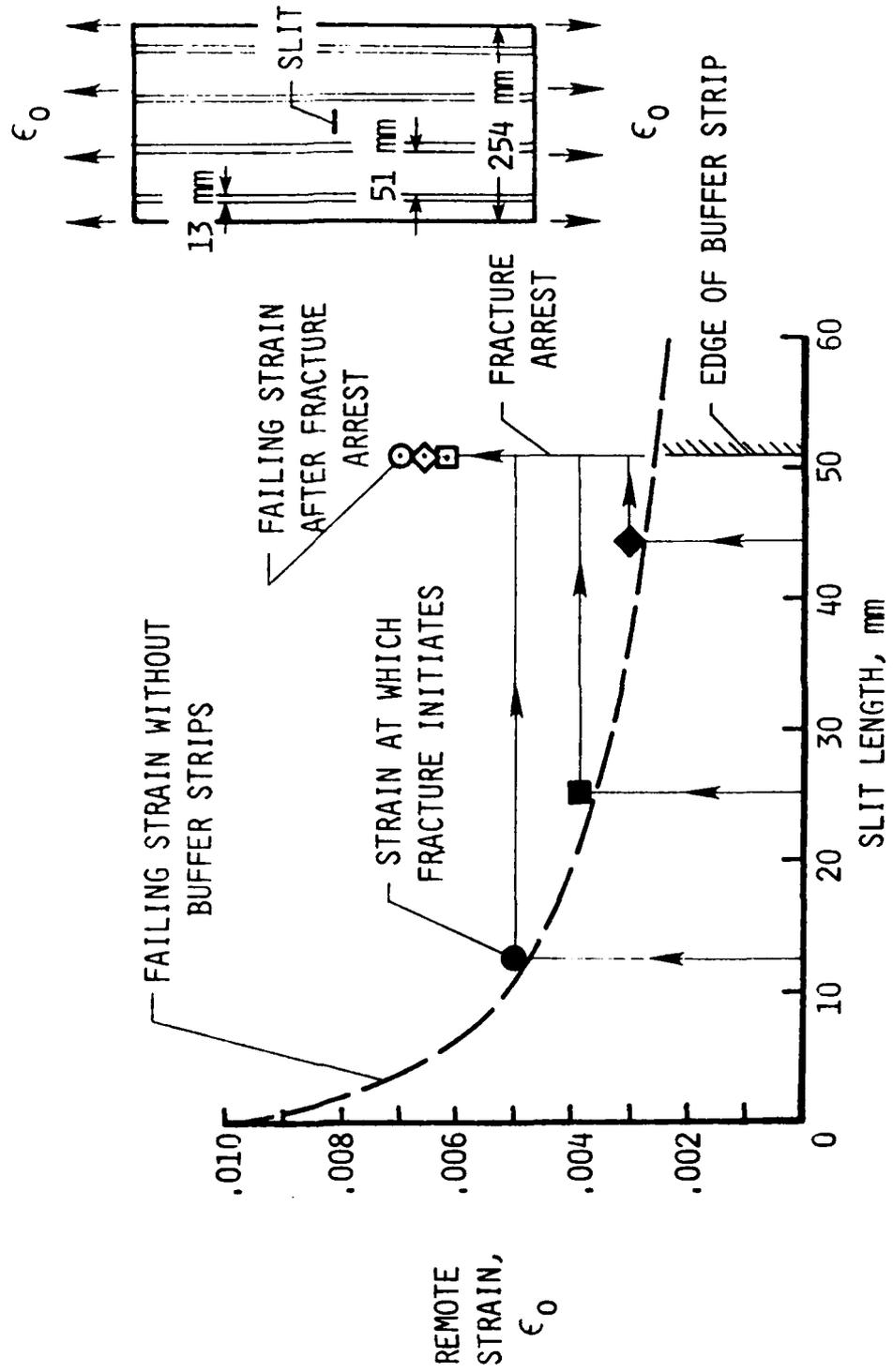
BUFFER STRIP PANEL CONFIGURATIONS

W_a , mm	W_b , mm	W , mm
20	5	102
51	7	229
51	13	254
102	13	457



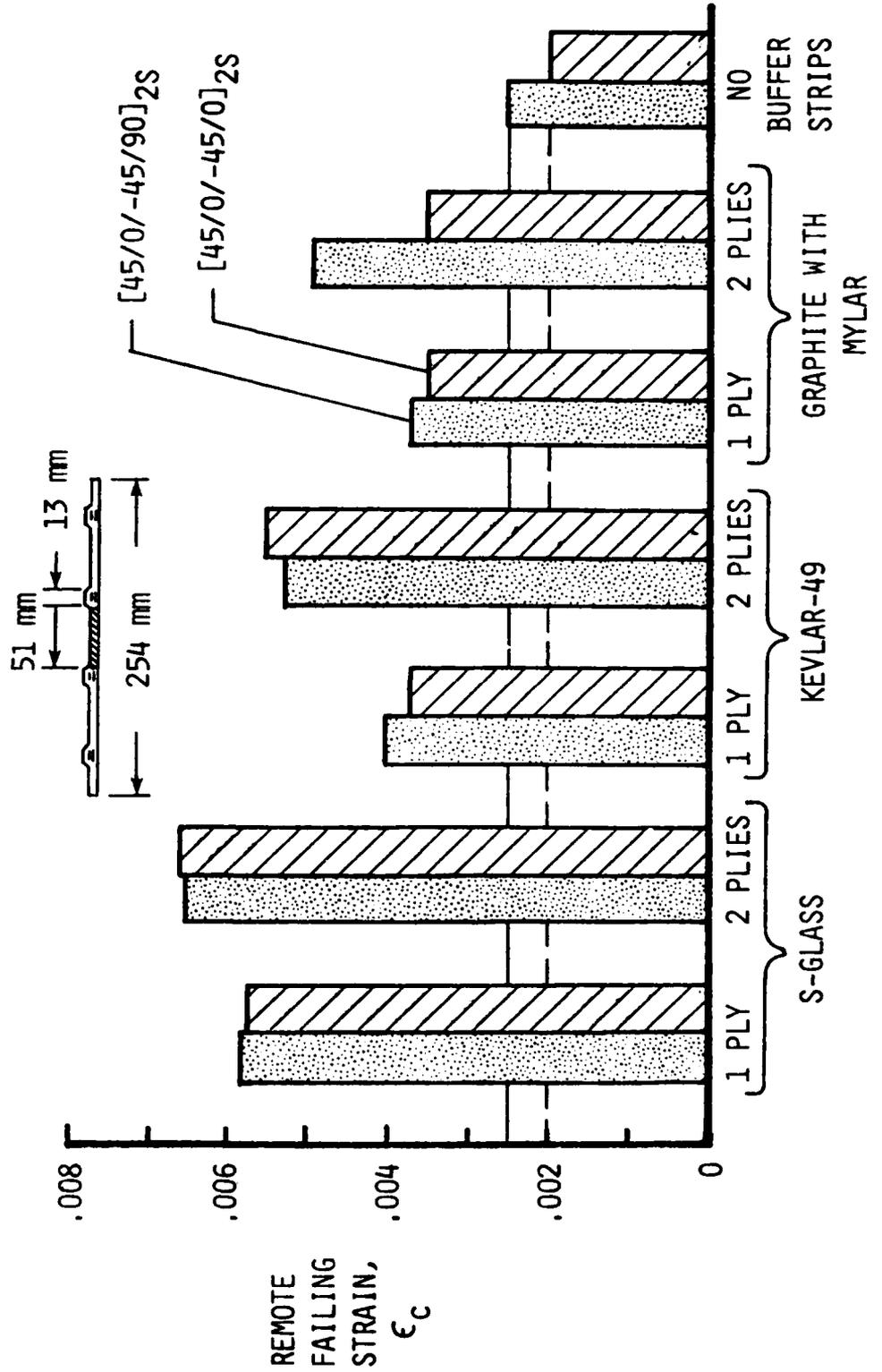
ONE OR TWO PLYS OF S-GLASS, KEVLAR-49, OR GRAPHITE WITH MYLAR

BUFFER STRIP TEST RESULTS
 [45/0/-45/90]_{2s} Panels with 2 Plies of S-Glass

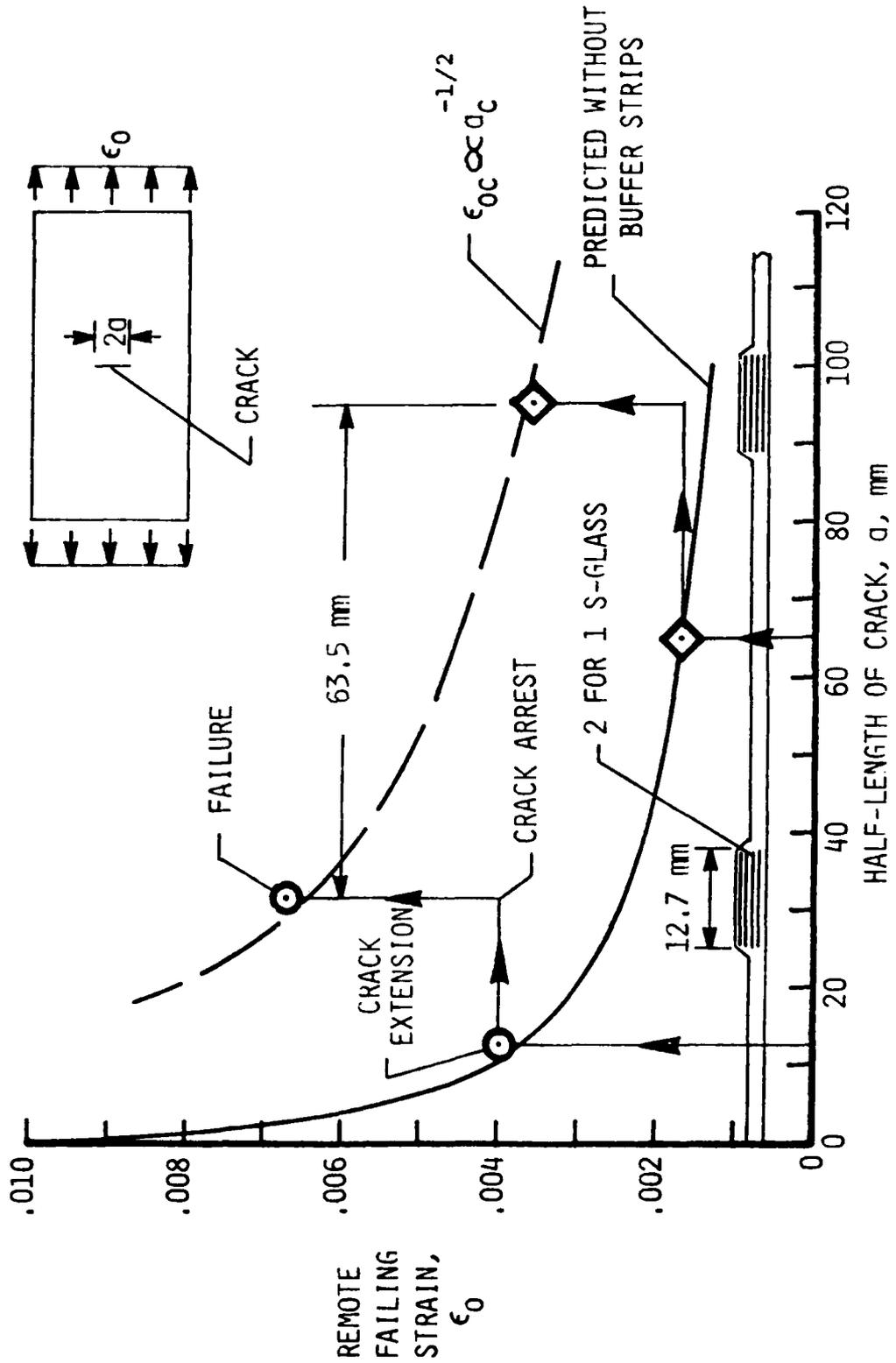


FAILING STRAINS OF PANELS WITH
ARRESTED CRACKS

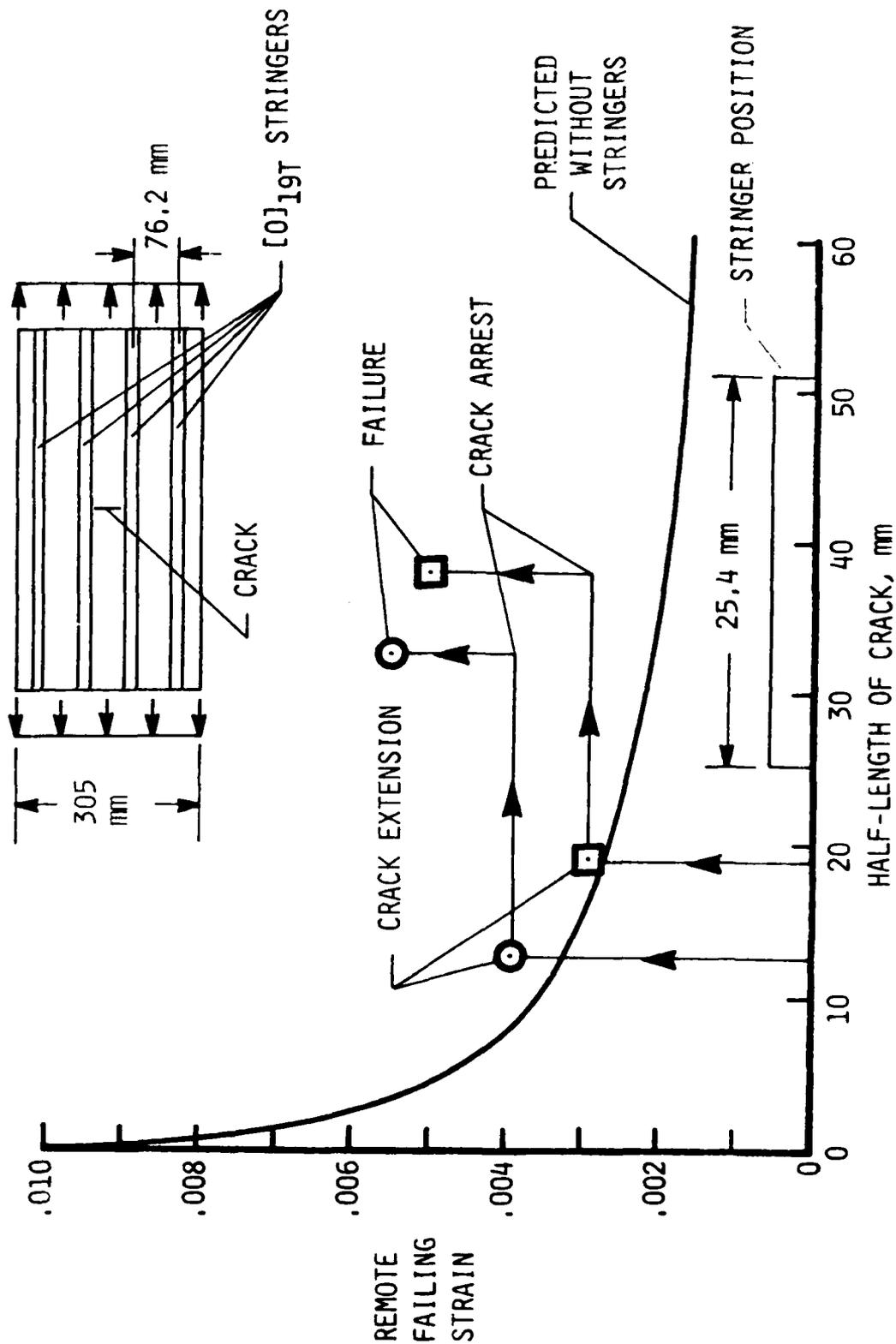
Different Buffer Strip Materials and Layouts



STRENGTHS OF [45/0/-45/90]_{2s} GR/EP BUFFER STRIP
 PANELS WITH DAMAGE OF VARIOUS SIZES



TEST RESULTS FOR STRINGER-STIFFENED
 [45/0/-45/90]_{2S} GR/EP PANELS



CAPTIVE BALL IMPACT STUDIES: METHODS, ANALYSIS,
AND RESULTS FOR GRAPHITE/EPOXY PLATES

WOLF ELBER
NASA LANGLEY RESEARCH CENTER

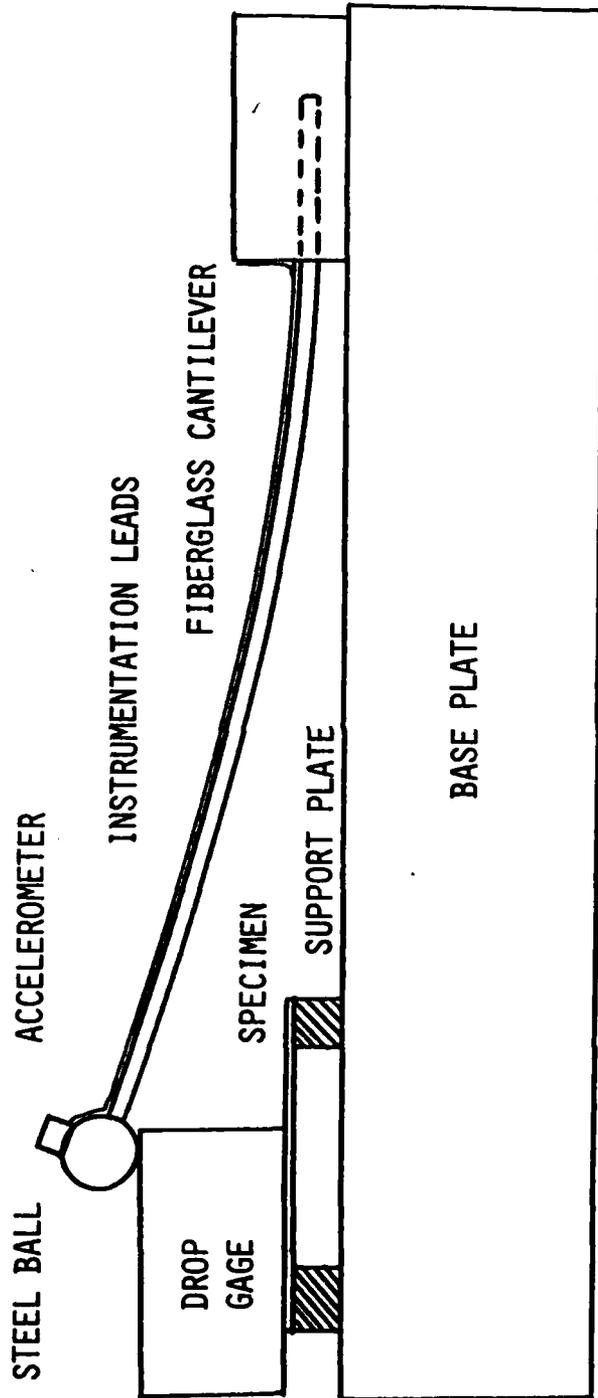
O B J E C T I V E S

- TO DEVELOP A SIMPLE LABORATORY TECHNIQUE FOR DETERMINING IMPACT DAMAGE SUSCEPTIBILITY.
- TO DEVELOP AN ANALYSIS OF LOAD AND STRESS HISTORY FOR A SPHERICAL INDENTER ON A RIGIDLY CLAMPED CIRCULAR PLATE.
- TO DEFINE AND MEASURE THE DAMAGE THRESHOLD FOR SEVERAL GRAPHITE/EPOXY MATERIALS.
- TO CORRELATE THE OBSERVED DAMAGE THRESHOLD WITH AN ANALYTICAL FAILURE CRITERION.

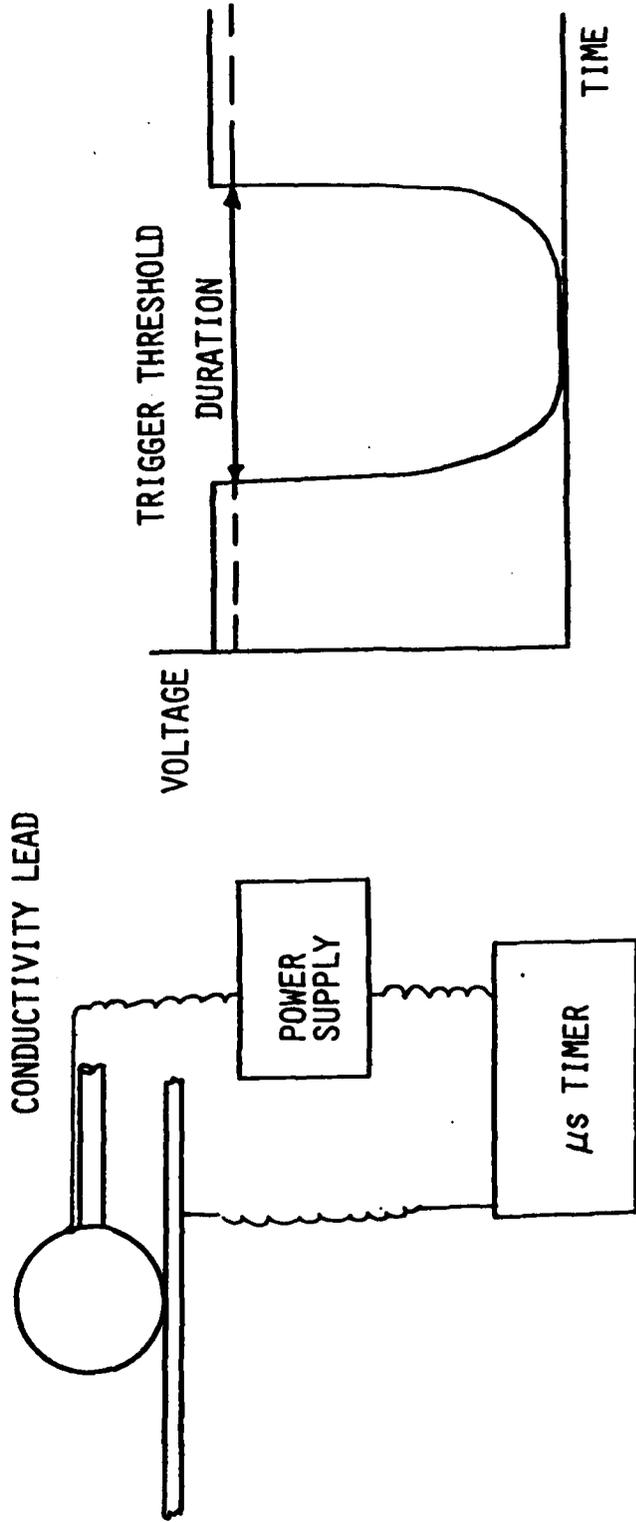
C O N C L U S I O N S

- IMPACT DURATION CHANGES ABRUPTLY AT THE DAMAGE THRESHOLD.
- THE CAPTIVE BALL IMPACT TESTER IS CHEAP AND SIMPLE.
- SPECIMEN SIZE IS THE DOMINANT TEST PARAMETER CONTROLLING THE FAILURE LEVEL AND FAILURE MODE UNDER LOW-VELOCITY IMPACT.
- INTERLAMINAR SHEAR STRENGTH IS THE DOMINANT MATERIAL PARAMETER CONTROLLING THE THRESHOLD OF IMPACT DAMAGE OF GRAPHITE/EPOXY MATERIALS.

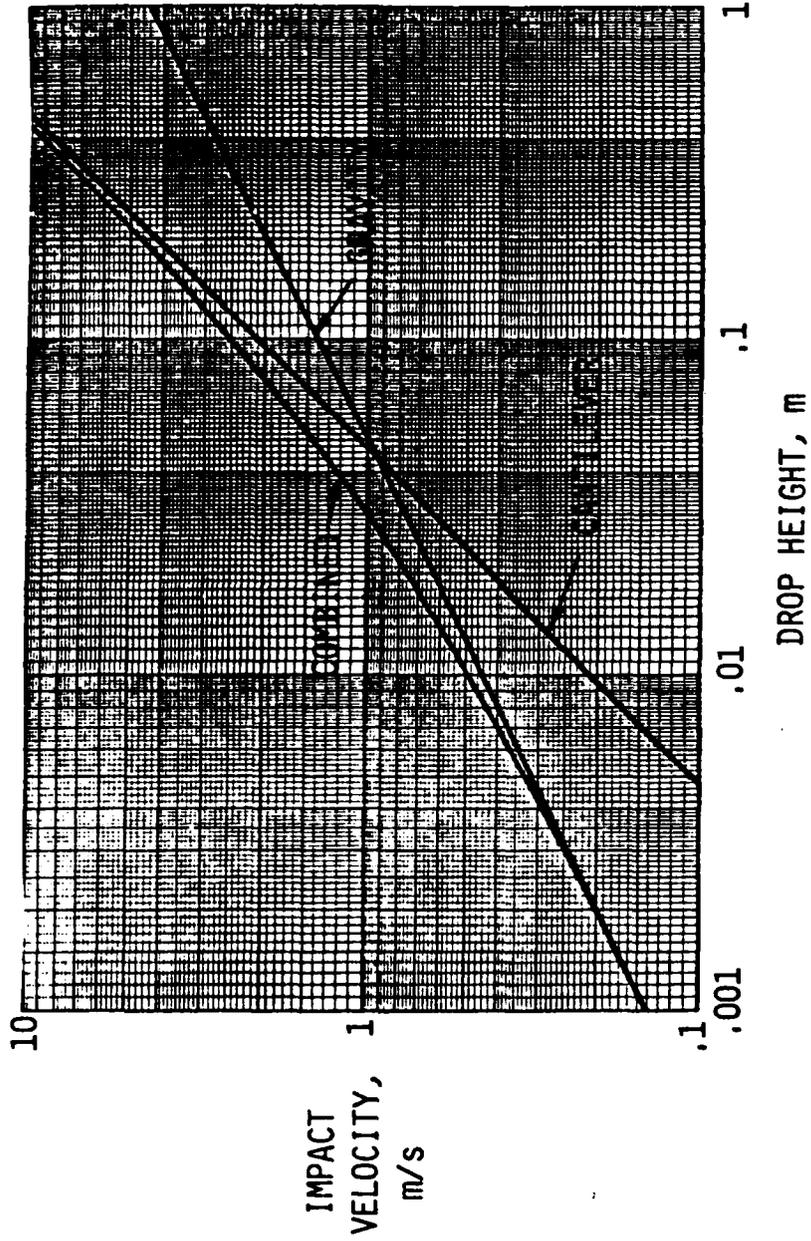
THE CAPTIVE BALL IMPACTOR



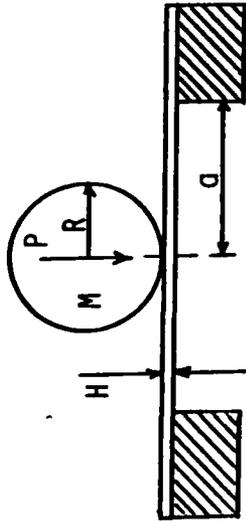
IMPACT DURATION INSTRUMENTATION



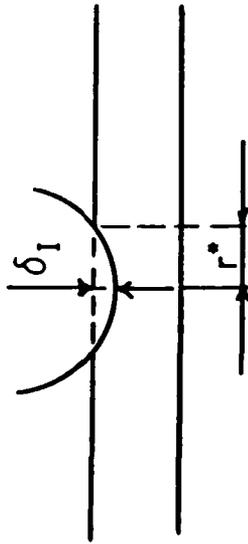
IMPACT VELOCITY CALIBRATION



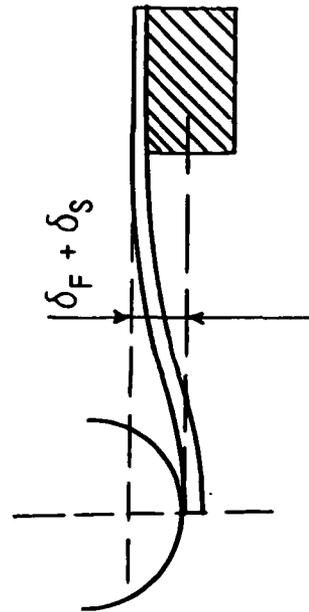
MATHEMATICAL MODEL - PLATE DEFORMATIONS



INDENTATION



FLEXURE AND SHEAR



● INDENTATION

$$P = K_I \delta_I^{1.5}$$

$$r^* = \sqrt{2R\delta_I}$$

● SHEAR

$$\delta_S = \frac{P}{2\pi GH} \ln \left(\frac{a}{r^*} \right)$$

● FLEXURE

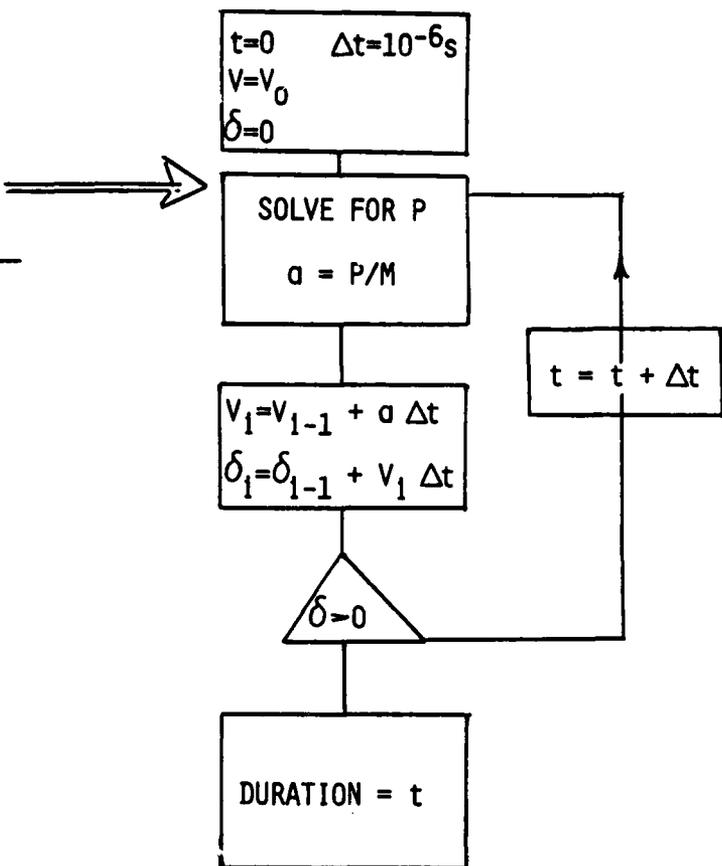
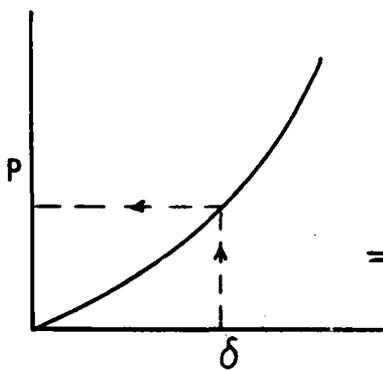
$$\delta_F + 0.43H \left(\frac{\delta_F}{H} \right)^3 = \frac{3Pq^2}{4\pi E^1 H^3}$$

● TOTAL DEFORMATIONS

$$\delta = \delta_I + \delta_F + \delta_S$$

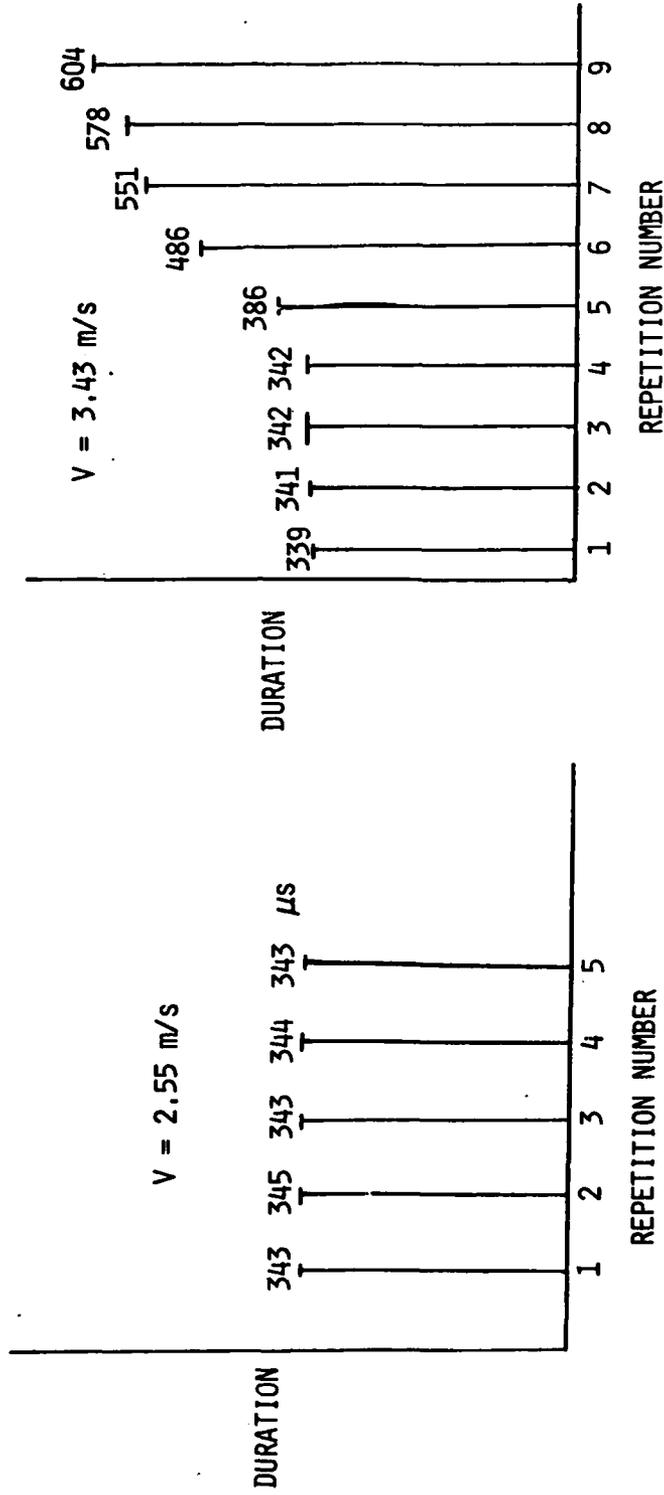
MATHEMATICAL MODEL
DYNAMICS

NUMERICAL TIME INTEGRATION:



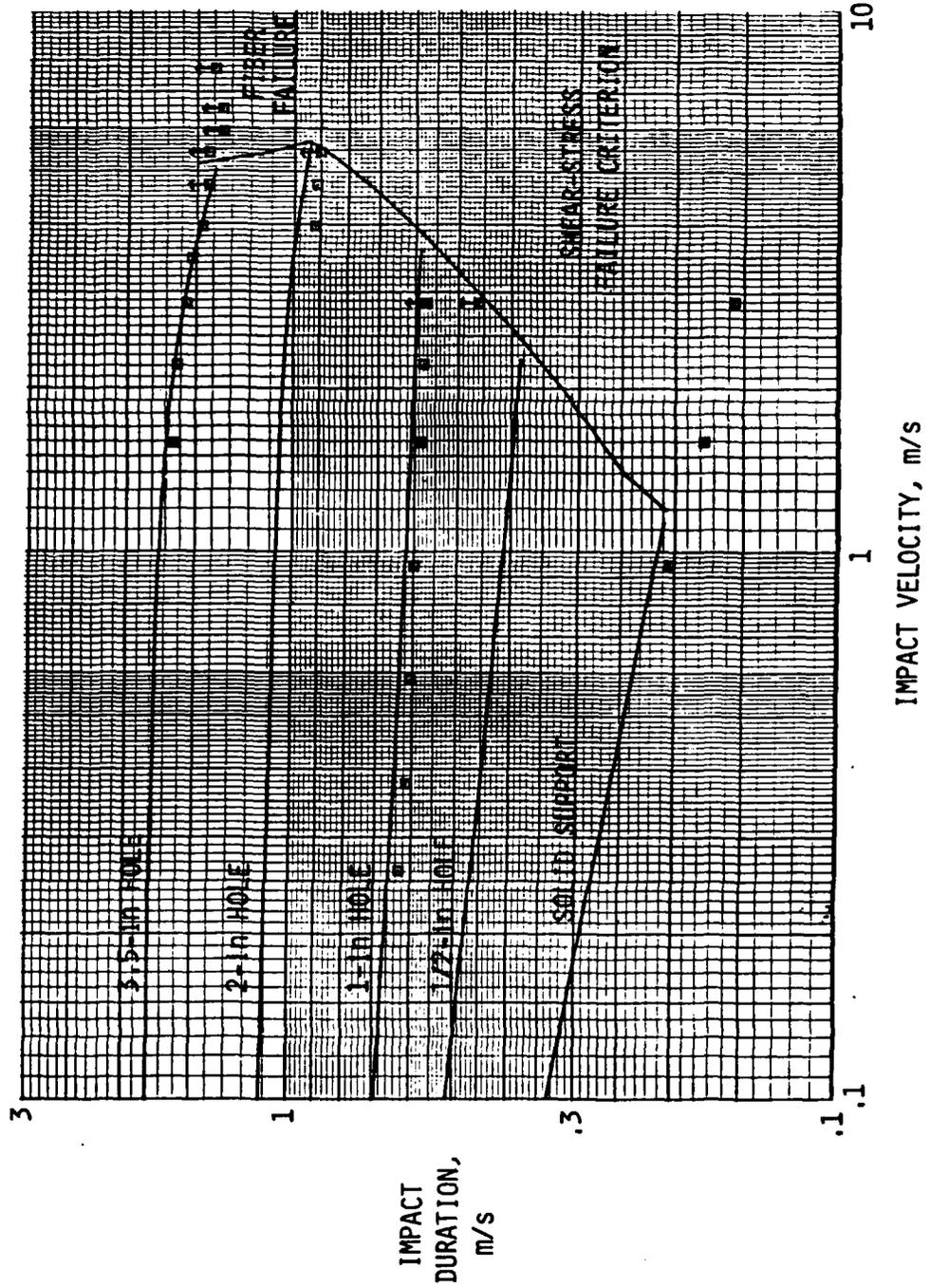
FAILURE INDICATION UNDER REPEATED IMPACT

5208/T300 1-INCH BALL

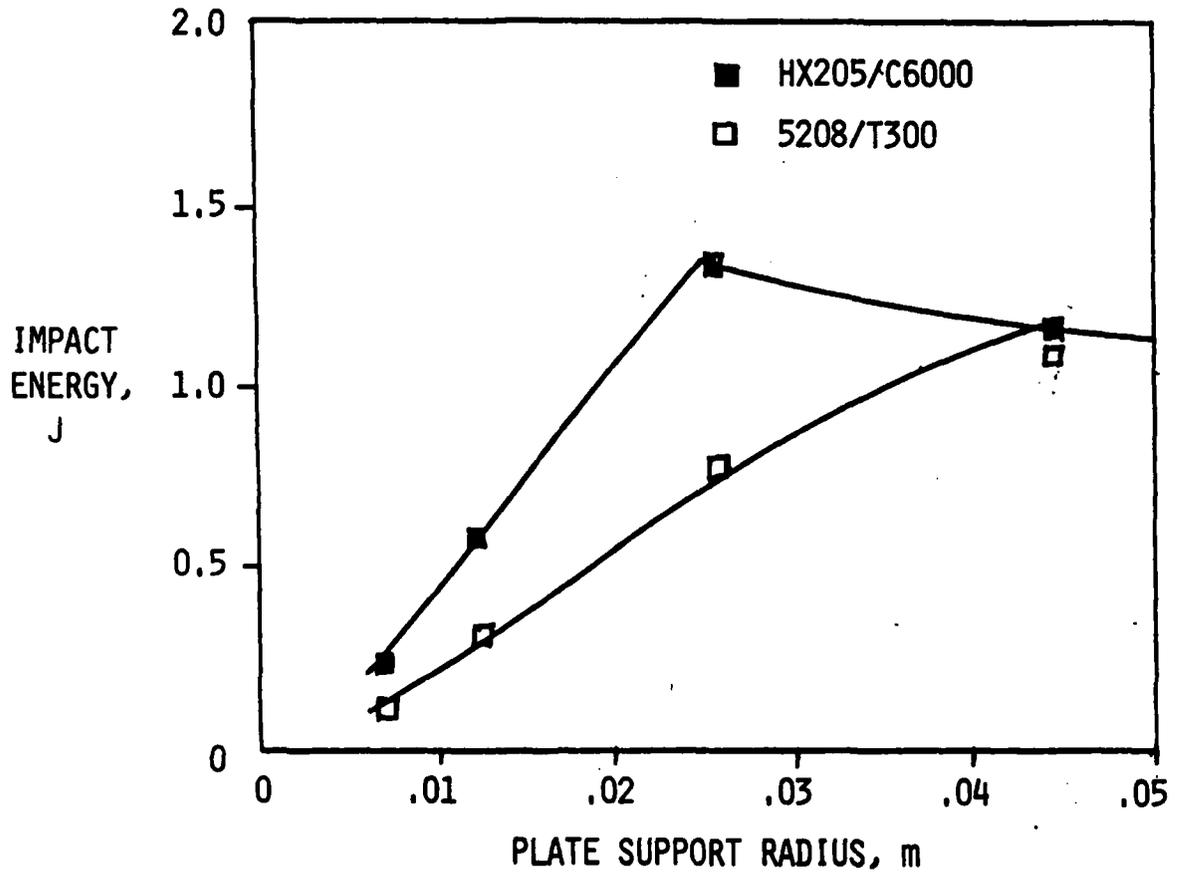


- BELOW THRESHOLD: REPEATED IMPACT SHOWS STABLE DURATION.
- ABOVE THRESHOLD: REPEATED IMPACT SHOWS RAPIDLY INCREASING DURATION.

COMPARISON OF TEST DATA WITH ANALYSIS



THRESHOLD IMPACT ENERGY FOR
TWO COMPOSITES



S U M M A R Y

- MEASURED DURATION OF IMPACT IS IN GOOD AGREEMENT WITH MATH MODEL PREDICTIONS.
- MEASURED DURATION OF IMPACT IS A GOOD INDICATOR OF DAMAGE UNDER REPEATED IMPACT.
- TEST DEVICE AND INSTRUMENTATION ARE SIMPLE.
- CRITICAL SHEAR STRESS AND FLEXURAL STRESS CRITERIA ARE IN GOOD AGREEMENT WITH DATA.
- MATERIALS HAVE VERY LOW IMPACT RESISTANCE NEAR SOLID SUPPORTS.
- INTERLAMINAR SHEAR STRENGTH CONTROLS THE DAMAGE THRESHOLD.

AFWAL-TR-82-4007

TEST SYSTEM FOR CONDUCTING
BIAXIAL TESTS OF COMPOSITE LAMINATES

BY

IIT RESEARCH INSTITUTE
CHICAGO, ILLINOIS 60616

FOR

AIR FORCE FLIGHT DYNAMICS LABORATORY
WRIGHT-PATTERSON AIR FORCE BASE
OHIO, 45433

OBJECTIVE

DESIGN, FABRICATE, DEMONSTRATE AND INSTALL TEST SYSTEM CAPABLE OF APPLYING, WITH MINIMAL CONSTRAINTS, IN-PLANE LOADS SINGLY OR IN ANY COMBINATION TO COMPOSITE LAMINATE SPECIMENS UNDER STATIC AND LOW CYCLE FATIGUE CONDITIONS AND AT DIFFERENT STRAIN RATES.

CONCLUSIONS

1. THE MOST CRITICAL DISCONTINUITY STRESSES ARE THE AXIAL BENDING STRESSES IN THE TRANSITION BETWEEN THE TEST AND TABBED SECTIONS FOR PRESSURE LOADING OF THE TUBULAR SPECIMEN.
2. TAPERED TABS WITH TAPERED EXTENSIONS OF A LOWER STIFFNESS MATERIAL RESULT IN THE LOWEST PEAK DISCONTINUITY STRESSES.
3. TORSIONAL LOADING DOES NOT INTRODUCE DISCONTINUITY STRESS PEAKS.
4. UNDER AXIAL LOADING, SIGNIFICANT BUT NOT EXCESSIVE AXIAL BENDING STRESSES ARE GENERATED IN THE TABS NEAR THE END GRIPS.
5. THE MOST EFFECTIVE MEANS OF INCREASING THE BUCKLING LOAD IS TO INCREASE THE SPECIMEN THICKNESS, RATHER THAN DECREASING THE SPECIMEN LENGTH OR APPLYING INTERNAL STABILIZING PRESSURE.

SCOPE

DESIGN

PROTOTYPE FABRICATION AND DEMONSTRATION

FABRICATION

INSTALLATION AND ACCEPTANCE TESTING

MAINTENANCE

SPECIMEN ANALYSIS

SPECIMEN: GRAPHITE/EPOXY
MINIMUM THICKNESS - 8 PLYS
TYPICAL LAYUPS: $[0_g]$, $[90_g]$,
 $[\pm 45]_{2s}$, $[0/\pm 45/90]_s$.

IBS: EPOXY AND GLASS/EPOXY

LOADING CONDITIONS: INTERNAL PRESSURE, P_i
EXTERNAL PRESSURE, P_o
AXIAL LOAD, σ_{xx}
TORSION, $\sigma_{x\theta}$

ANALYSES: FINITE-ELEMENT STRESS ANALYSIS
BUCKLING ANALYSIS

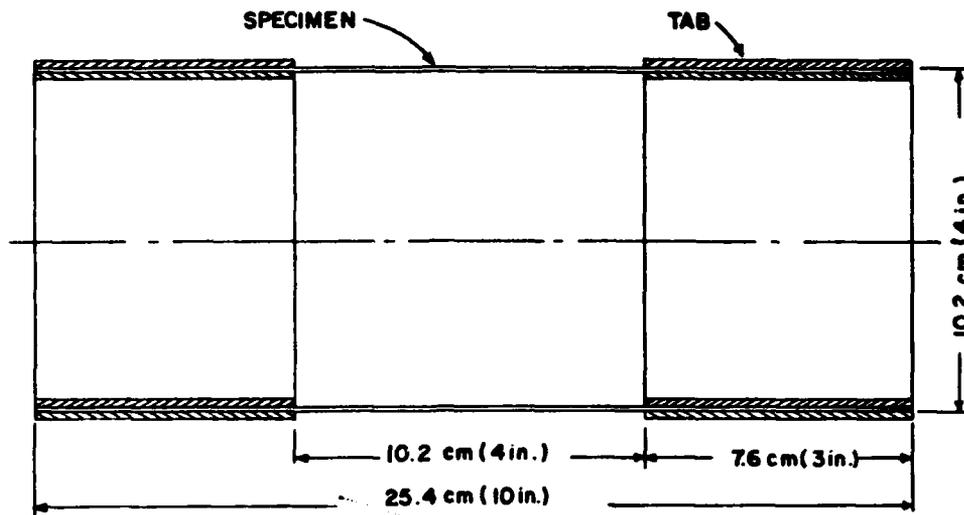


Figure 1. Tubular Specimen Geometry

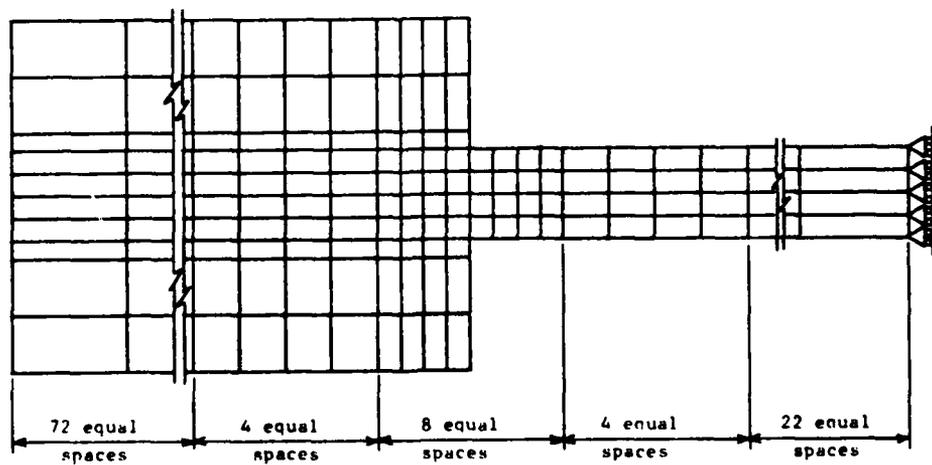


Figure 2. Finite Element Mesh for Specimen with Rectangular Section Tabs (Mesh 8)

TABLE 1
 MATERIAL PROPERTIES OF TUBULAR SPECIMEN, TABS AND ADHESIVE

Material [Layup]	Young's Moduli GPa (10 ⁶ psi)		Shear Moduli GPa (10 ⁶ psi)			Poisson's Ratio			
	E _{rr}	E _{zz}	E _{θθ}	G _{θz}	G _{rz}	G _{θr}	ν _{zθ}	ν _{zr}	ν _{rθ}
Specimen Graphite/Epoxy [0/±45/90] _s	10.0 (1.45)	55.2 (8.0)	55.2 (8.0)	6.9 (1.00)	6.9 (1.00)	6.9 (1.00)	0.30	0.50	0.09
End Tabs E-Glass/Epoxy [±45] ₃	9.7 (1.4)	11.0 (1.6)	11.0 (1.6)	6.9 (1.00)	6.9 (1.00)	6.9 (1.00)	0.30	0.30	0.26
Adhesive Epoxy	3.45(0.5)	3.45(0.5)	3.45(0.5)	1.34(0.19)	1.34(0.19)	1.34(0.19)	0.35	0.35	0.35

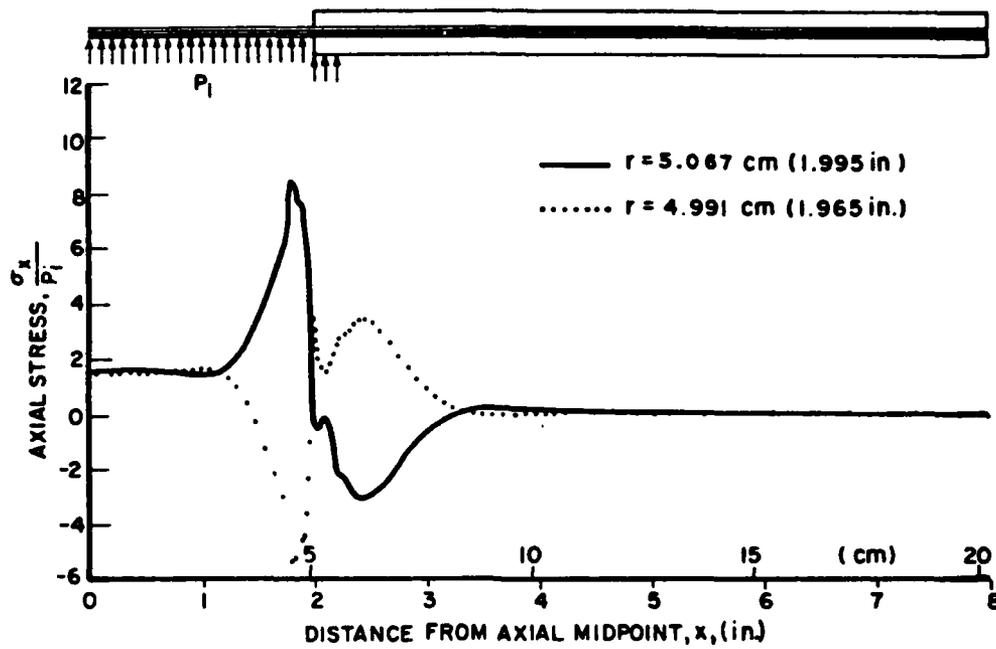


Figure 3. Axial Stress Distribution in $[0/\pm 45/90]_s$ Laminate Tube for Loading Condition 1 (Mesh 8)

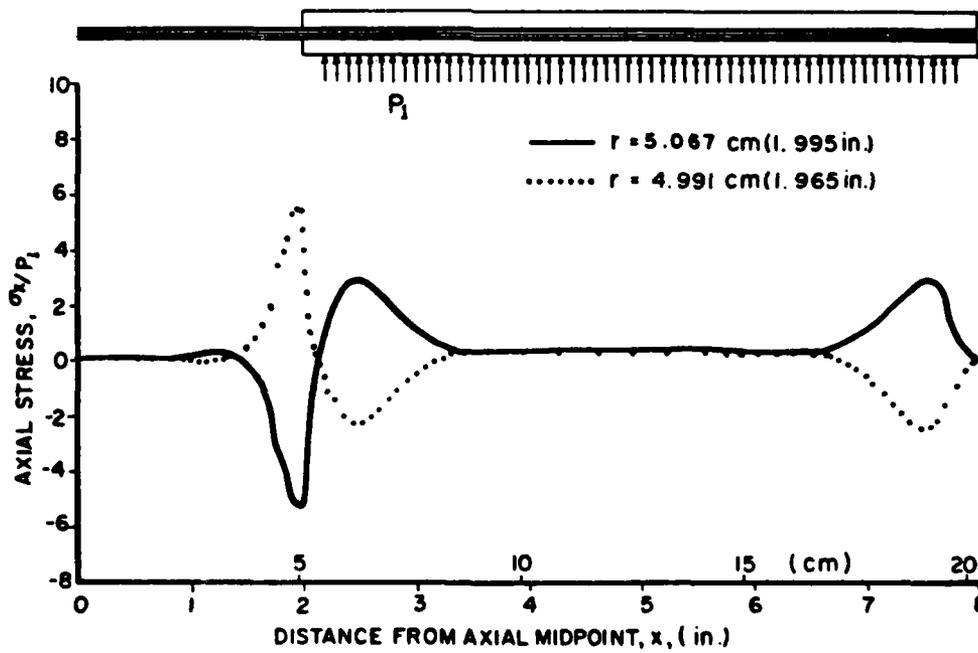


Figure 4. Axial Stress Distribution in $[0/\pm 45/90]_s$ Laminate Tube for Loading Condition 2 (Mesh 8)

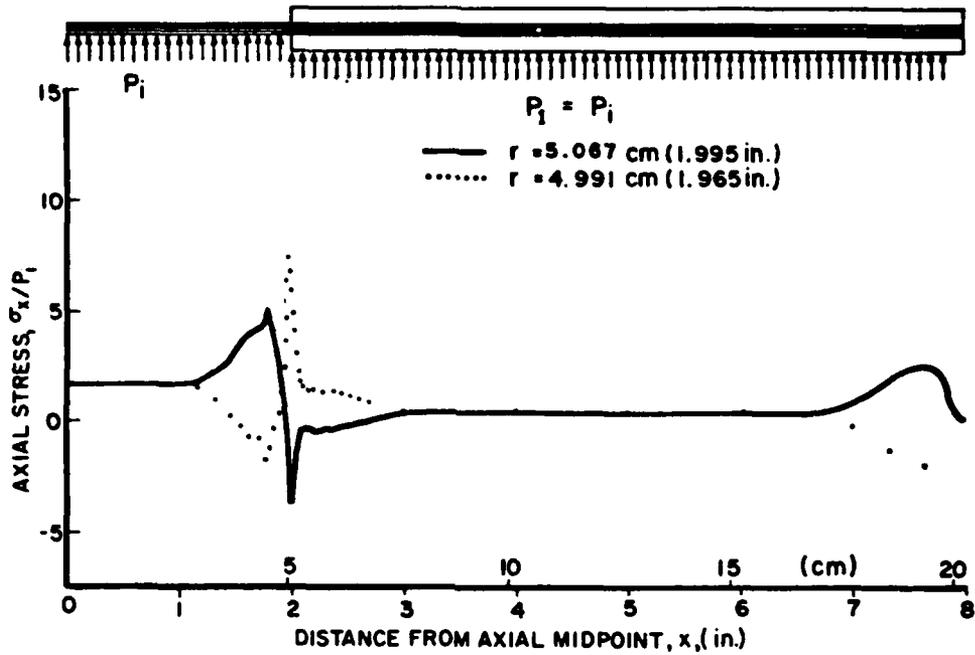


Figure 5. Axial Stress Distribution in $[0/\pm 45/90]_S$ Laminate Tube for Superposition of Loading Conditions S_1 and 2 (Mesh 8)

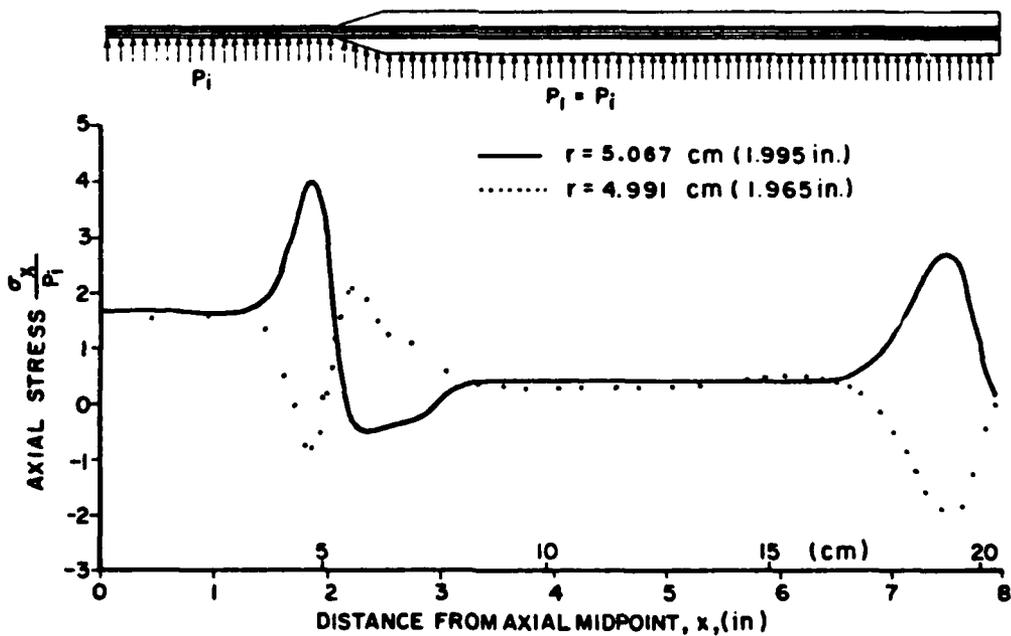


Figure 6. Superposition of Axial Stresses in $[0/\pm 45/90]_S$ Laminate Tube for Loading Conditions 1 and 2 (Mesh 11)

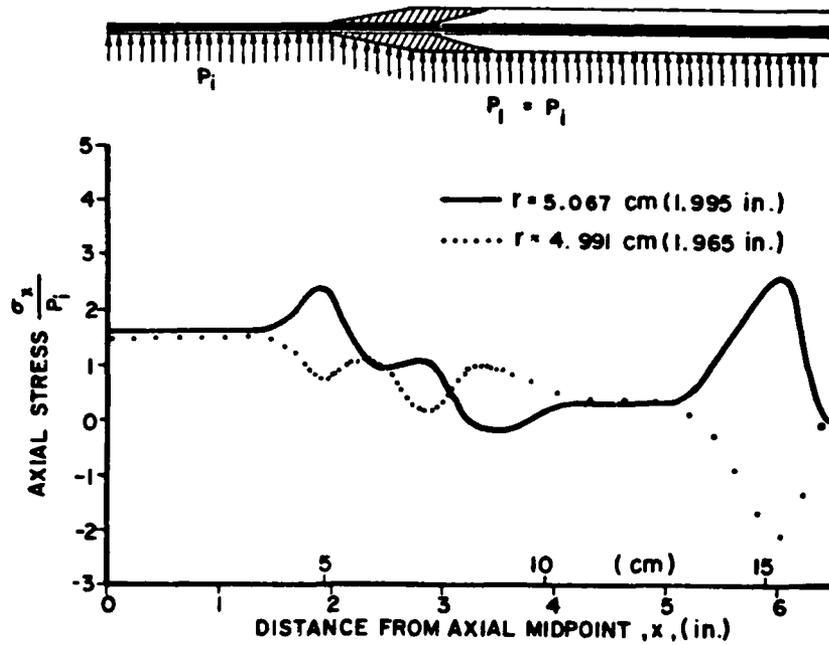


Figure 7. Superposition of Axial Stress Distribution in Laminate Tube for Loading Conditions 1 and 2 for $p_1 = p_i$ (Mesh 19)

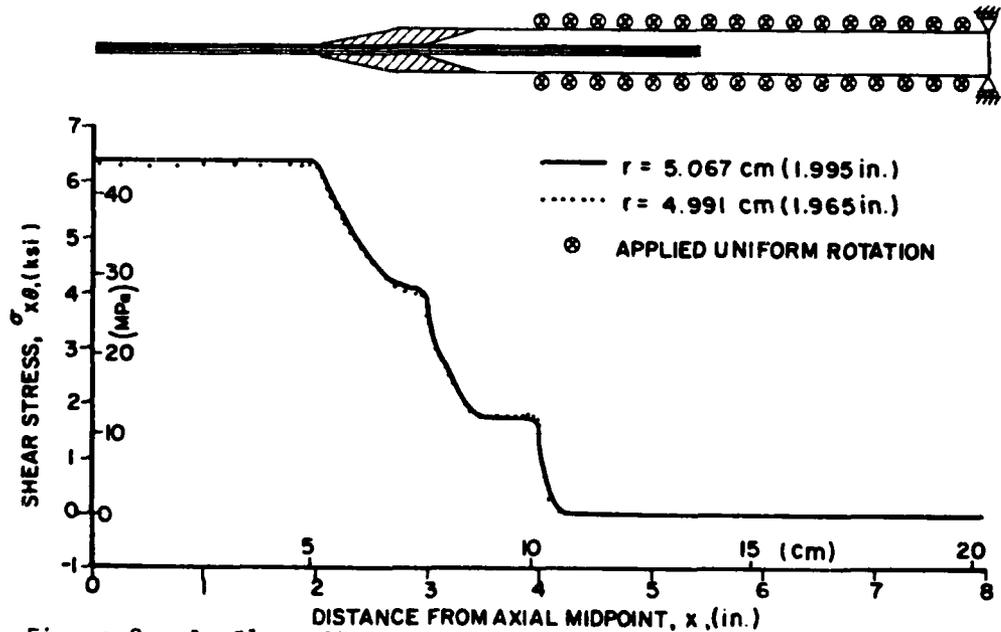
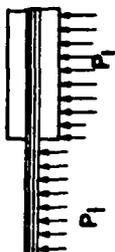
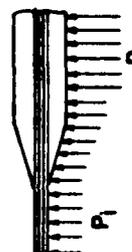
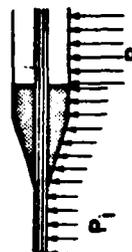
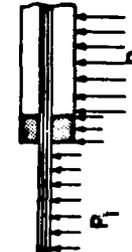
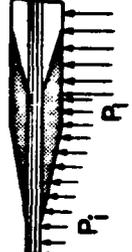


Figure 8. In-Plane Shear Stress Distribution in $[0/\pm 45/90]_s$ Graphite/Epoxy Laminate Tube Due to 0.01 Radian Uniform Rotation at Part of Tab Relative to the Specimen Middle $x = 0$ (Mesh 19C)

TABLE 2
 PEAK AXIAL STRESSES IN TRANSITION BETWEEN TEST SECTION AND TAB
 FOR INTERNALLY PRESSURIZED GRAPHITE/EPOXY TUBULAR SPECIMEN

Mesh No.	Specimen Layup	Tab Materials	Tab Geometry	Tab Compensation Pressure, P_1/P_i	$\frac{\sigma_{xx}}{\sigma_{\theta\theta}}$ max	$\frac{\sigma_{xx}}{\sigma_{\theta\theta}}$ min
8	$[0/\pm 45/90]_s$	$[\pm 45]_3$ G/E		0 1	0.164 0.132 0.150	-0.108 -0.070 -0.076
11	$[0/\pm 45/90]_s$	$[\pm 45]_3$ G/E		0 1	0.105 0.080	-0.058 -0.016
14	$[0/\pm 45/90]_s$	$[\pm 45]_3$ Epoxy Extension		0 1 1.45	0.094 0.055 0.056	-0.066 -0.010 -0.004
15	$[0/\pm 45/90]_s$	$[\pm 45]_3$ Epoxy Extension		0 1 1.2	0.166 0.082 0.072	-0.108 -0.022 -0.030
19	$[0/\pm 45/90]_s$	$[\pm 45]_3$ Epoxy Extension		0 0.75 1	0.096 0.046 0.048	-0.090 -0.020 -0.004

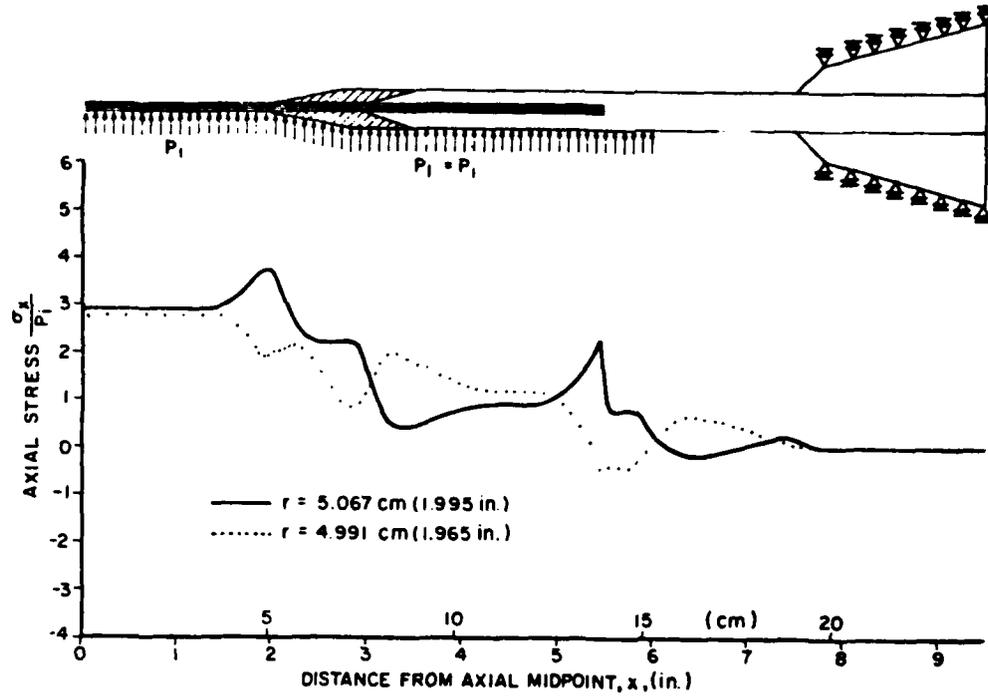


Figure 9. Axial Stress Distribution in $[0/\pm 45/90]_S$ Graphite/Epoxy Laminate Tube for Internal Pressure Loading

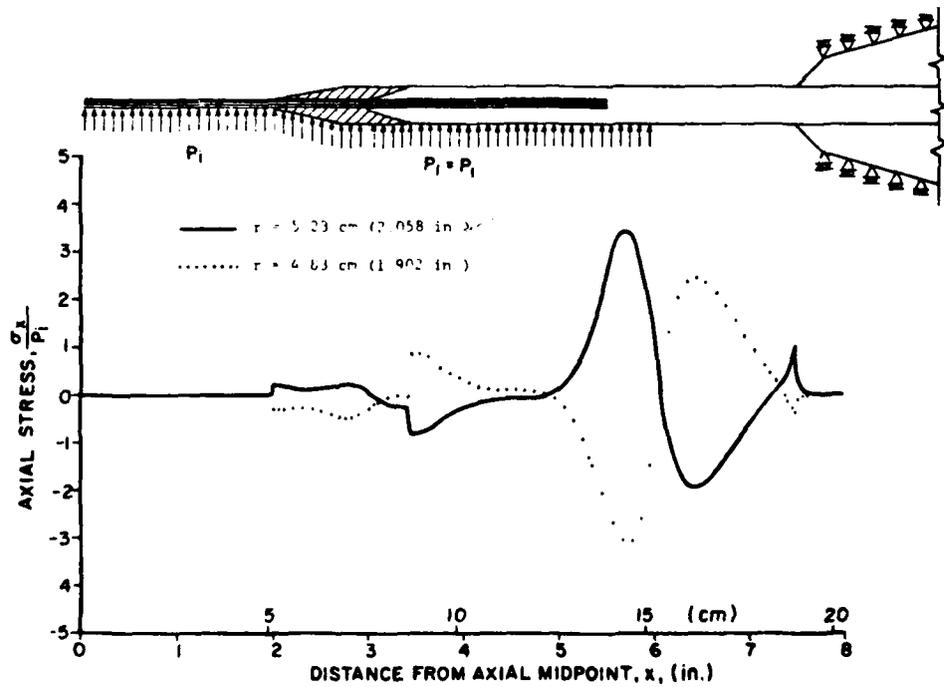


Figure 10. Axial Stress Distribution along Inner and Outer Rows of Tab Elements for $[0/\pm 45/90]_S$ Tab for Internal Pressure Loading

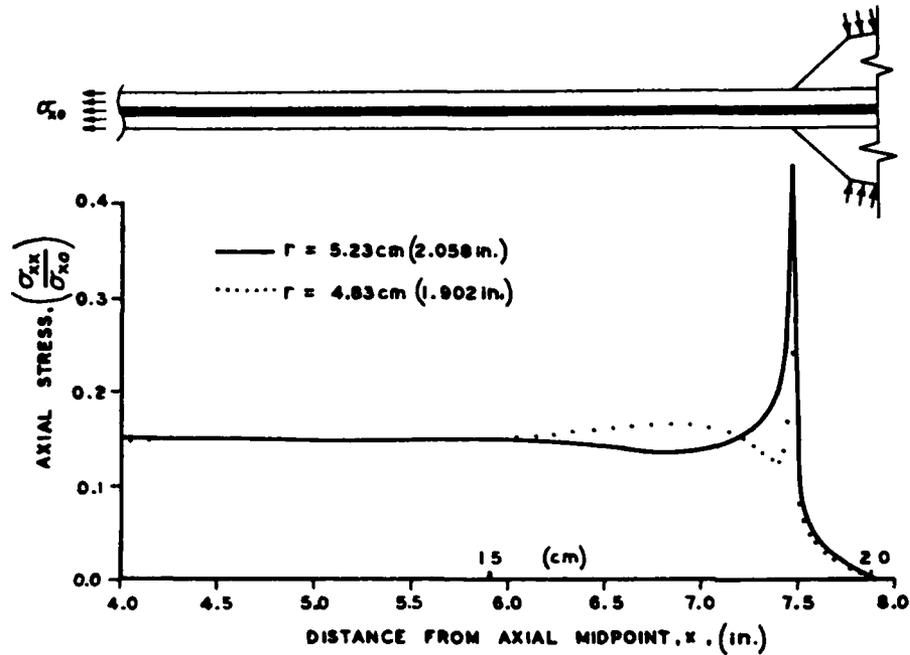


Figure 11. Axial Stress Distribution along Centroids of Inner and Outer Tab Elements for $[0/\pm 45/90]_s$ Graphite/Epoxy Specimen and Tab Layout for Axial Tensile Loading

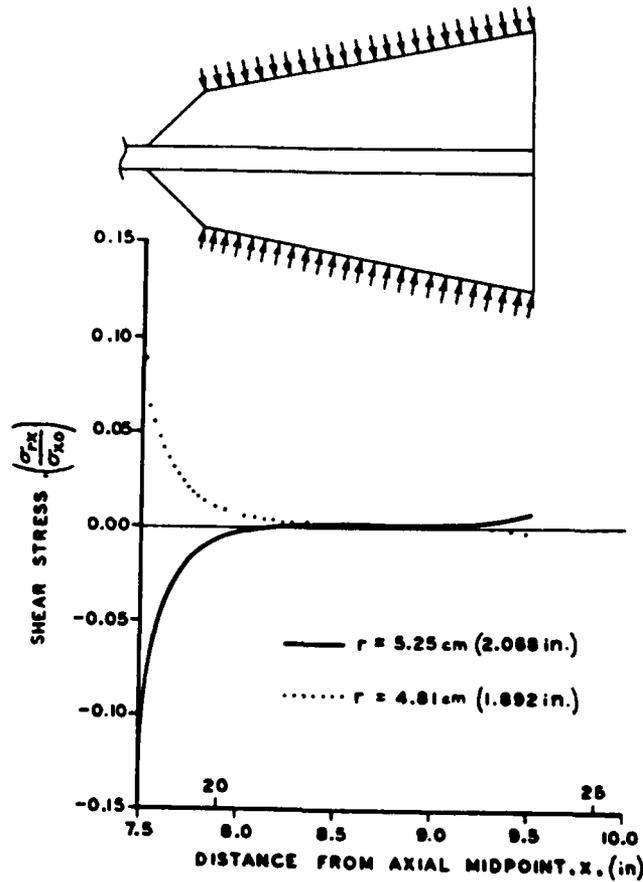


Figure 12. Shear Stress Distribution at Tab/Grip Interfaces under Axial Loading for $[0/\pm 45/90]_s$ Graphite/Epoxy Specimen and Tab Layout

**STIFFNESS, STRENGTH, FATIGUE LIFE RELATIONSHIPS
FOR COMPOSITE LAMINATES**

T. K. O'BRIEN - USARTL (AVRADCOM) - NASA LANGLEY

J. T. RYDER - LOCKHEED - RYE CANYON*

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* CONTRACT NAS1 - 16406

NASA

L-5533-21

T.K. O'BRIEN

10/28/81

OBJECTIVE

DEVELOP A "STRUCTURAL" MECHANICS ANALYSIS THAT
CAN PREDICT THE RELATIONSHIP OF MATRIX CRACKING
AND DELAMINATION TO THE STIFFNESS, STRENGTH, AND
FATIGUE LIFE OF UNNOTCHED GRAPHITE EPOXY LAMINATES
HAVING ARBITRARY LAYUPS.

NASA

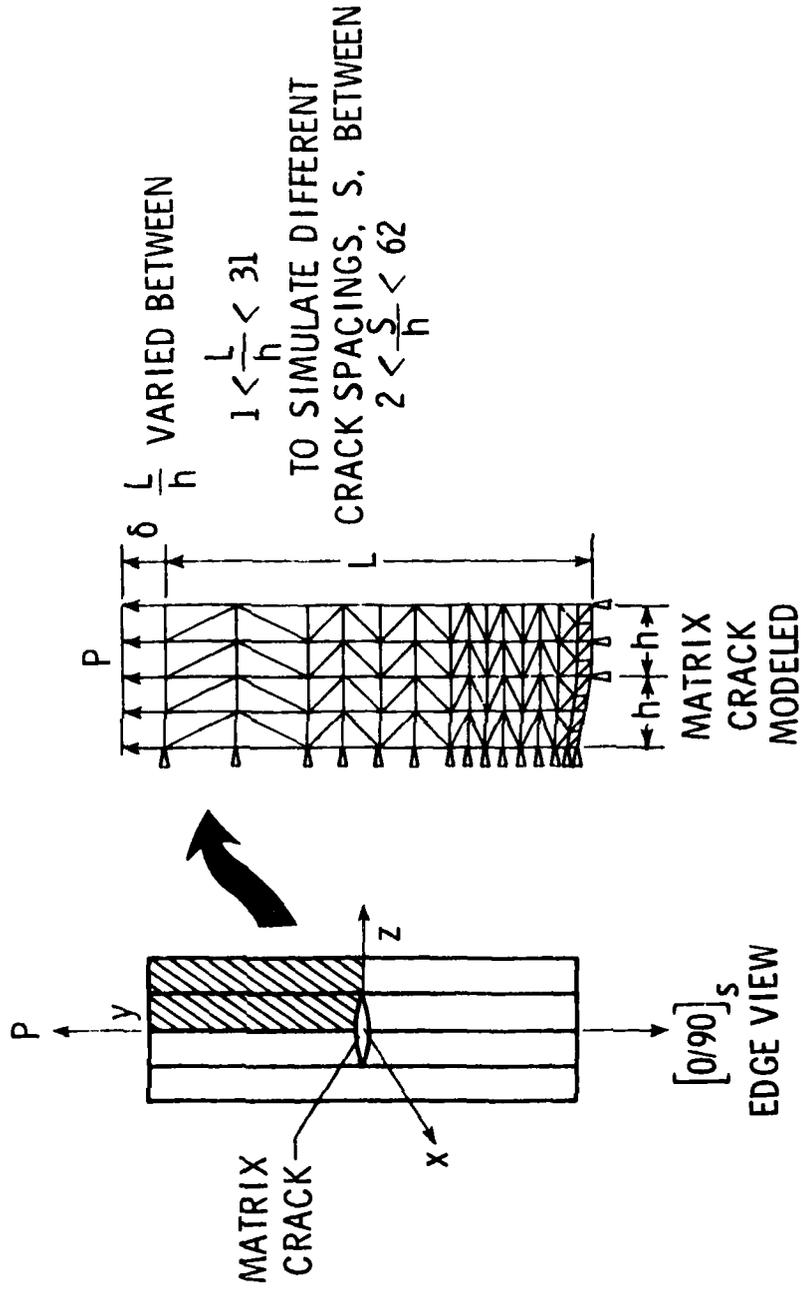
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T.K. O'BRIEN

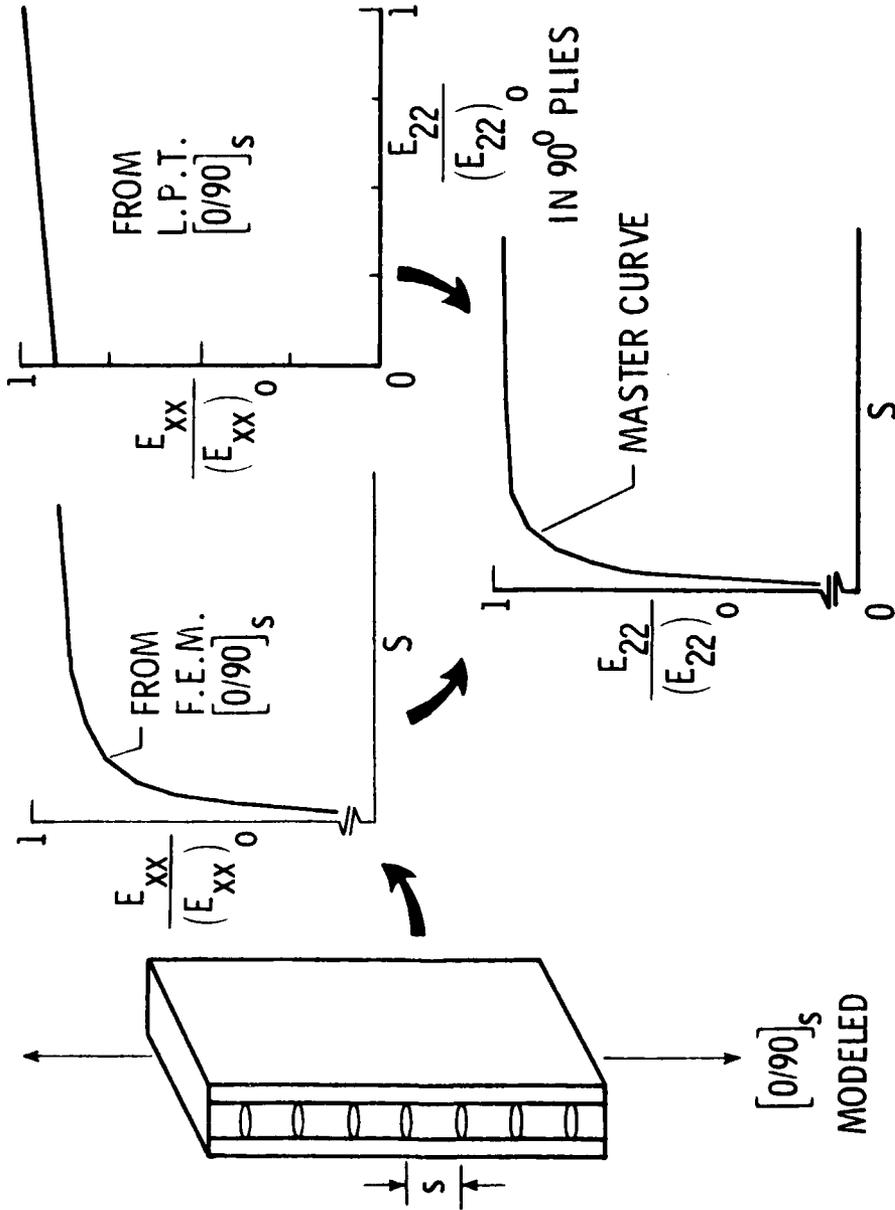
10/28/81

FINITE ELEMENT ANALYSIS OF STIFFNESS LOSS AS A FUNCTION OF CRACK SPACING

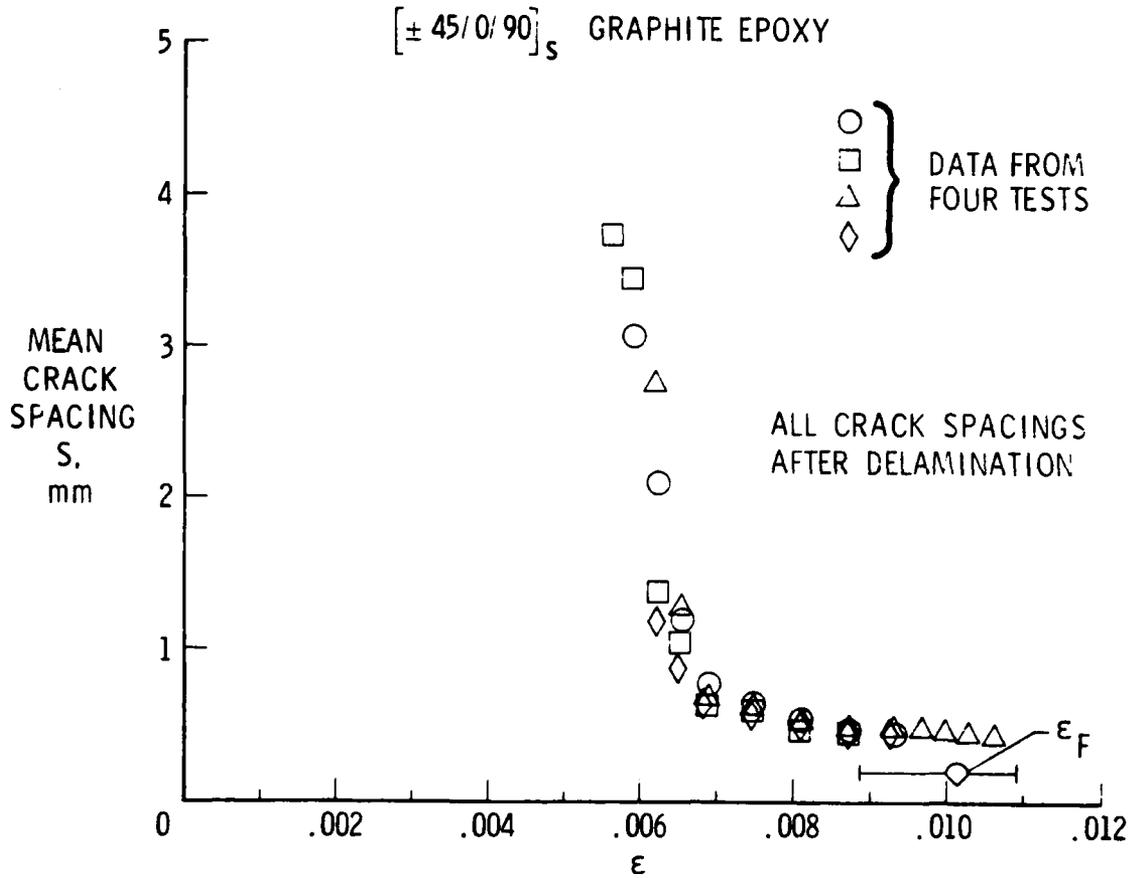
- CONSTANT STRAIN Δ ELEMENTS
- THREE D.O.F. PER NODE
- UNIFORM DISPLACEMENT PRESCRIBED
- $\Sigma F_x \neq 0$ GENERALIZED PLANE STRAIN



AXIAL STIFFNESS REDUCTION AS A FUNCTION OF CRACK SPACING



NINETY DEGREE PLY CRACK SPACING AS A FUNCTION OF TENSILE STRAIN



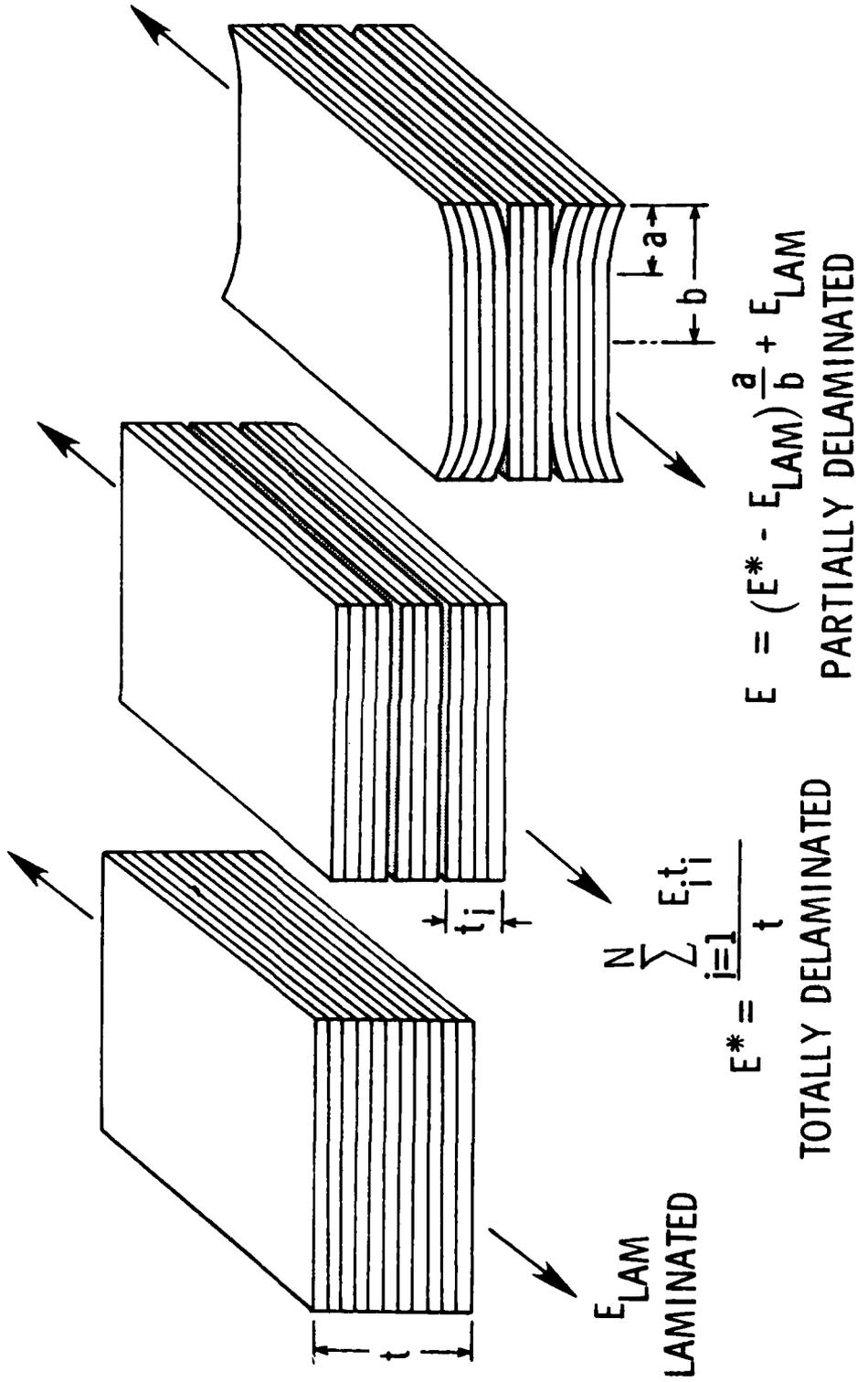
NASA

L-5533-36

T.K. O'BRIEN

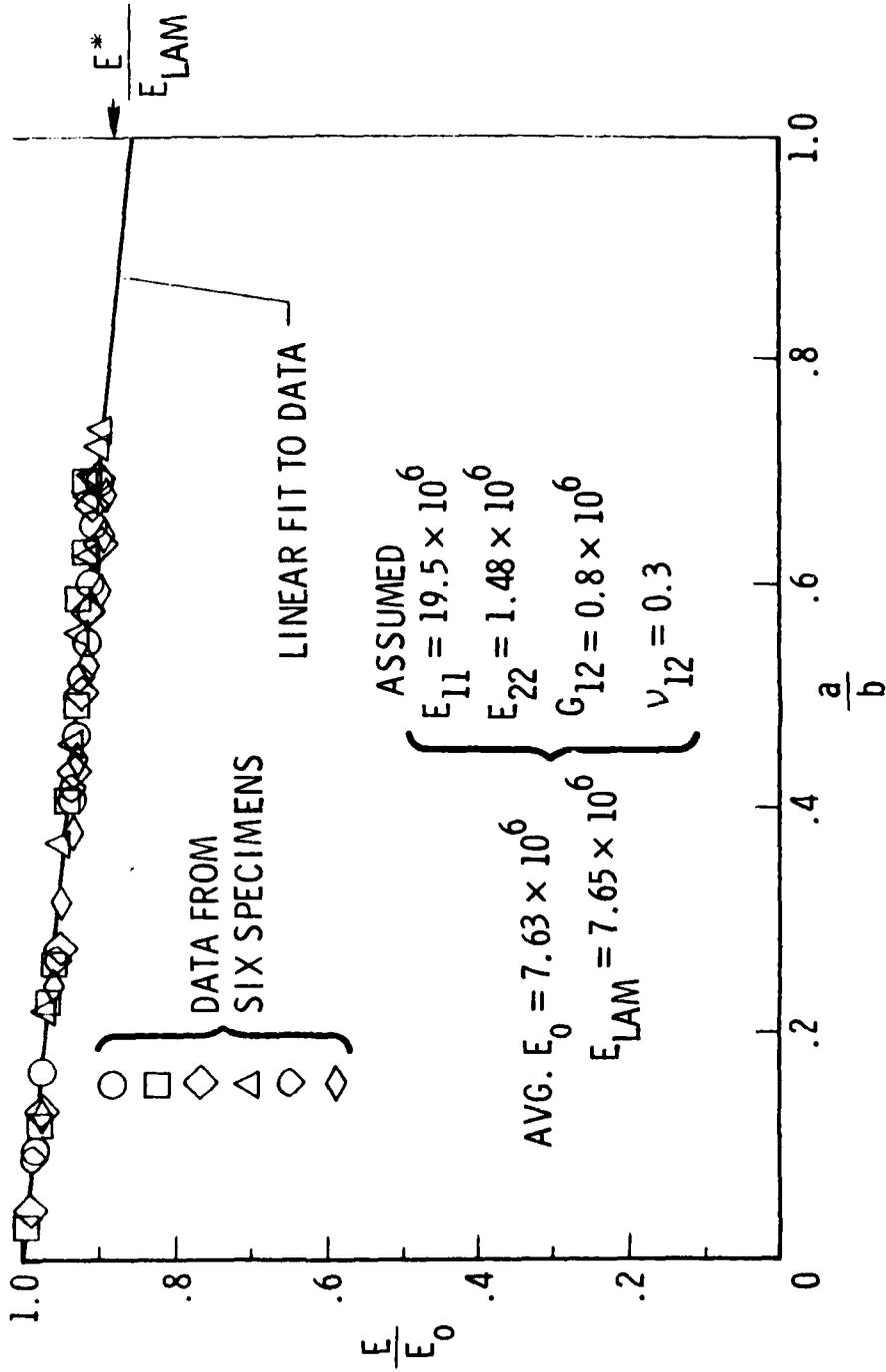
10/28/81

RULE OF MIXTURES ANALYSIS OF STIFFNESS LOSS

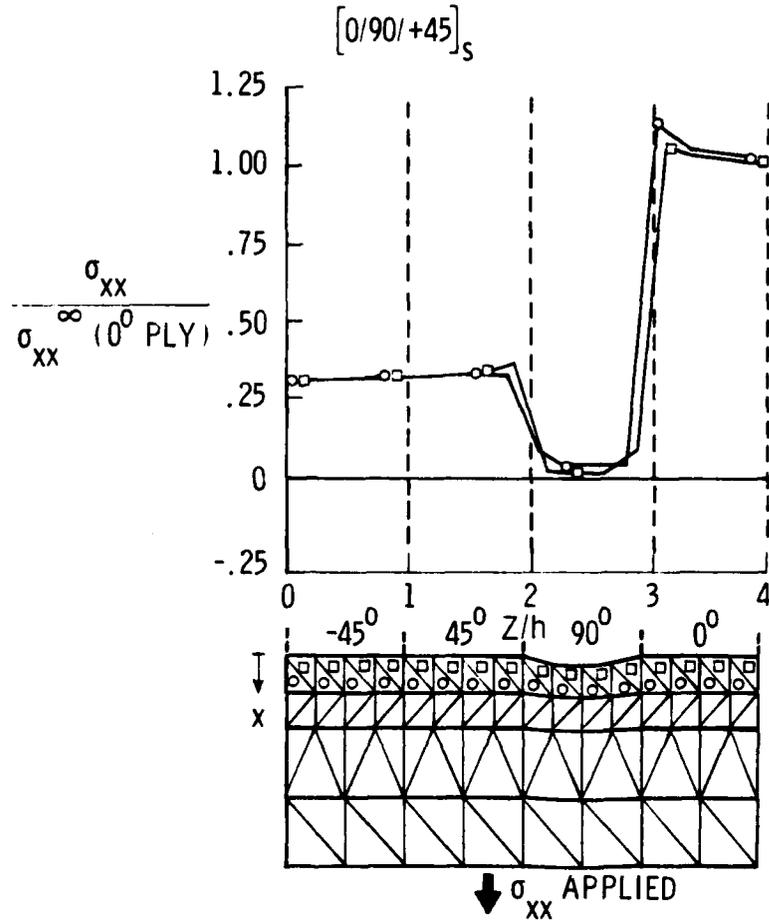


STIFFNESS LOSS AS A FUNCTION OF DELAMINATION SIZE

$[\pm 45/0/90]_s$ T300-5208 GRAPHITE EPOXY



LOCAL STRESS CONCENTRATION DUE TO MATRIX CRACK



NASA

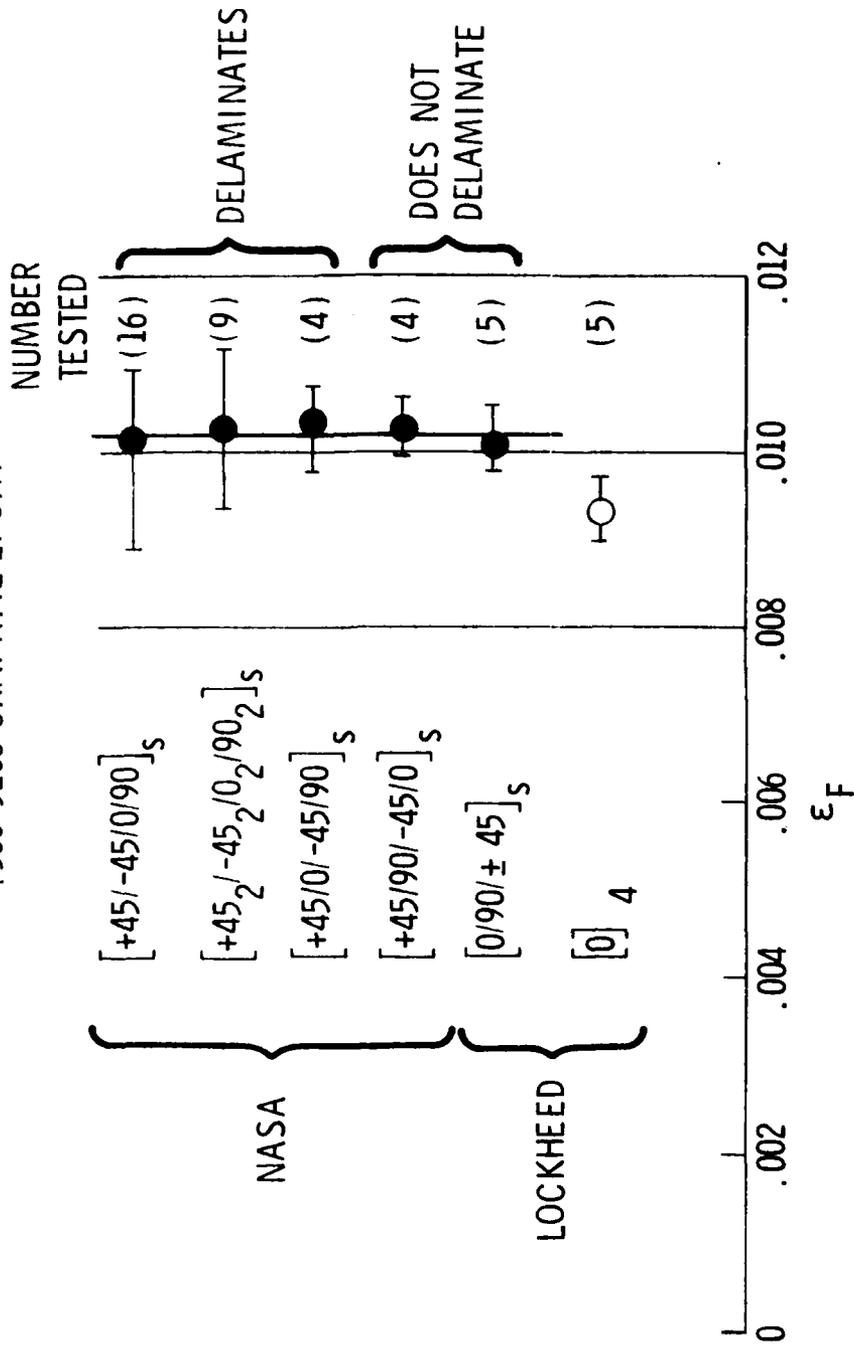
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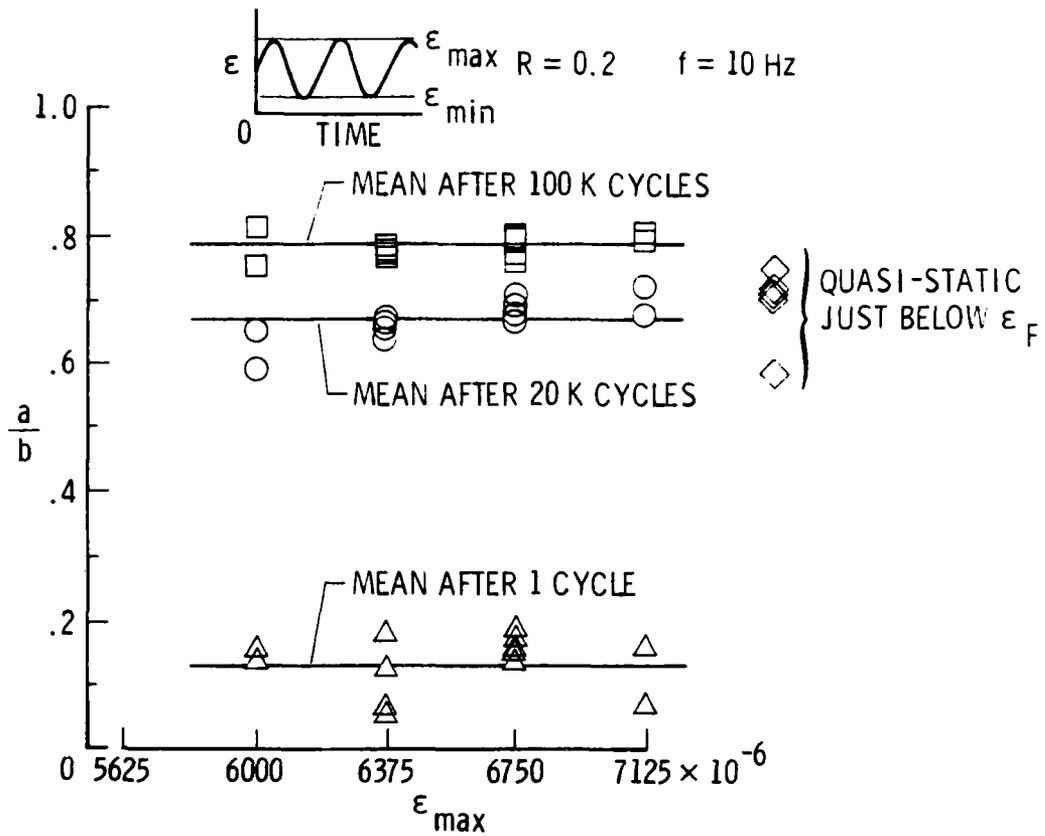
NOMINAL TENSILE FRACTURE STRAIN

T300-5208 GRAPHITE EPOXY



DELAMINATION GROWTH IN FATIGUE

$[\pm 45/0/90]_s$



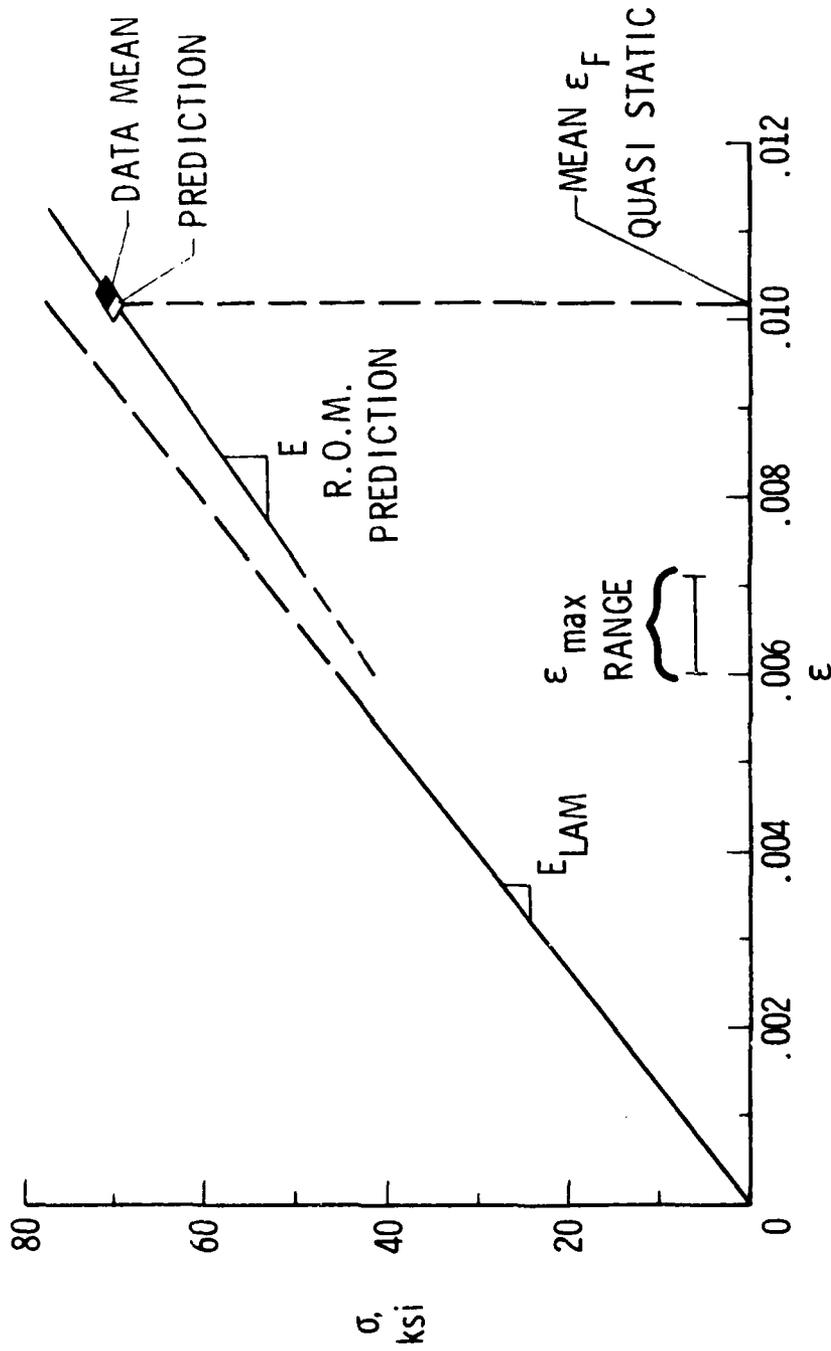
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L-5533-12

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RESIDUAL STRENGTH PREDICTION
 [+ 45/0/90]_s T300-5208 GRAPHITE EPOXY



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AIR FORCE WRIGHT AERONAUTICAL LABS WRIGHT-PATTERSON AFB OH F/G 11/4
PROCEEDINGS OF THE SEVENTH ANNUAL MECHANICS OF COMPOSITES REVIE--ETC(U)
APR 82 S D GATES, L A WILSON

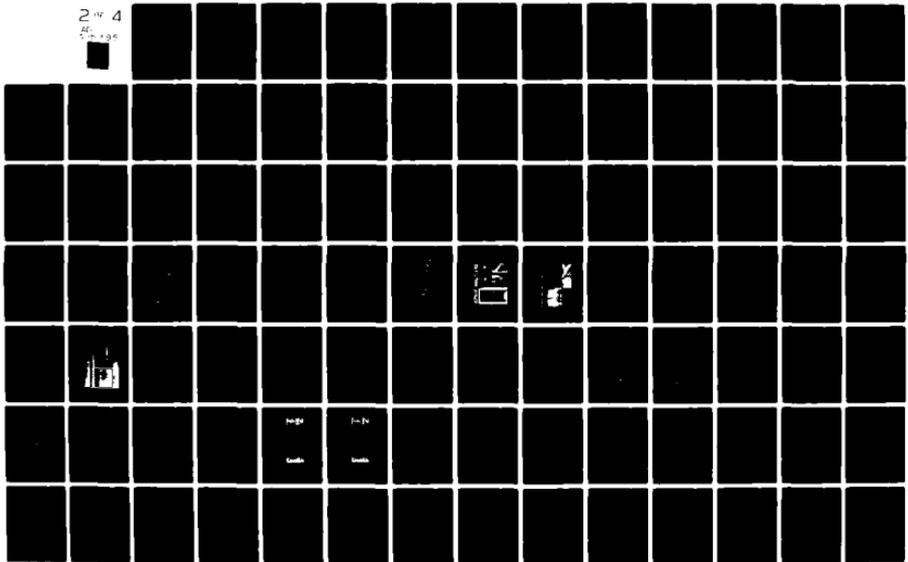
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CONCLUSIONS

HAVE DEVELOPED A SIMPLE ANALYSIS, USING LAMINATED PLATE THEORY, THAT PREDICTS THE TENSILE STIFFNESS AND TENSILE STRENGTH OF UNNOTCHED GRAPHITE EPOXY LAMINATES WITH DIFFERENT LAY-UPS.

HAVE DEMONSTRATED FOR LAYUPS TESTED THAT:

LAMINATE STIFFNESS LOSS RESULTS PRIMARILY FROM DELAMINATION, WITH ONLY A SMALL CONTRIBUTION FROM MATRIX CRACKS IN OFF-AXIS PLYS.

THE MEAN NOMINAL FRACTURE STRAIN OF UNNOTCHED QUASI-ISOTROPIC GRAPHITE EPOXY LAMINATES IS A CONSTANT INDEPENDENT OF LAYUP.

TENSILE STRENGTH CAN BE ESTIMATED FROM LAMINATE STIFFNESS CALCULATED AT THE FRACTURE STRAIN.

NASA

L-5533-24

T.K. O'BRIEN

10/28/81

FRACTURE GROWTH IN COMPOSITE LAMINATES

A study on the fracture mechanisms of multiple transverse cracking and free edge delamination in a series of graphite/epoxy composite laminates under uniaxial tension.

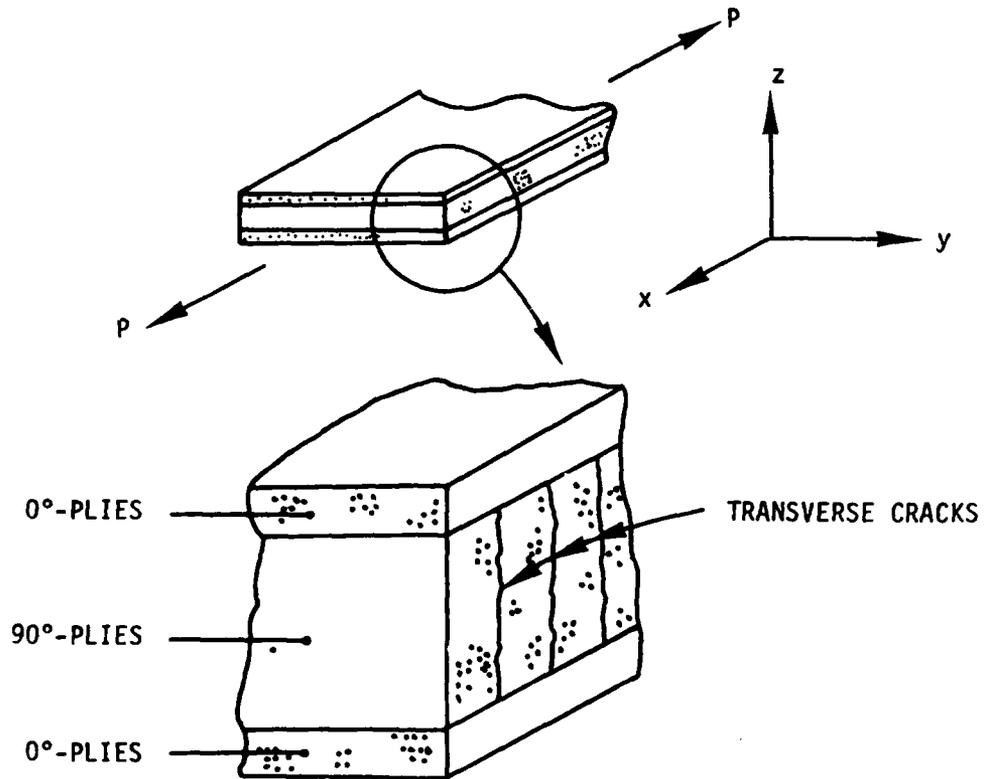
A.S.D. Wang, Drexel University; and
F.W. Crossman, Lockheed Research Laboratory

APPROACHES FOR STUDY

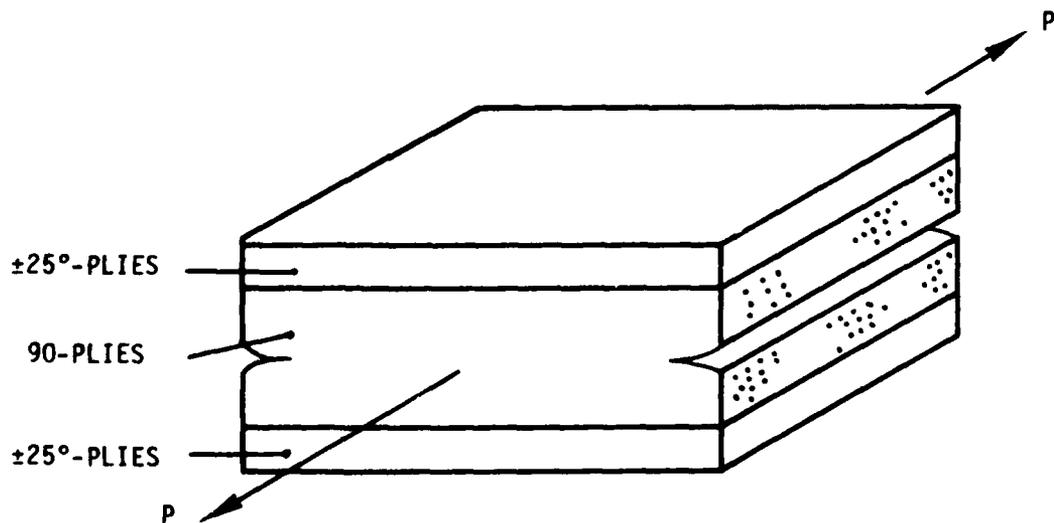
- linear elastic fracture mechanics;
- energy release rate as fracture criterion;
- finite element method as a numerical tool;
- crack-closure technique to calculate energy release rate;
- experiment to verify the analysis and the theory;
- experiment to observe other important parameters;
- correlation between experiment and analysis.

DEFINITION OF THE PROBLEMS

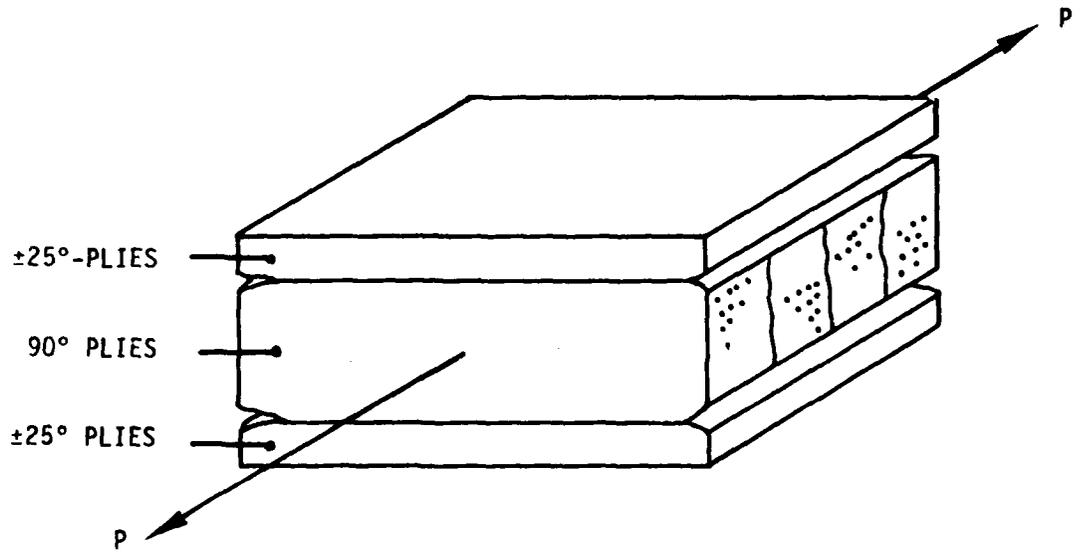
* Transverse Cracking (mode I)



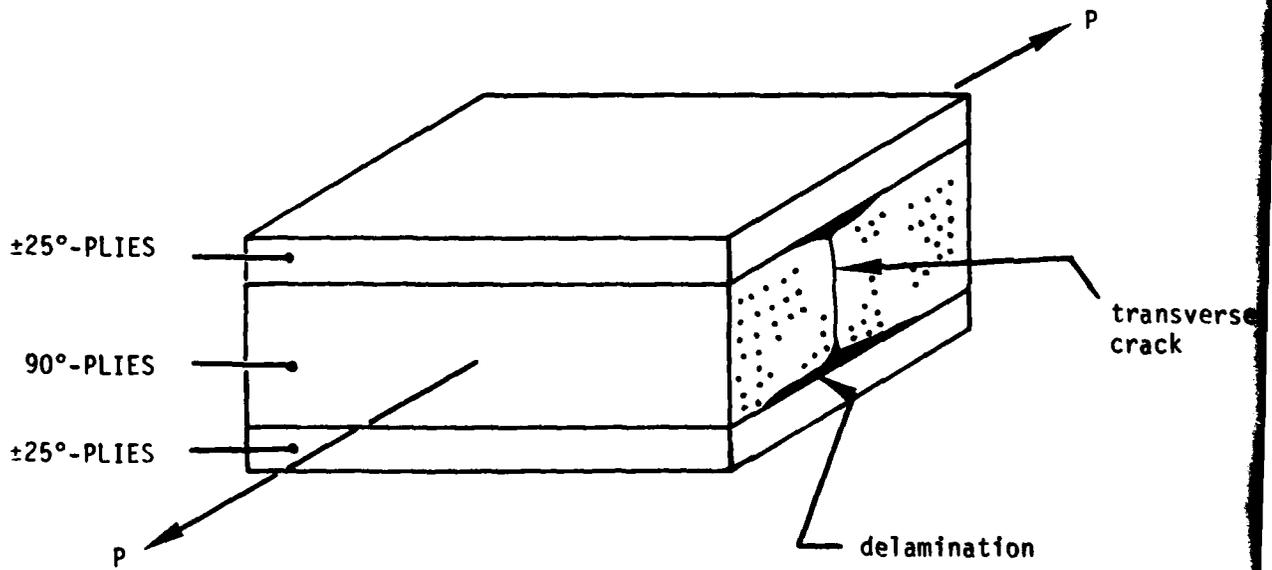
* Free Edge Delamination (along center plane, mode I)



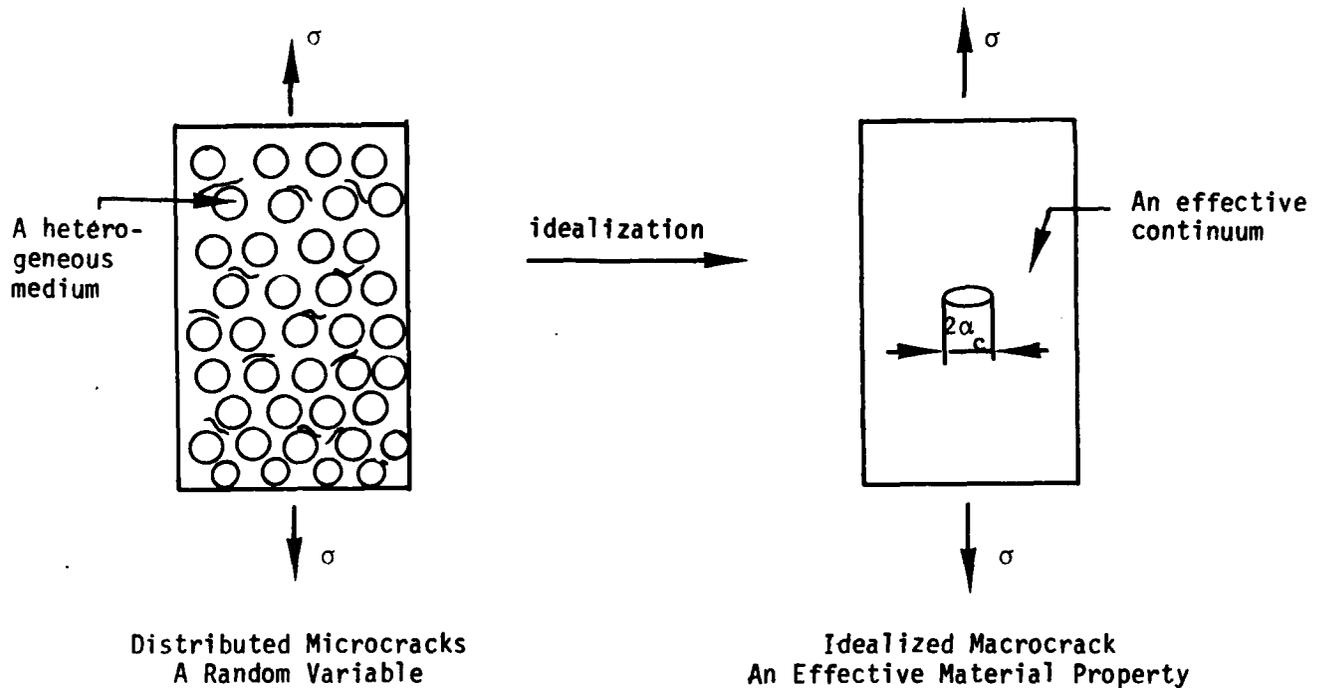
* Free Edge Delamination (along 25/90 plane, mixed mode)



* Delamination emanating from the root of a transverse crack (mixed mode)



CLASSICAL FRACTURE MECHANICS AS APPLIED TO MATRIX DOMINANT CRACK PROBLEMS



Also 2 Material Constants:

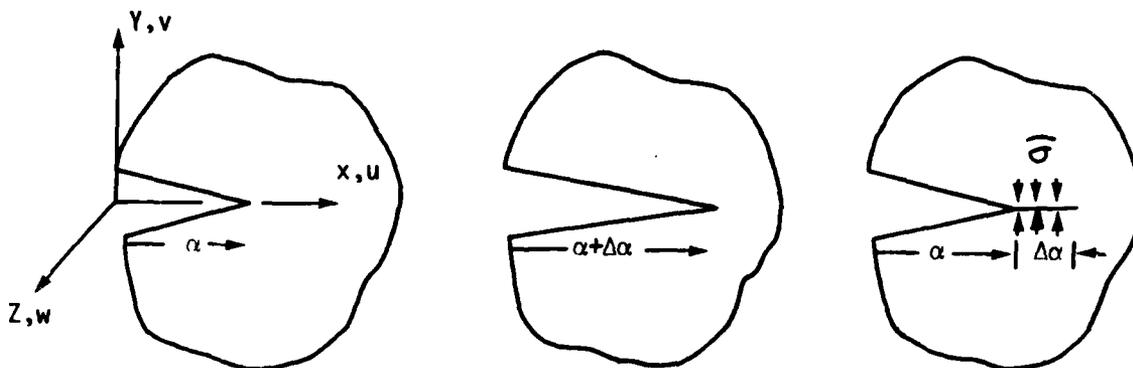
G_c , measured at the macroscopic level: $\sim 10^4 \text{ in-lb/in}^2$

α_c , an idealized (imaginary) material defect whose effect is measured at the macroscopic level: $\sim 10^{-2} \text{ in.}$

In Addition -----

α_c is assumed a random variable, whose size and location have characteristic distribution.

CRACK CLOSURE EQUIVALENCE



$$\Delta W = \frac{1}{2} \int_0^{\Delta a} (\tilde{\sigma} \cdot \Delta \tilde{u}) da$$

ENERGY RELEASE RATE

$$G = \lim_{\Delta a \rightarrow 0} \frac{1}{2\Delta a} \int_0^{\Delta a} (\tilde{\sigma} \cdot \Delta \tilde{u}) da$$

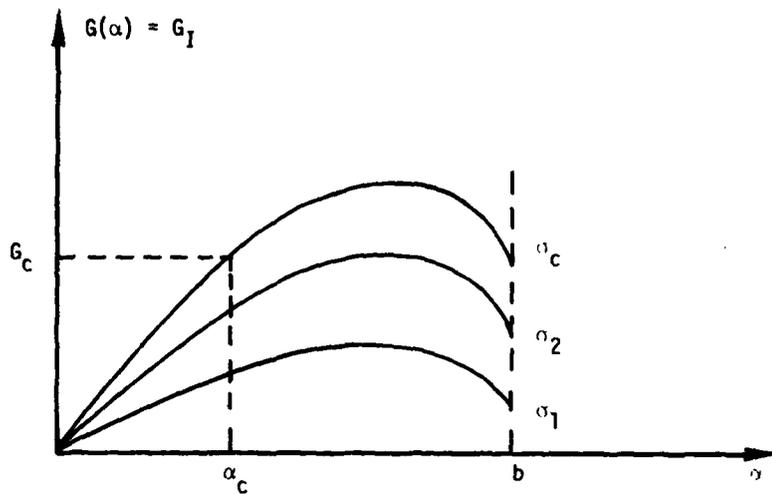
$$G_I = \lim_{\Delta a \rightarrow 0} \frac{1}{2\Delta a} \int_0^{\Delta a} (\sigma_y \Delta v) da$$

$$G_{II} = \lim_{\Delta a \rightarrow 0} \frac{1}{2\Delta a} \int_0^{\Delta a} (\tau_{xy} \Delta u) da$$

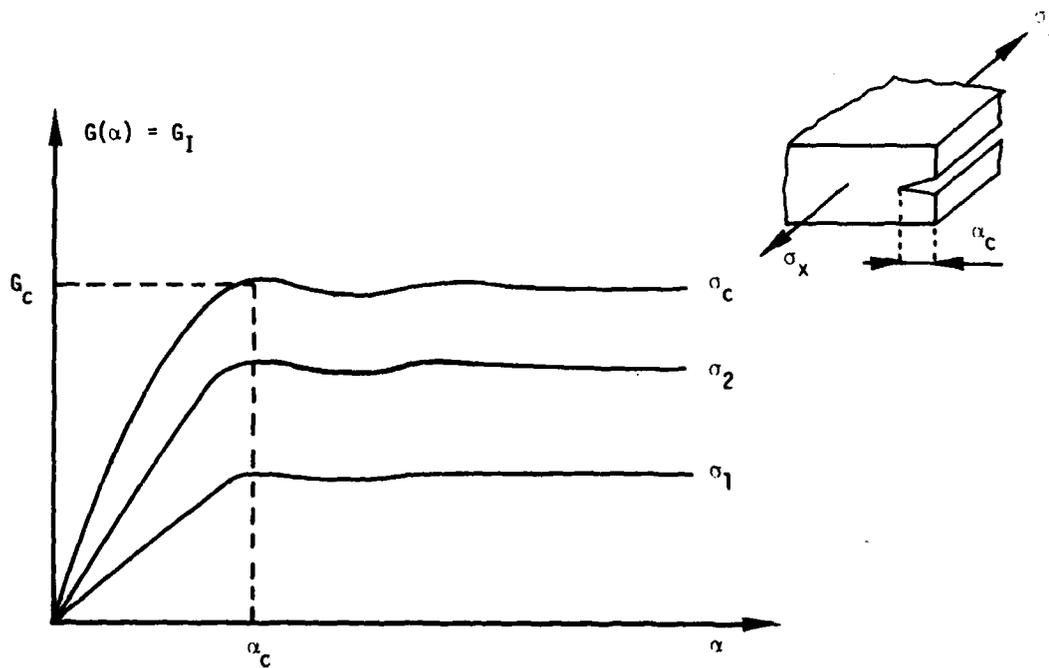
$$G_{III} = \lim_{\Delta a \rightarrow 0} \frac{1}{2\Delta a} \int_0^{\Delta a} (\tau_{yz} \Delta w) da$$

* Energy release rates are approximated by finite element procedure.

* CRITERIA FOR CRACK INITIATION



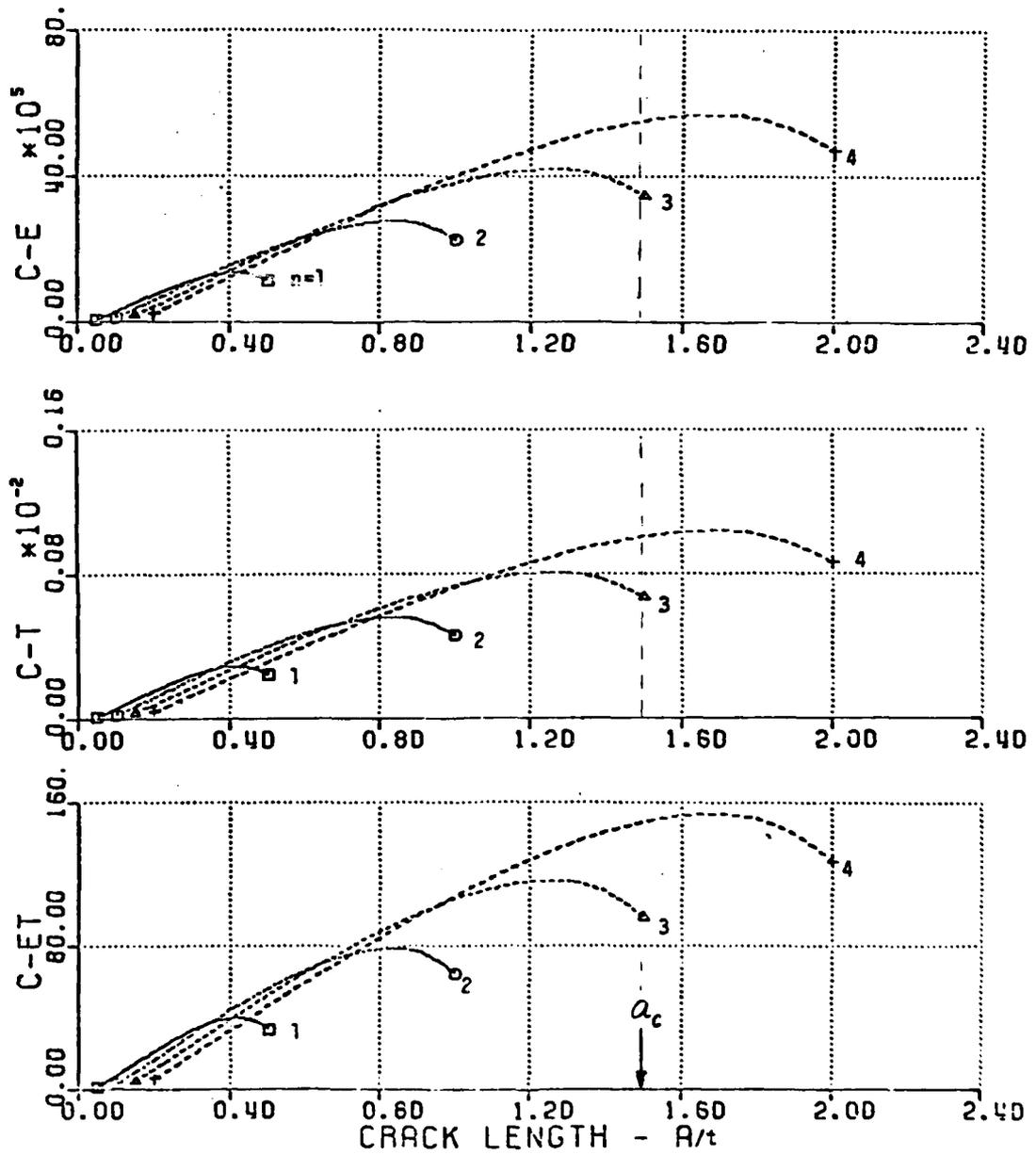
Typical $G(\alpha)$ for Transverse Crack

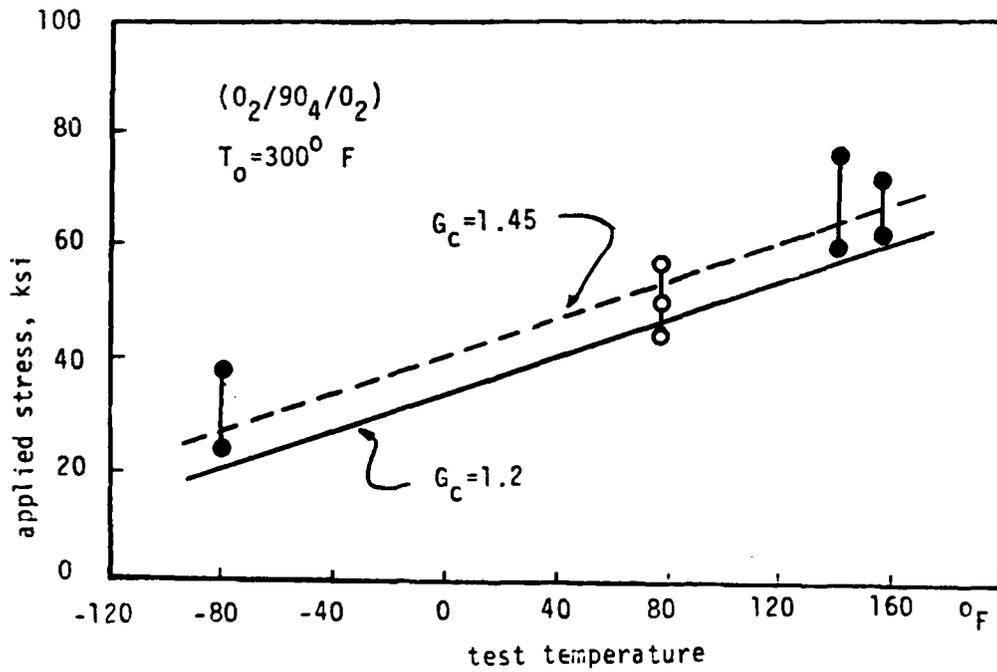
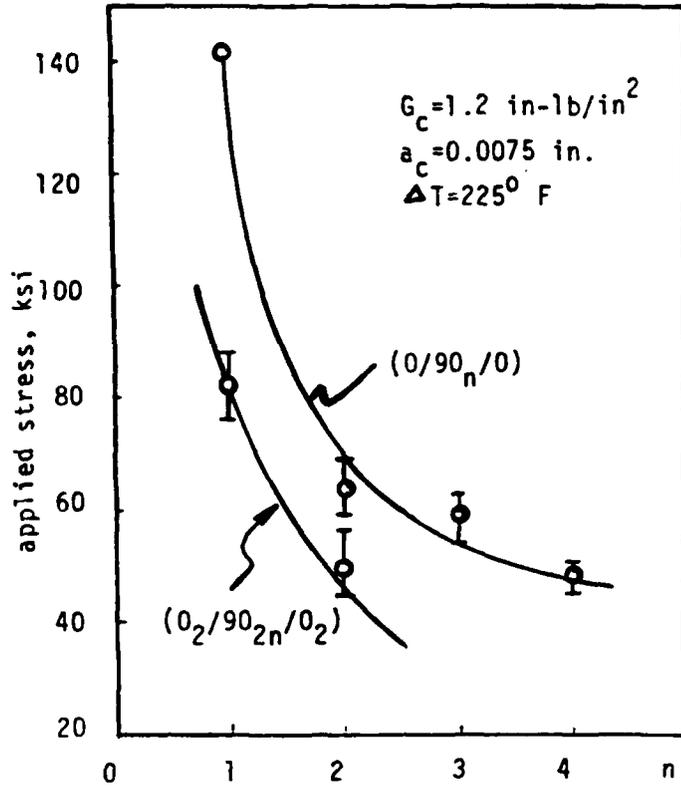


Typical $G(\alpha)$ for Edge Delamination

* CASE STUDY I: Multiple transverse cracking using T300/934 graphite/epoxy
 (0/90_n/0), n=1,2,3,4 and (0₂/90_{2n}/0₂), n=1,2.

$$G(a) = [C_e e_x^2 + C_{eT} e_x \Delta T + C_T \Delta T^2] t$$

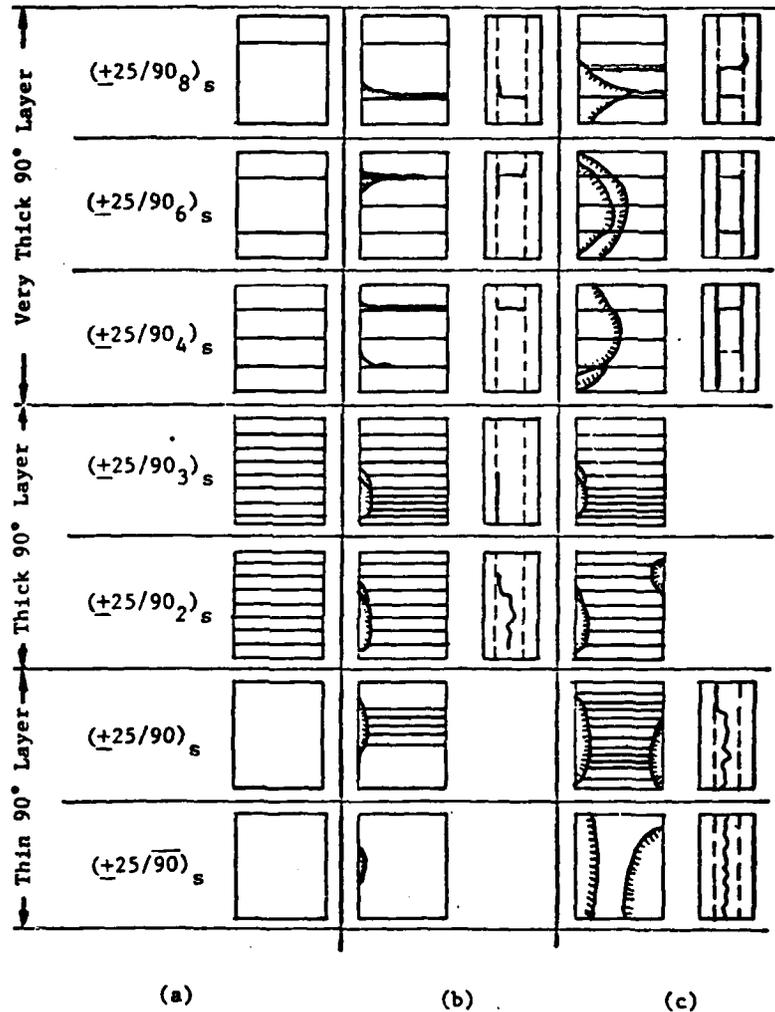




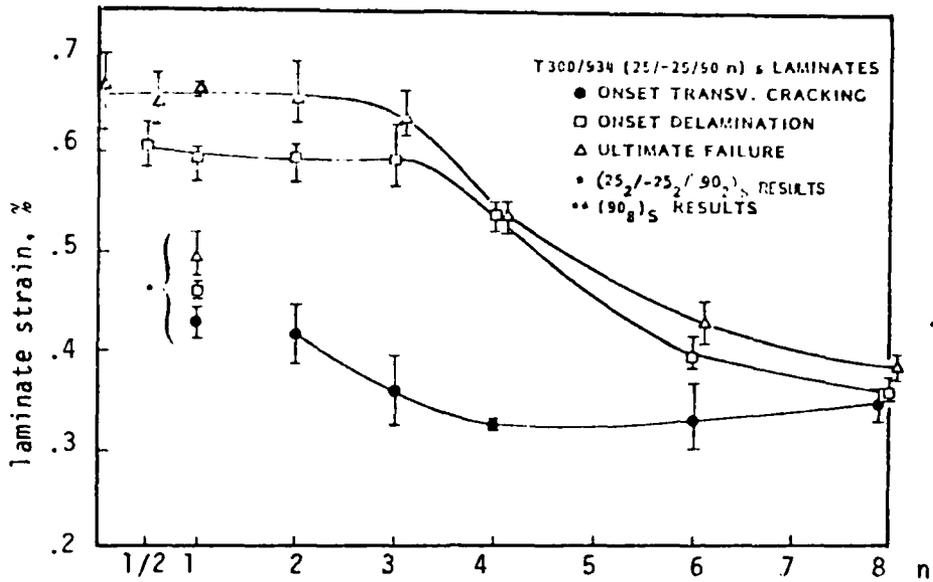
Comparison Between Theory (solid lines) and Experiment (dots)

* CASE STUDY II: Transverse cracking/Delamination/Final failure Sequence.

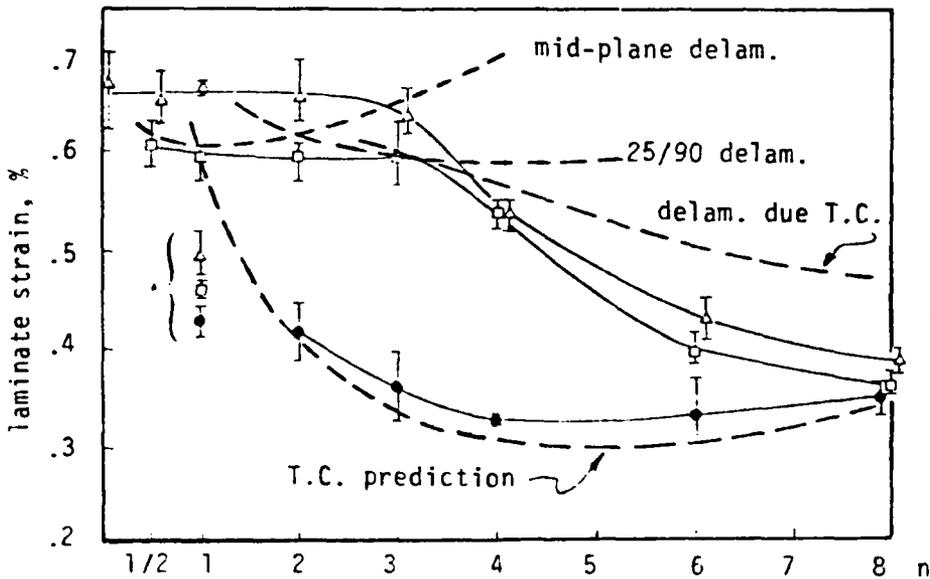
T300/934 $(\pm 25/90_n)_s$, $n=1/2, 1, 2, 3, 4, 6, 8$.



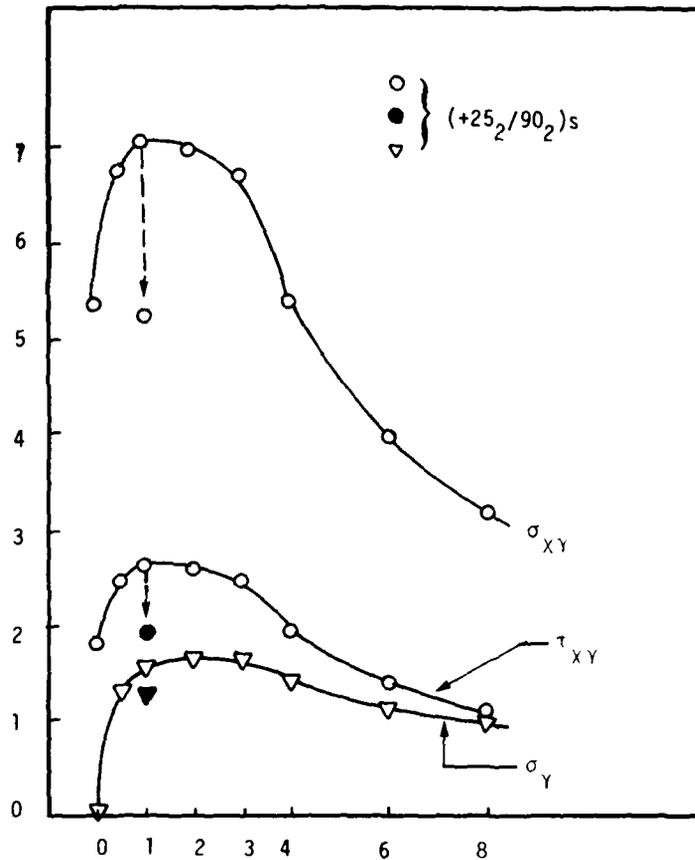
SCHEMATIC OF THE FRACTURE SEQUENCE IN THE $(\pm 25/90_n)_s$ LAMINATES
 (a) JUST PRIOR TO EDGE DELAMINATION, (b) SUBSEQUENT TO EDGE
 DELAMINATION, (c) JUST PRIOR TO FINAL FAILURE



Observed laminate strain ϵ_x for onset of transverse cracking edge delamination and final failure vs. the number of 90-ply layers.



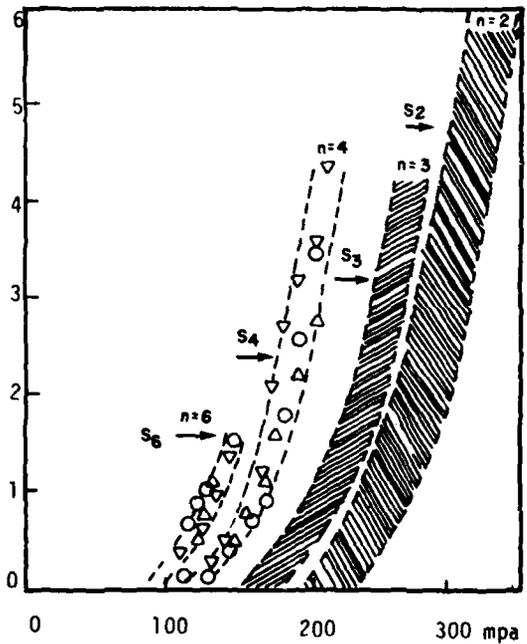
Comparison between theory (dotted lines) and experiment (prediction based on $G_c=1.4$; $a_c=0.008^*$ and $\Delta T=225^{\circ}F$)



In-situ stresses in the 25°-plies at laminate failure of $(+25/90)_n$ laminates vs. the number of 90-ply, n.

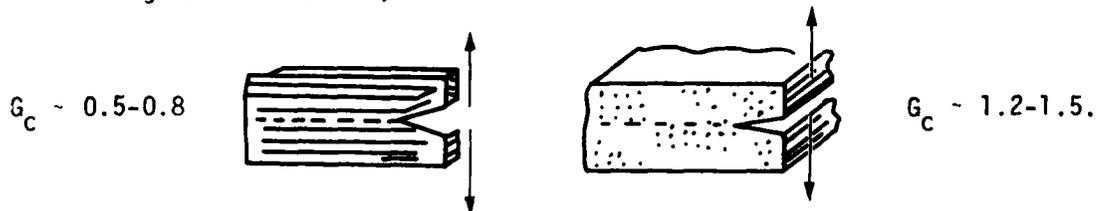
Density of transverse cracks (cracks per cm) vs. applies laminate stress in $(+25/90)_n$ laminates for n=2,3,4,6.

S_n is theoretical crack density based on shear-lag prediction.



CONCLUSIONS AND DISCUSSIONS:

- * methods of classical fracture mechanics can be viable crack growth criteria for matrix-dominated sub-laminate cracks, such as transverse cracking and ply-delamination.
- * the energy release rate increases (generally) with the size of crack, which is constrained by the physical dimension of the laminate's ply-structure, such as the thickness of the plies. Thus, ply-thickness has a profound influence on the growth process of sub-laminate cracking, and even the final failure of the laminate;
- * the finite-element/crack-closure technique is a useful computational tool to simulate sub-laminate crack growth, if the crack paths are relatively simple;
- * the DIB-enhanced x-radiography is a useful NDI tool to monitor the growth of sub-laminate cracks;
- * (open question) for the material used in this study, the value of G_c is in the range of 1.2 to 1.5 in-lb/in²; but other experiments found it in the range of 0.5 to 0.8;



the difference should be verified by careful experiment on the above.

- * (open question) for the best-fit of data, the critical material crack size a_c is taken as 0.008 in.; can a microscopic study verify this? a_c is (generally) a function of the size of inhomogeneity (fiber), the stiffness property surrounding the crack and other processing variables; can a_c depend also on the ply-structure of the laminate?

- * (open question) in this study, all predictions were based on the total energy release rate $G=G_I + G_{II} + G_{III}$ for both mode-I and mixed mode cracks; experimental correlation indicates a need for a mixed mode crack criterion, such as

$$G_I/G_{Ic} + G_{II}/G_{IIc} + G_{III}/G_{IIIc} = 1$$

does G_{IIc} or G_{IIIc} exists? and how to determine them?

- * (open question) some of the observed cracks were actually 'planar cracks'; the crack front is a complicated contour; is there a 2-D crack growth criterion readily applicable?

RELATED PUBLICATIONS:

- * An Energy Method for Multiple Transverse Cracks In Graphite-Epoxy Laminates.
- in Modern developments in composite materials and structures, ed. J.R. Vinson, ASME 1979, pp. 17-29.
- * Initiation and Growth of Transverse Cracks and Edge Delamination In Composite Laminates; Part I. An Energy Method.
- in Journal of Composite Materials, suppl. vol. 1980, pp. 71-87.
- * Initiation and Growth of Transverse Cracks and Edge Delamination In Composite Laminates; Part II. Experimental Correlation.
- in Journal of Composite Materials, suppl. vol. 1980, pp. 88-108.
- * Growth Mechanisms of Transverse Cracks and Ply Delamination in Composite Laminates.
- in Advances In Composite Materials, Proc. ICCM-III, Paris, 1980, pp. 170-182.
- * The Dependence of Transverse Cracking and Delamination on Ply Thickness In Graphite-Epoxy Laminates.
- to appear in ASTM STP.

- * Fracture Analysis of $(\pm 25/90_n)_s$ Graphite-Epoxy Composite Laminates.
- Ph.D. dissertation, by G.E. Law, Drexel University, 1981.

- * The Influence of Thickness of 90°-Ply On the Tensile Failure Strain of $(\pm\theta/90_n)_s$ Laminates.
- in preparation.

- * The Role of Thermal Stresses In the Transverse Cracking Process of Cross-Ply Laminates.
- in preparation.

- * Width Effect On the Growth of Edge Delamination in $(\pm 45/0/90)_s$ Laminates.
- in preparation.

- * A Mixed-Mode Fracture Criterion For the Notched and Unnotched Off-Axis Strength of Unidirectional Composite.
- in preparation.

AFWAL-TR-82-4007

RESEARCH ON COMPOSITE MATERIALS
FOR STRUCTURAL DESIGN

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SPONSORED BY THE AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
UNDER CONTRACT No. F49620-78-C-0034

OBJECTIVES

GENERAL: STUDY DEFORMATION AND FRACTURE BEHAVIOR OF ADVANCED STRUCTURAL COMPOSITES WITH EMPHASIS ON POLYMER MATRIX DOMINATED PHENOMENA. MOST TOPICS ARE SELECTED SO THAT WORK CAN BE DONE AS PART OF ONE-YEAR M.S. DEGREE PROGRAM.

SPECIFIC: OF THE SEVEN M.S. AND ONE PH.D. STUDIES CONDUCTED DURING THE 1980-81 ACADEMIC YEAR, THE FOLLOWING FOUR WILL BE REVIEWED.

STUDENT/
FACULTY ADVISOR
TITLE

OBJECTIVE

1. P. S. VANDERKLEY/
W.L. BRADLEY
"MODE I - MODE II DELAMINATION
FRACTURE TOUGHNESS OF A
UNIDIRECTIONAL GRAPHITE/EPOXY
COMPOSITE"
INVESTIGATE EXPERIMENTALLY
THE EFFECT OF THE MODE II/
MODE I STRESS RATIO ON CRITICAL
ENERGY RELEASE RATE AND FRACTURE
SURFACES USING UNIDIRECTIONAL
SPLIT LAMINATES.
2. D. R. WILLIAMS/
W. L. BRADLEY
"MODE I TRANSVERSE CRACKING
IN EPOXY AND A GRAPHITE/
EPOXY COMPOSITE"
STUDY CRACK GROWTH THROUGH
MATRIX UNDER CONDITION OF CON-
STANT APPLIED DISPLACEMENT
USING COMPACT TENSION SPECI-
MENS, AND COMPARE CRITICAL
ENERGY RELEASE RATES AND
FRACTURE SURFACES IN NEAT
RESIN AND IN COMPOSITES FOR
TRANSVERSE CRACKING AND
DELAMINATION.

STUDENT/
FACULTY ADVISOR
TITLE

OBJECTIVE

- | | |
|---|--|
| 3. J. S. CULLEN/
K. L. JERINA
"MODE I DELAMINATION OF
UNIDIRECTIONAL GRAPHITE/
EPOXY COMPOSITE UNDER COMPLEX
LOAD HISTORIES" | INVESTIGATE ENERGY RELEASE
RATE REQUIRED FOR DELAMINA-
TION AS A FUNCTION OF CRACK
SPEED FOR COMPLEX LOADING
HISTORIES UNDER AMBIENT AND
ELEVATED TEMPERATURE AND
HUMIDITY ENVIRONMENTS. |
| 4. J. W. EARLEY/
K. L. JERINA
"COMPRESSION INDUCED
DELAMINATION IN A UNIDIREC-
TIONAL GRAPHITE/EPOXY
COMPOSITE" | STUDY APPLICABILITY OF
LINEAR ELASTIC FRACTURE
MECHANICS AND BEAM-COLUMN
THEORY TO AXIAL COMPRESSION-
INDUCED DELAMINATION IN A
SPLIT LAMINATE. |

CONCLUSIONS

(NUMBERS CORRESPOND TO THOSE FOR OBJECTIVES)

1. MIXED-MODE DELAMINATION:

- (I) IN DELAMINATION FRACTURE IN PURE MODE I, CRACKING OCCURS THROUGH THE MATRIX WITH VERY LITTLE FIBER BREAKAGE AND PULLOUT. AS THE MODE II COMPONENT IS INCREASED, THE TOTAL ENERGY ABSORBED IN FRACTURE IS THEN FOUND TO INCREASE DUE TO GREATER INCIDENCE OF FIBER BREAKAGE AND PULLOUT.
- (II) A STRONG HISTORY EFFECT HAS ALSO BEEN OBSERVED. WHERE A HIGH MODE II FRACTURE CONDITION IS USED EARLY IN THE TEST, THE ENERGY ABSORBED IN FRACTURE SUBSEQUENTLY FOR LOWER MODE II COMPONENT IS HIGHER THAN IF A LOW MODE II COMPONENT WERE USED THROUGHOUT THE TEST.

2. TRANSVERSE CRACKING:

- (I) ENERGY RELEASE RATE REQUIRED IN CT COUPON IN TRANSVERSE CRACKING OF A 90° COMPOSITE IS 1.5 TIMES THAT FOR DELAMINATION OF A COMPOSITE AND 3 TIMES THAT OF THE NEAT RESIN.
- (II) FRACTURE SURFACE FOR TRANSVERSE CRACKING OF THE COMPOSITE SHOWS CONSIDERABLE FIBER BREAKAGE AND PULLOUT AND MUCH MORE MATRIX DAMAGE THAN THE NEAT MATERIAL.

3. DELAMINATION UNDER COMPLEX LOADING:

- (I) ENERGY RELEASE RATE G INCREASES WITH INCREASE IN TEMPERATURE/MOISTURE AND DECREASE IN CROSSHEAD RATE.
- (II) MORE UNSTABLE (STOP-START) CRACK GROWTH OCCURS AT HIGHER T , M AND LOWER CRACK SPEEDS.
- (III) DATA INDICATES CRACK ARREST ENERGY IS APPROXIMATELY 90% OF INITIATION ENERGY.

4. DELAMINATION UNDER AXIAL COMPRESSION:

- (I) FOR THE LONG DELAMINATION LENGTHS STUDIED, CLASSICAL BEAM-COLUMN ANALYSIS COUPLED WITH LINEAR ELASTIC FRACTURE MECHANICS ACCURATELY PREDICTED DEFLECTIONS AND CRACK GROWTH.
- (II) CRACK GROWTH CONSISTENT WITH CONSTANT CRITICAL ENERGY RELEASE RATE MEASURED IN MODE I SPLIT LAMINATE TESTS WAS FOUND.

TABLE OF CRITICAL ENERGY RELEASE RATES
FOR AMBIENT CONDITION (24°C, 50% RH)

NEAT EPOXY

3502	69 J/m ²
DELAMINATION CRACKING	135-160
(11 TO FIBER IN PLANE 11 TO LAMINA BUT BETWEEN LAMINA, I.E., IN RESIN RICH REGION)	(40-50% HIGHER FOR 93°C 95% RH)
TRANSVERSE CRACKING	225
(11 TO FIBER BUT IN PLANE ⊥ TO LAMINA, I.E., NOT IN RESIN RICH REGION)	
MIXED MODE I/MODE II	158*-800**

$$* \frac{G_{11}}{G_1 + G_{11}} = 0$$

$$** \frac{G_{11}}{G_1 + G_{11}} = 0.5$$

SIGNIFICANT HISTORY DEPENDENCE NOTED WHERE HIGH MODE II
CRACKING PRECEDES LOWER RATIO MODE II CRACKING.

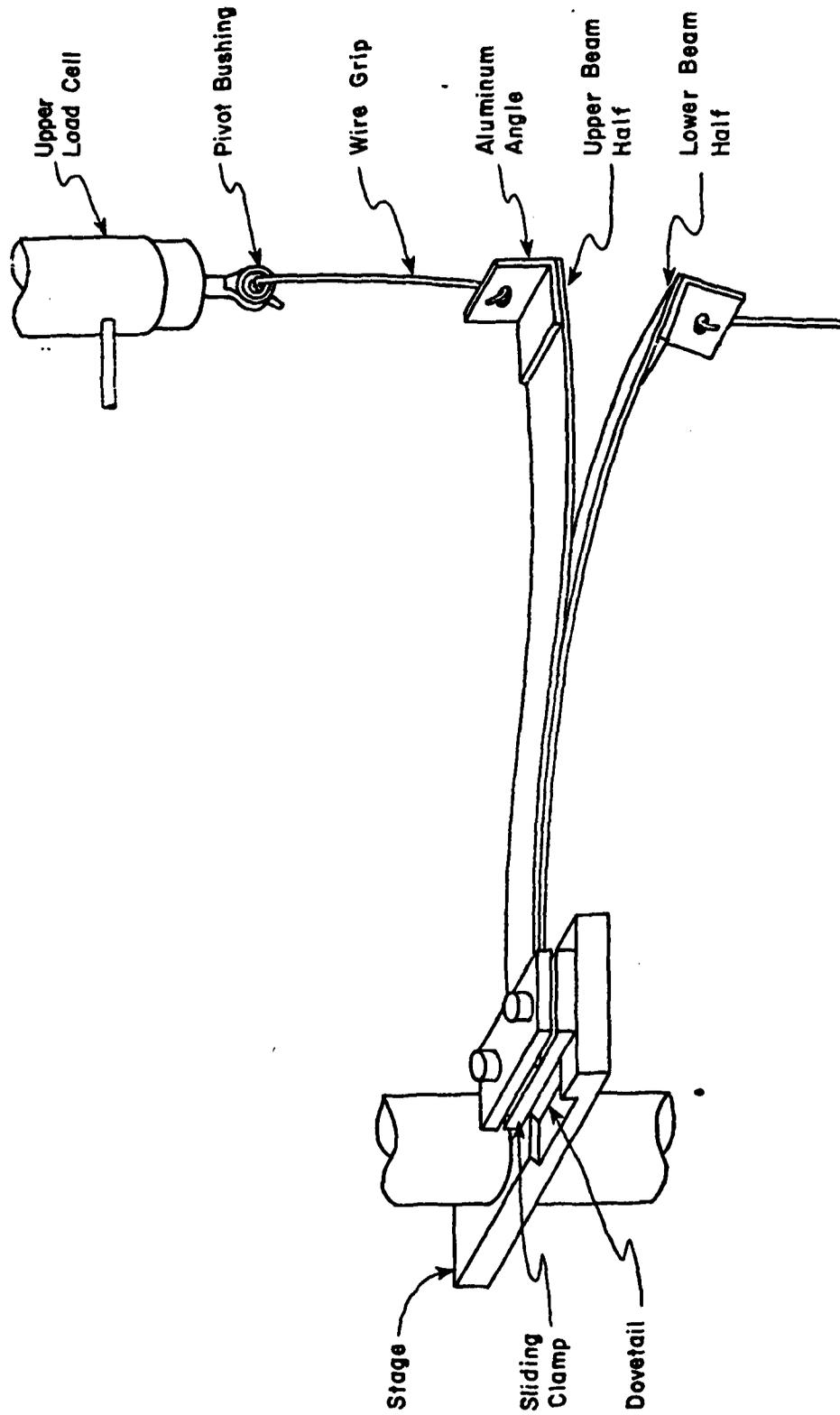


Figure 1.. Stage, specimen, and grip configuration

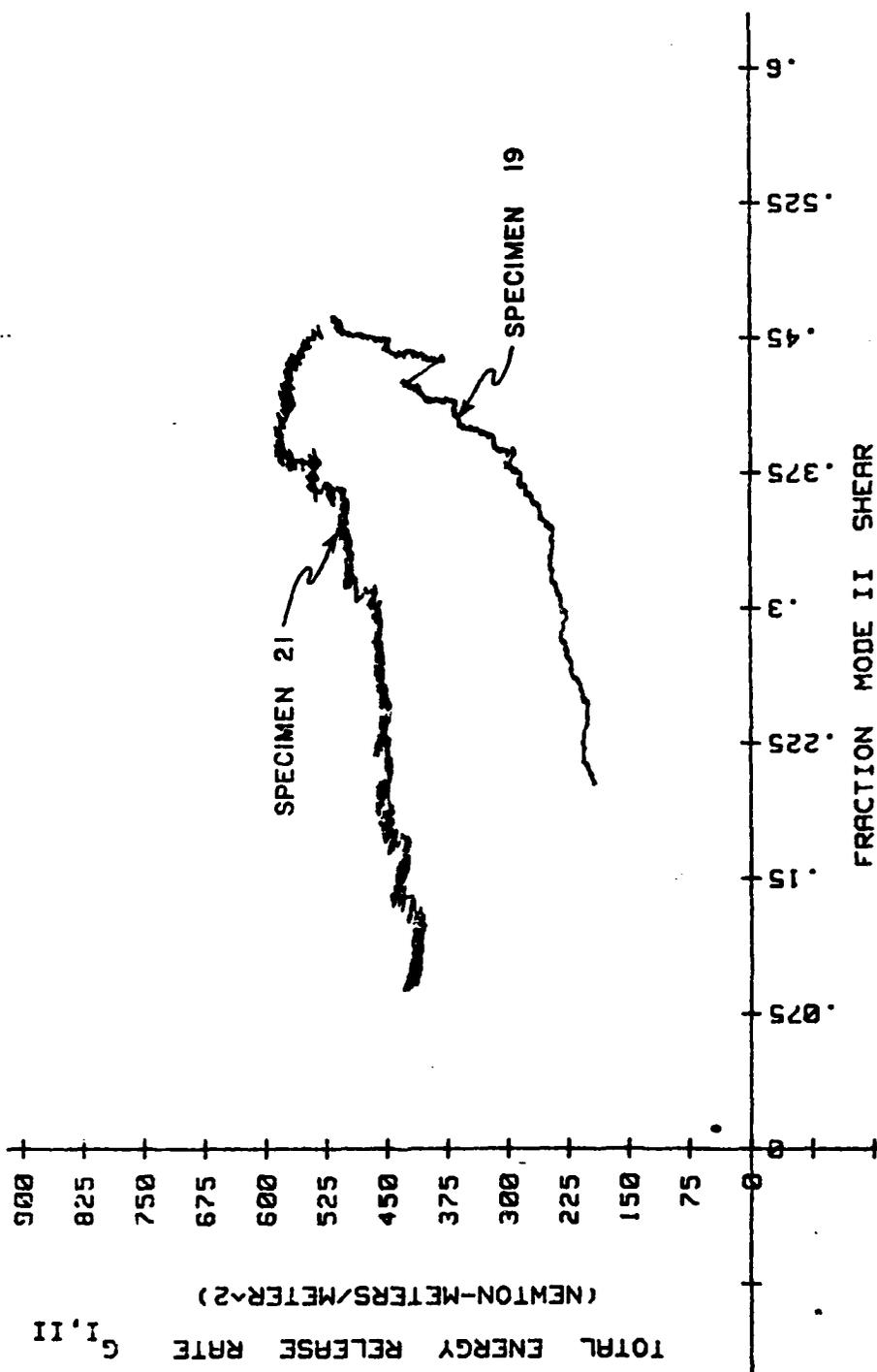


Figure 2. Effect of increasing (specimen 19), and decreasing (specimen 21) Mode II shear loads on total energy release rate.

MICROSCOPY RESULTS

1. PURE MATRIX CRACKING - FLAT, BRITTLE, NO INDICATION OF FLOW.
2. DELAMINATION - OCCASIONAL FIBER BREAKAGE AND/OR PULLOUT WITH SCALLOPED PATTERN LEFT ON MATRIX INDICATING SOME MATRIX DEFORMATION AS WELL.
3. TRANSVERSE CRACKING - MORE FREQUENT BUT STILL SINGLE FIBER BREAKAGE AND PULLOUT WITH SCALLOPES ASSOCIATED WITH FIBER PULLOUT.
4. MIXED MODE - INCREASING MODE II INCREASES FREQUENCY OF FIBER BREAKAGE AND PULLOUT WITH SOME BUNDLE OR MULTI-FIBER FRACTURE AND JUMPING TO ADJACENT PLY INTERFACE AT SOME POSITIONS ALONG CRACK FRONT.

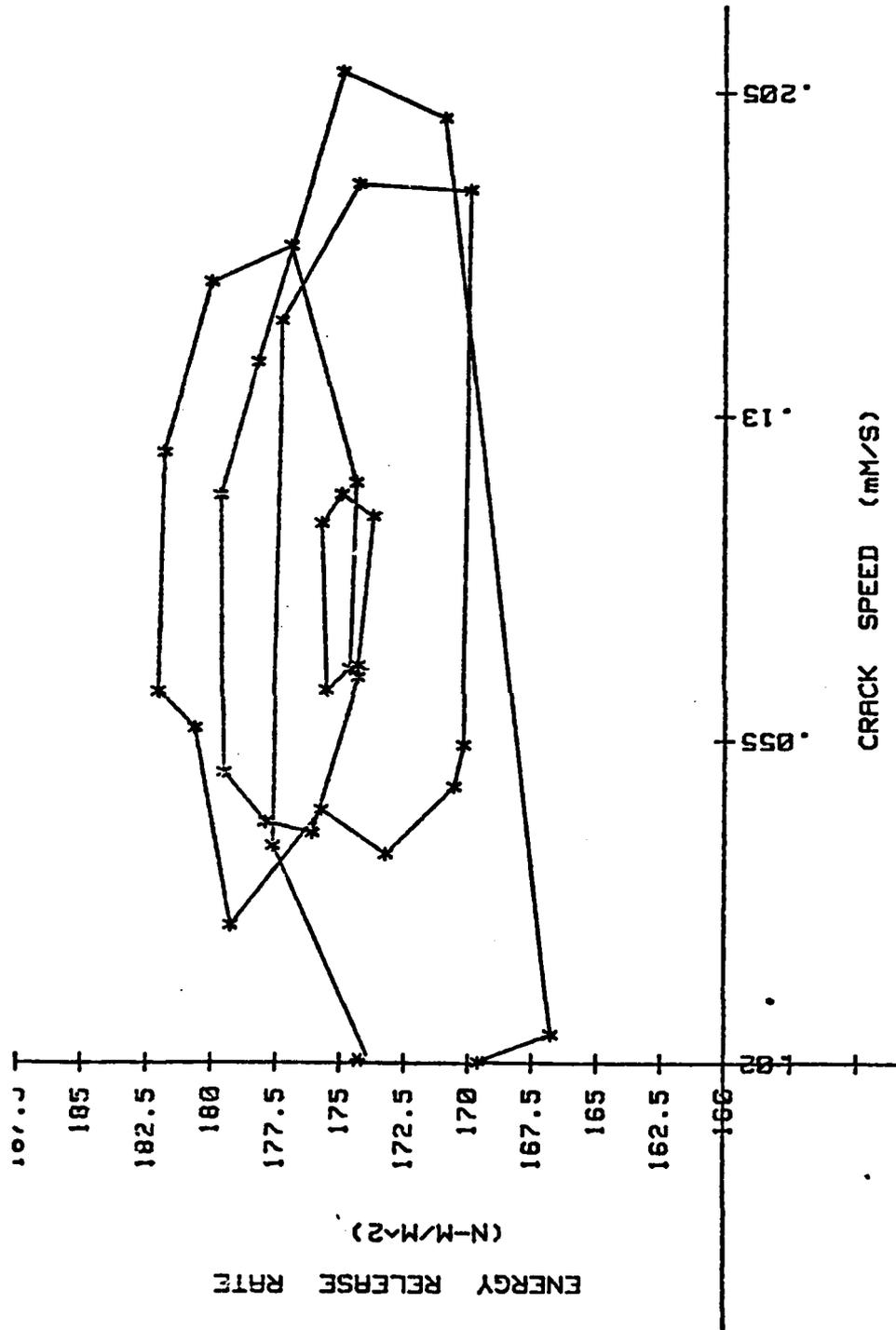


Figure 3. Energy Release Rate vs. Crack Speed Showing Local Unstable Crack Growth ($dg/da < 0$).

$\dot{\Delta} = 8.467$ E-5 m/s, elevated T/RH

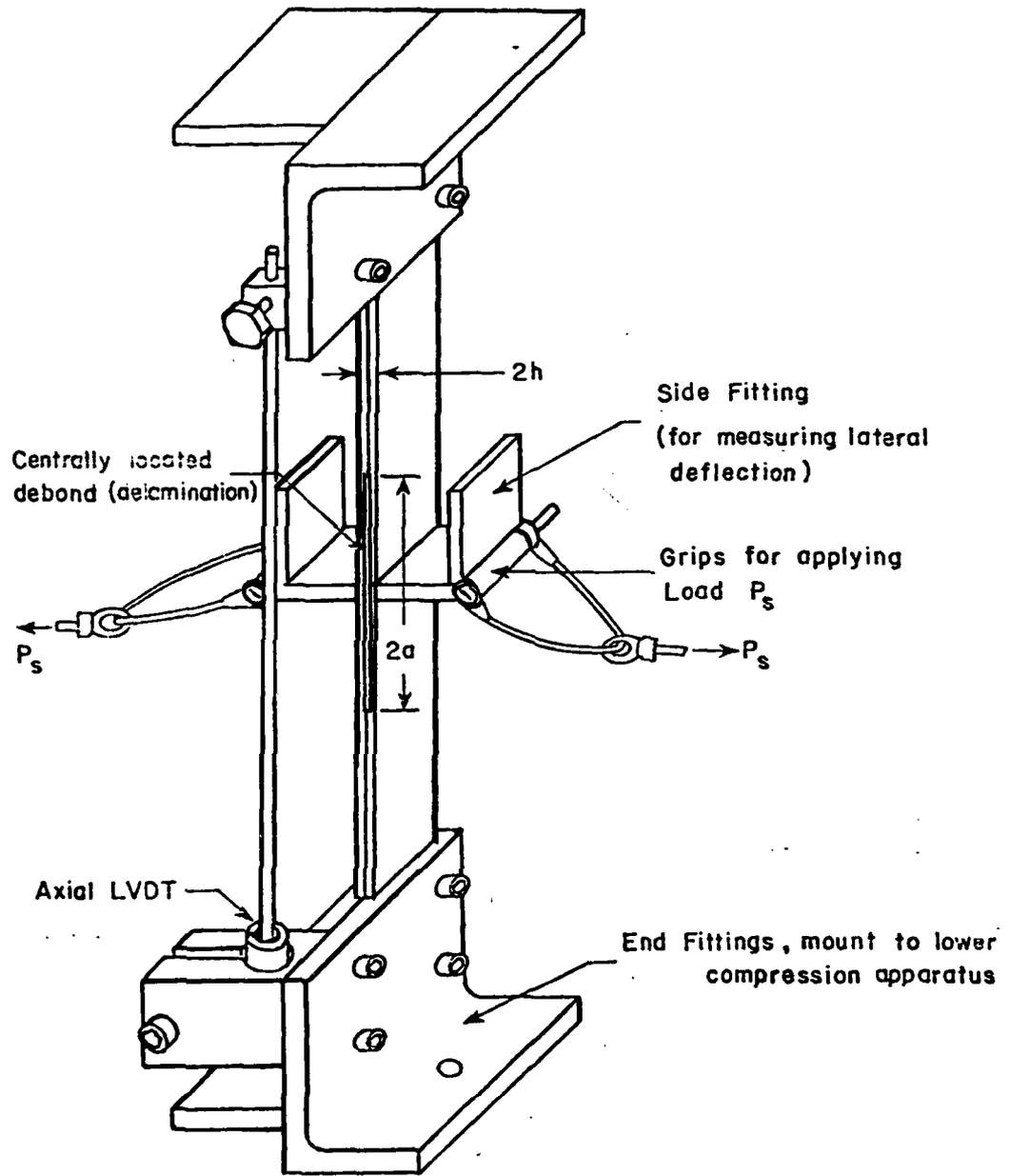


Figure 4. Test Specimen

ADDITIONAL INVESTIGATIONS
(1980-81 ACADEMIC YEAR)

M.S. THESES

STUDENT/ FACULTY ADVISOR	TITLE
5. R. T. ARENBURG/ R. A. SCHAPERY	THE EFFECT OF MATRIX DEGRADATION ON FATIGUE STRENGTH OF A GRAPHITE/ EPOXY LAMINATE
6. J. L. BRASWELL/ R. M. ALEXANDER	THE EFFECT OF GEOMETRY ON THE DESIGN OF FILAMENT-WOUND FIBER- GLASS TENSION LUGS
7. B. A. COULTER/ Y. WEITSMAN	SHEAR DEFORMATION EFFECTS IN COMPOSITE LAMINATES

PH.D. DISSERTATION (IN PROGRESS)

B. D. HARPER/ Y. WEITSMAN	ON THE EFFECTS OF POST CURE COOL DOWN AND ENVIRONMENTAL CONDITION- ING ON RESIDUAL STRESSES IN COMPOSITE LAMINATES
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IN ADDITION TO RESEARCH CONDUCTED AS PART OF THESIS/DISSER-
TATION WORK, THERE ARE STUDIES UNDERWAY ON THE DEVELOPMENT OF
VISCOELASTIC CONSTITUTIVE MODELS WHICH INCLUDE EFFECTS OF
TRANSIENT TEMPERATURE AND MOISTURE, AND ON THE DEVELOPMENT OF
CRACK GROWTH MODELS. THESE EFFORTS ARE DIRECTED TOWARD A
MAJOR OBJECTIVE TO ESTABLISH A THEORETICAL AND EXPERIMENTAL
BASIS FOR CHARACTERIZING AND PREDICTING CRACK AND DISTRIBUTED
DAMAGE GROWTH (AND ARREST) IN VISCOELASTIC LAMINATES. A SIG-
NIFICANT AMOUNT OF PROGRESS WAS MADE THIS YEAR WITH THE
DEVELOPMENT OF GENERALIZED J-INTEGRAL THEORY FOR NONLINEAR
VISCOELASTIC MEDIA. EMPHASIS IS NOW ON APPLYING THIS THEORY
TO PROBLEMS INVOLVING ELASTIC AND VISCOELASTIC INTERACTIONS
BETWEEN CONSTITUENT MATERIALS, SUCH AS FIBERS AND RESIN, AND
ON ACCOUNTING FOR A GLASS-TO-RUBBER PHASE TRANSITION AT CRACK
TIPS IN THE RESIN.

AFWAL-TR-82-4007

CURE PROCESS MODEL OF EPOXY MATRIX COMPOSITES

GEORGE S. SPRINGER
ALFRED C. LOOS

DEPARTMENT OF MECHANICAL ENGINEERING
The University of Michigan

OBJECTIVE

TO CONSTRUCT A MODEL WHICH PROVIDES:

- 1) THE OPTIMUM CURE CYCLE
 - a) CURE TEMPERATURE AS A FUNCTION OF TIME
 - b) CURE PRESSURE AS A FUNCTION OF TIME

OPTIMUM CURE CYCLE RESULTS IN PARTS

- a) CURED UNIFORMLY
 - b) HAVING SPECIFIED RESIN CONTENT
 - c) HAVING MINIMUM VOID CONTENT
 - d) HAVING "BEST" PROPERTIES
 - e) CURED IN THE SHORTEST POSSIBLE TIME
- 2) EFFECTS OF MATERIAL PROPERTIES ON THE CURING PROCESS
 - 3) MANUFACTURING TOOL
 - a) INTERACTIVE MANUFACTURING
 - b) QUALITY CONTROL

THE PROBLEM

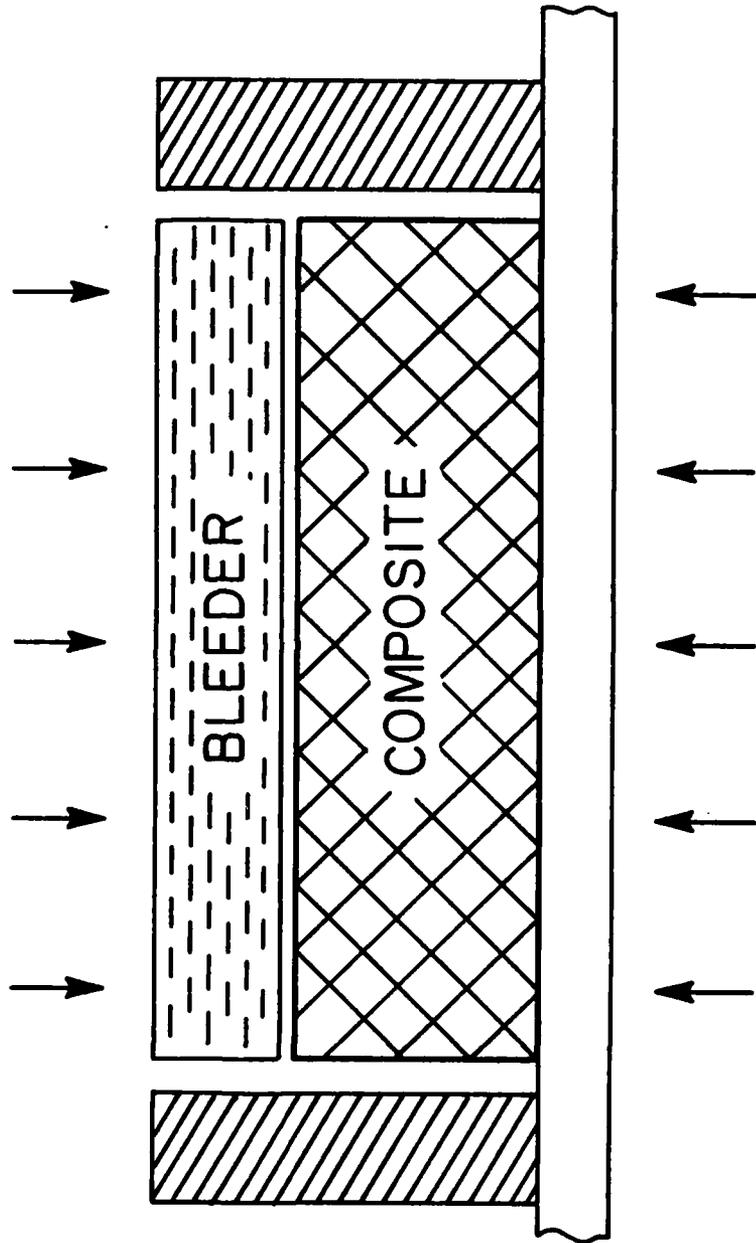
GIVEN:

- 1) GEOMETRY
- 2) MATERIAL PROPERTIES
- 3) CURE TEMPERATURE AS A FUNCTION OF POSITION AND TIME
- 4) CURE PRESSURE AS A FUNCTION OF POSITION AND TIME

FIND:

- 1) TEMPERATURE INSIDE MATERIAL AS FUNCTION OF POSITION AND TIME
- 2) DEGREE OF CURE OF THE RESIN AS FUNCTION OF POSITION AND TIME
- 3) VISCOSITY OF RESIN AS A FUNCTION OF POSITION AND TIME
- 4) RESIN FLOW INTO BLEEDER AS A FUNCTION OF TIME
- 5) RESIDUAL STRESSES

TEMPERATURE
PRESSURE



MODEL

1) THERMO-CHEMICAL

- a) TEMPERATURE AS FUNCTION OF POSITION AND TIME
- b) DEGREE OF CURE AS FUNCTION OF POSITION AND TIME
- c) VISCOSITY AS FUNCTION OF POSITION AND TIME

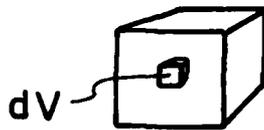
2) FLOW

- a) RESIN FLOW INTO BLEEDER AS FUNCTION OF TIME
- b) RESIN CONTENT OF COMPOSITE AS FUNCTION OF TIME

3) MECHANICAL

- a) RESIDUAL STRESSES AS FUNCTION OF POSITION

THERMO-CHEMICAL MODEL



GIVEN: T_{INITIAL}
 T_{CURE}
 GEOMETRY
 MATERIAL PROPERTIES

1) CONS. OF ENERGY

$$\underbrace{\left\{ \begin{array}{l} \text{RATE OF} \\ \text{CHANGE OF} \\ \text{E IN } dV \end{array} \right\}}_{(\rho \dot{c}_p)} = \underbrace{\left\{ \begin{array}{l} \text{NET RATE OF E} \\ \text{TRANSFERRED} \\ \text{INTO } dV \text{ BY} \\ \text{CONDUCTION} \end{array} \right\}}_{(k_T)} + \underbrace{\left\{ \begin{array}{l} \text{RATE OF E} \\ \text{LIBERATED (OR} \\ \text{ABSORBED) IN} \\ \text{dV BY CHEM.} \\ \text{REACTIONS} \end{array} \right\}}_{(\dot{H}_R = \frac{d\alpha}{dt} H_R)}$$

2) KINETIC MODEL

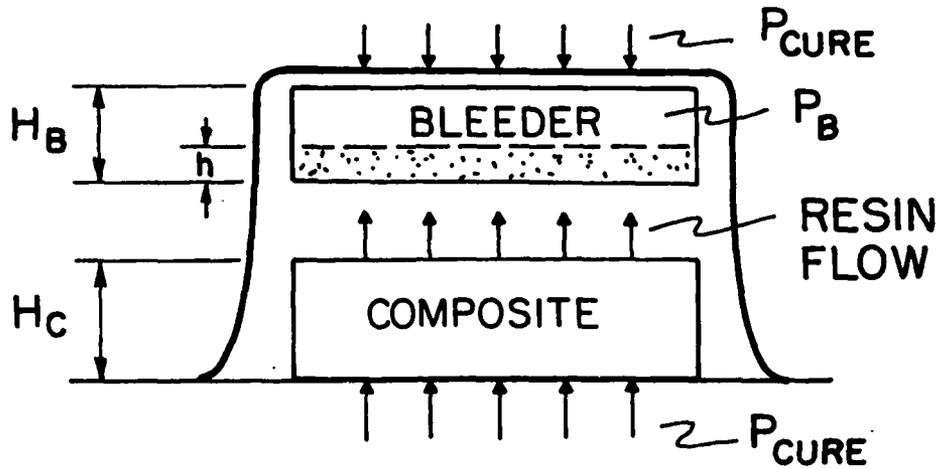
$$\frac{d\alpha}{dt} = \underbrace{(A_1 e^{-E_1/RT} + A_2 e^{-E_2/RT} \alpha^m)}_{(?) } (1-\alpha)^n$$

RESULT: TEMPERATURE
 VISCOSITY
 DEGREE OF CURE
 $\alpha = \int \frac{d\alpha}{dt} dt$

}

FUNCTIONS OF
 POSITION AND
 TIME

FLOW MODEL

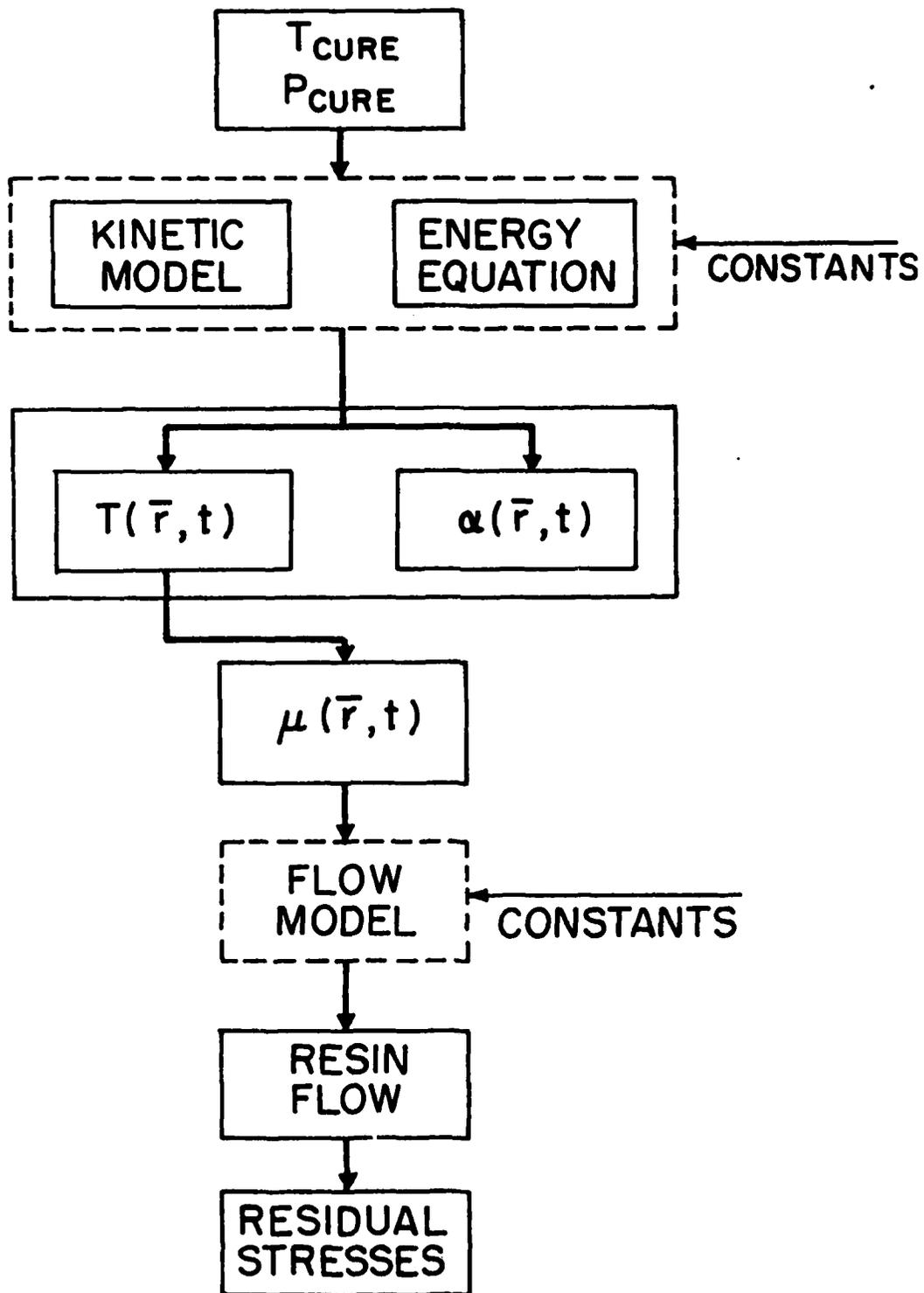


GIVEN: P_{CURE} , P_B , μ_C , μ_B , H_C , H_B , A

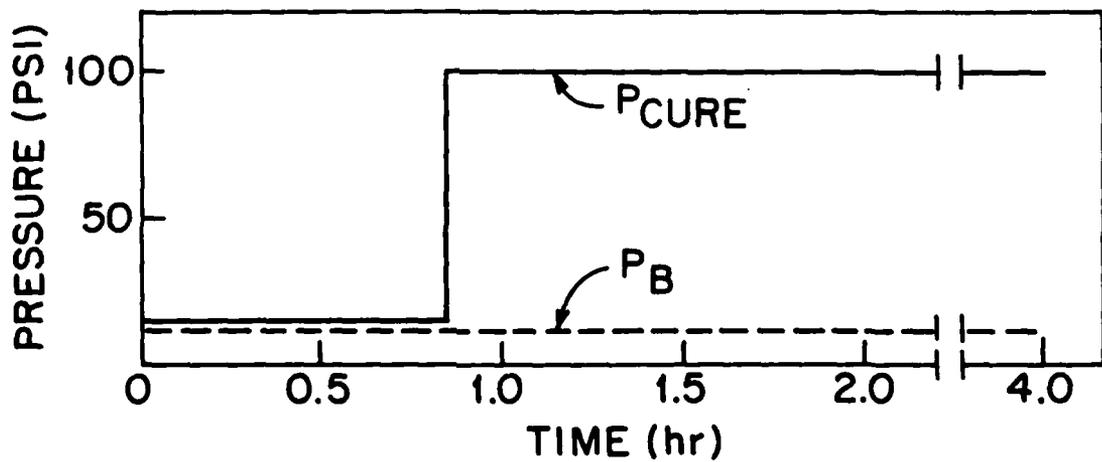
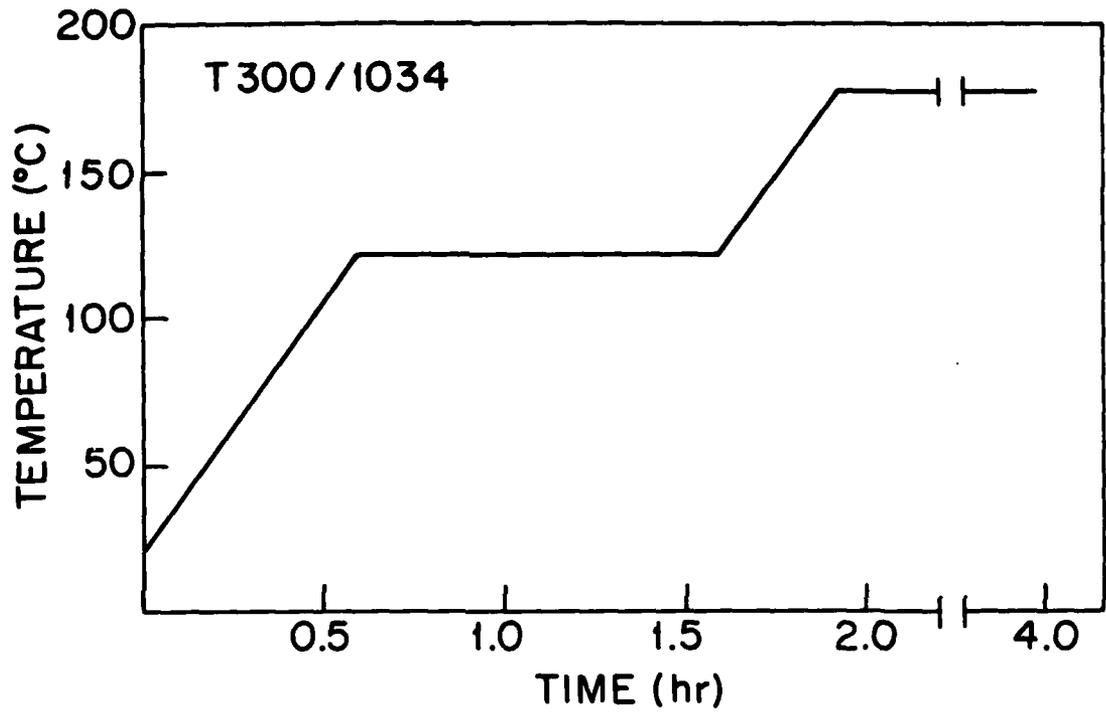
DARCY'S LAW (FLOW THROUGH POROUS MEDIUM)

$$Q = \frac{K_p A (P_2 - P_1)}{\mu t}$$

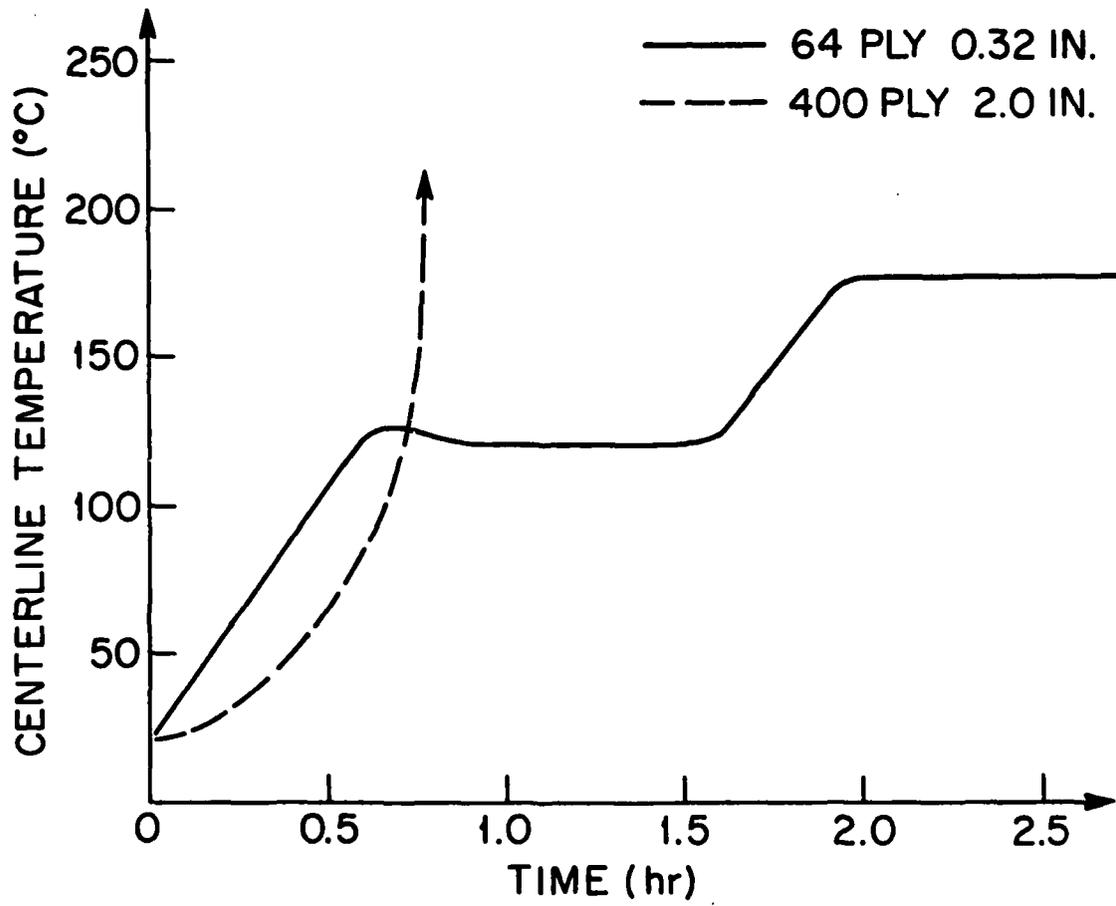
RESULT: RESIN FLOW: Q
 RESIN IN BLEEDER PLIES: h
 RESIN IN COMPOSITE



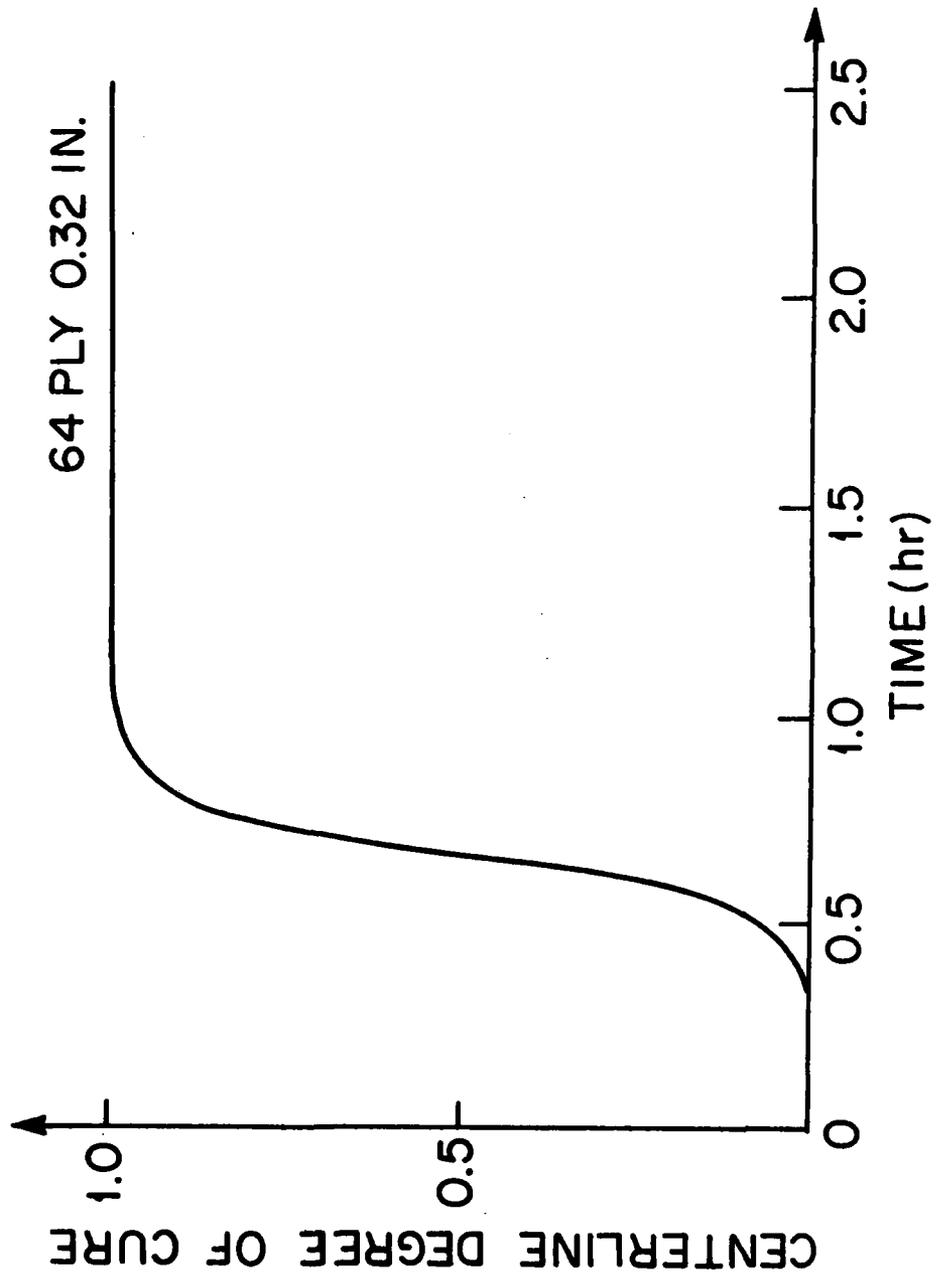
MANUFACTURER RECOMMENDED CURE CYCLE

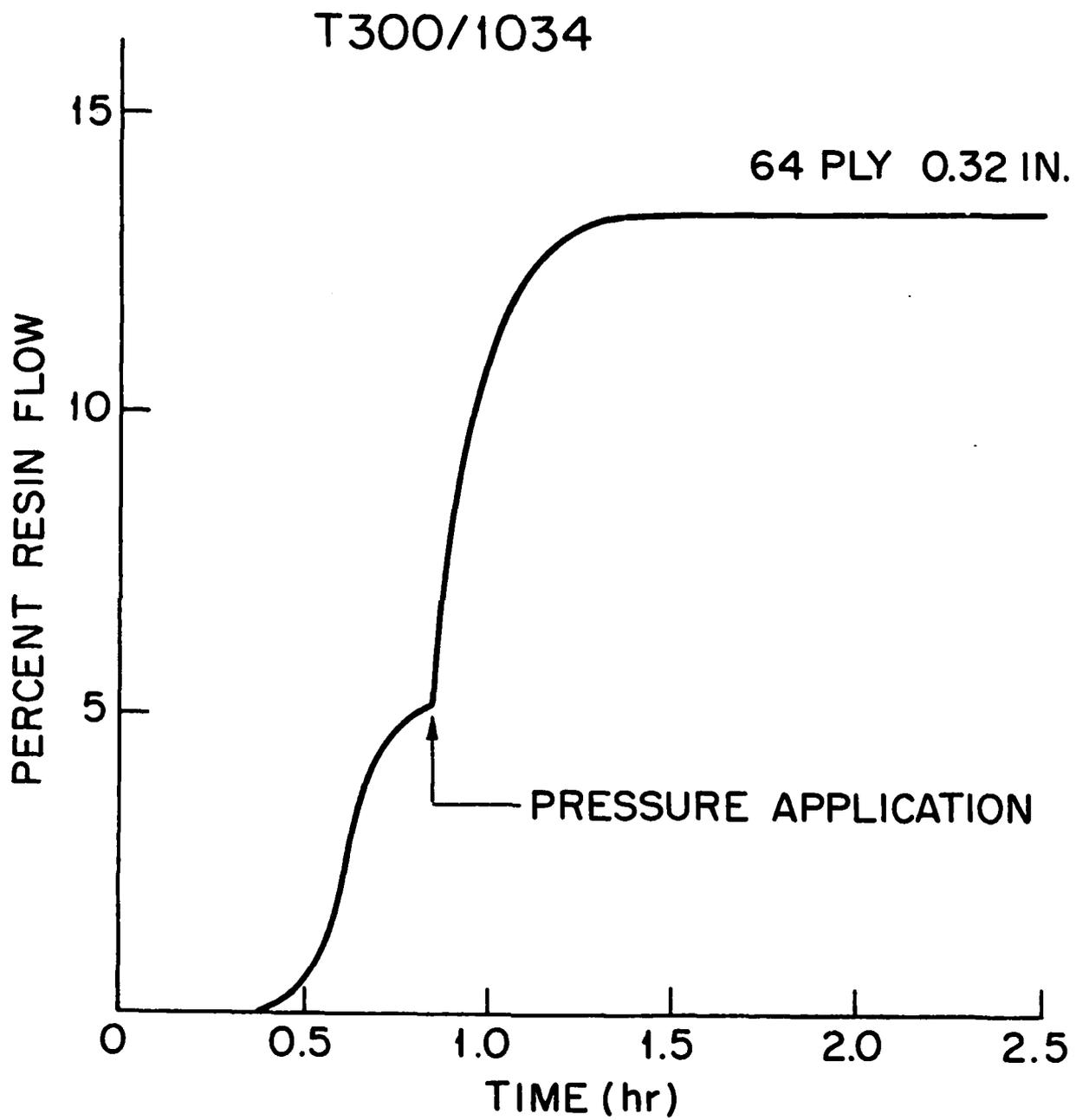


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SUMMARY

- 1) MODEL DEVELOPED WHICH PROVIDES:
 - a) TEMPERATURE
 - b) VISCOSITY
 - c) DEGREE OF CURE
 - d) RESIN FLOW
 - e) RESIDUAL STRESSES
- 2) IDENTIFIED MATERIAL PROPERTIES (CONSTANTS) NEEDED IN MODELING THE CURING PROCESS
- 3) DEVELOPED COMPUTER CODE FOR ONE DIMENSIONAL GEOMETRY
- 4) ESTABLISHED PROCEDURE FOR CURE CYCLE OPTIMIZATION

**IMPACT DAMAGE CONTAINMENT IN STRENGTH
CRITICAL GRAPHITE/EPOXY COMPRESSION STRUCTURES**

MARVIN D. RHODES

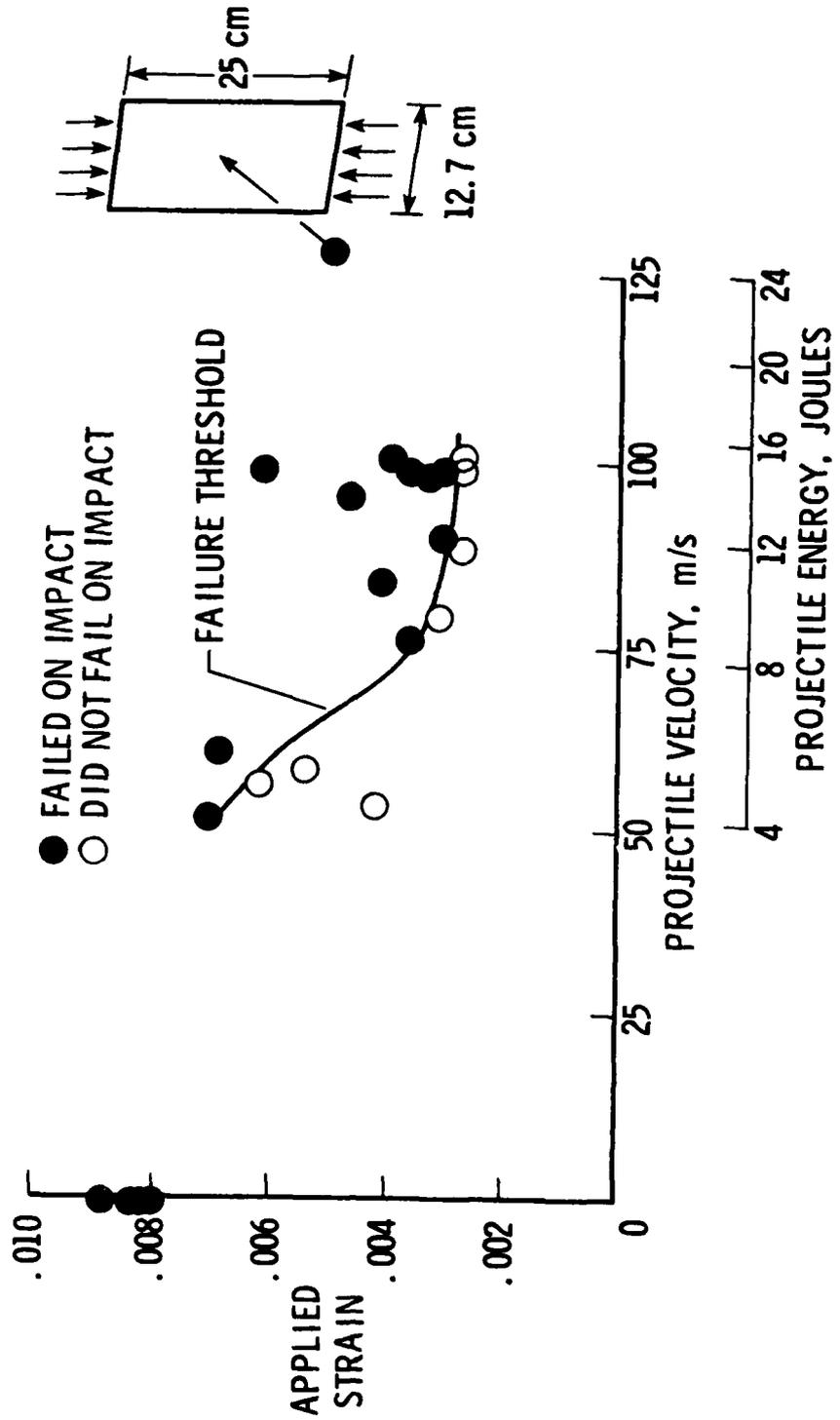
STRUCTURES AND DYNAMICS DIVISION

NASA - LANGLEY RESEARCH CENTER

OBJECTIVE

IDENTIFY RESIN PROPERTIES WHICH WILL
IMPROVE LOCAL DAMAGE TOLERANCE AND
EVALUATE THE BROADER STRUCTURAL ASPECTS
OF DAMAGE CONTAINMENT

EFFECT OF IMPACT DAMAGE ON COMPRESSION STRENGTH (±45/0₂/±45/0₂/±45/0/90)_{2S} TAPE



DAMAGE TOLERANT ASPECTS EVALUATED

<u>MATERIAL CHARACTERISTICS</u>	<u>CONFIGURATION DETAILS</u>	<u>DESIGN FOR DAMAGE</u>
● MATRIX RESINS	● DISCRETE STIFFNESS	● FAILURE PREDICTION
● TRANSVERSE REINFORCEMENT	● CROSS-SECTION TAILORING	
	● MECHANICAL FASTENING	

MATERIAL CHARACTERISTICS — MATRIX RESINS

NASA-INDUSTRY RESIN EVALUATION

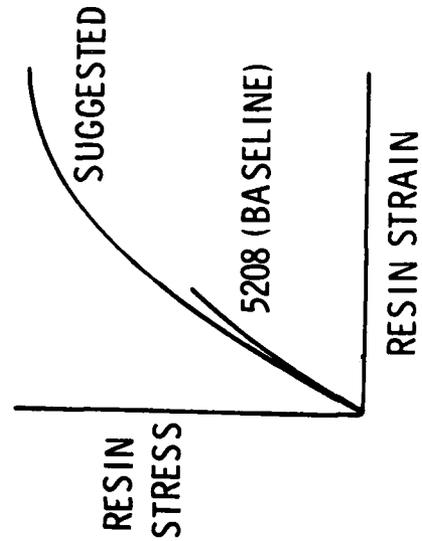
GUIDELINES

- IMPROVE DAMAGE TOLERANCE
- IGNORE PROCESSING AND ENVIRONMENTAL FACTORS
- FORMULATIONS MAY BE EXPERIMENTAL
- RECOMMEND PROCESSING CYCLE
- USE THORNEL 300 FIBER

PREPREG SUPPLIERS

- AIR LOGISTICS (1)
- AMERICAN CYANAMID (4)
- CIBA-GEIGY (7)
- FIBERITE (1)
- HEXCEL (3)
- NARMCO (5)
- U.S. POLYMERIC (2)
- VOLUME FRACTION VARIATION (3)

TOTAL (26)



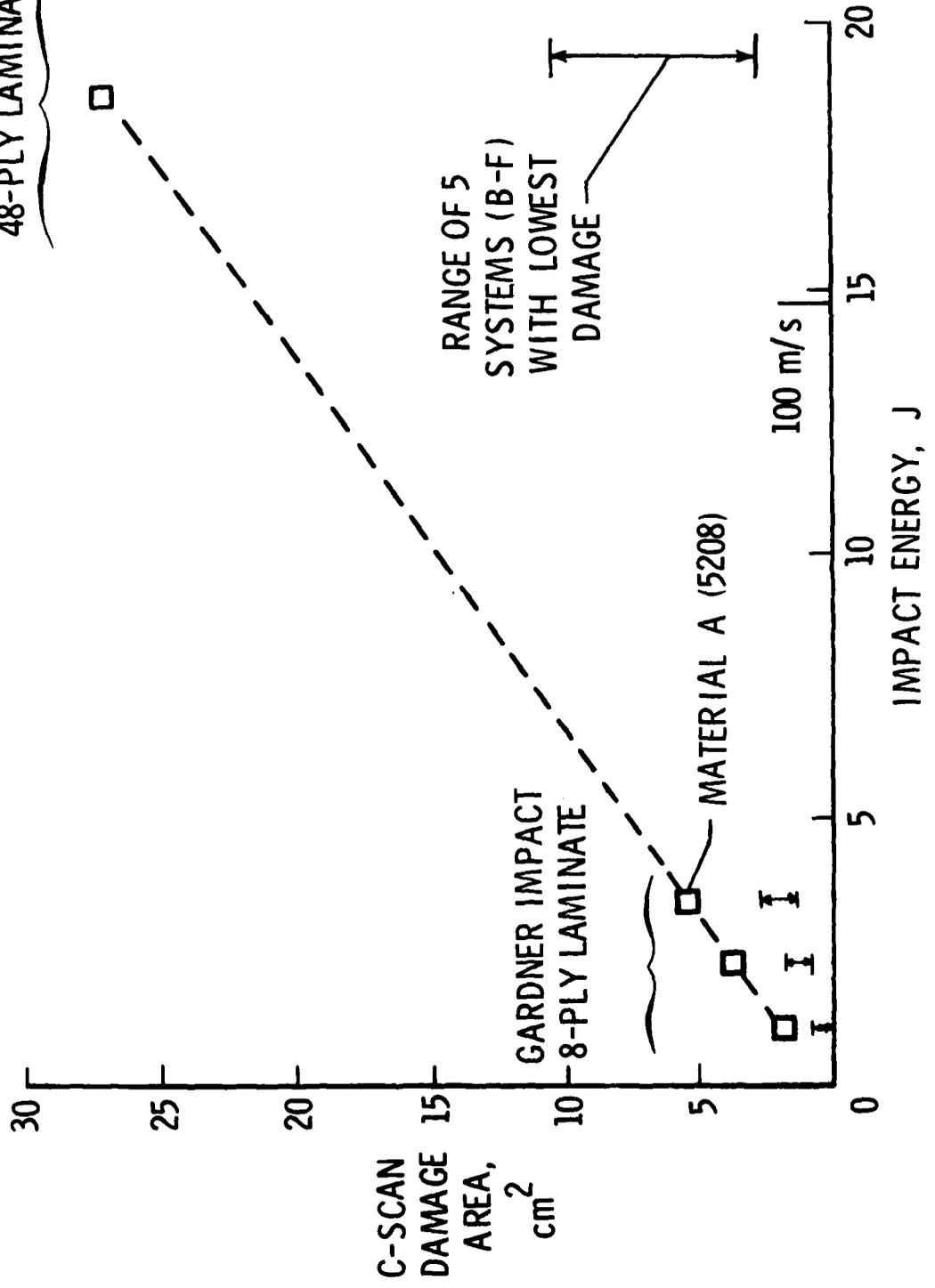
APPROACHES

- DIFFERENT EPOXY
- ELASTOMER ADDITIVE
- THERMOPLASTIC ADDITIVE
- VINYL ADDITIVE
- DIFFERENT CURING AGENTS

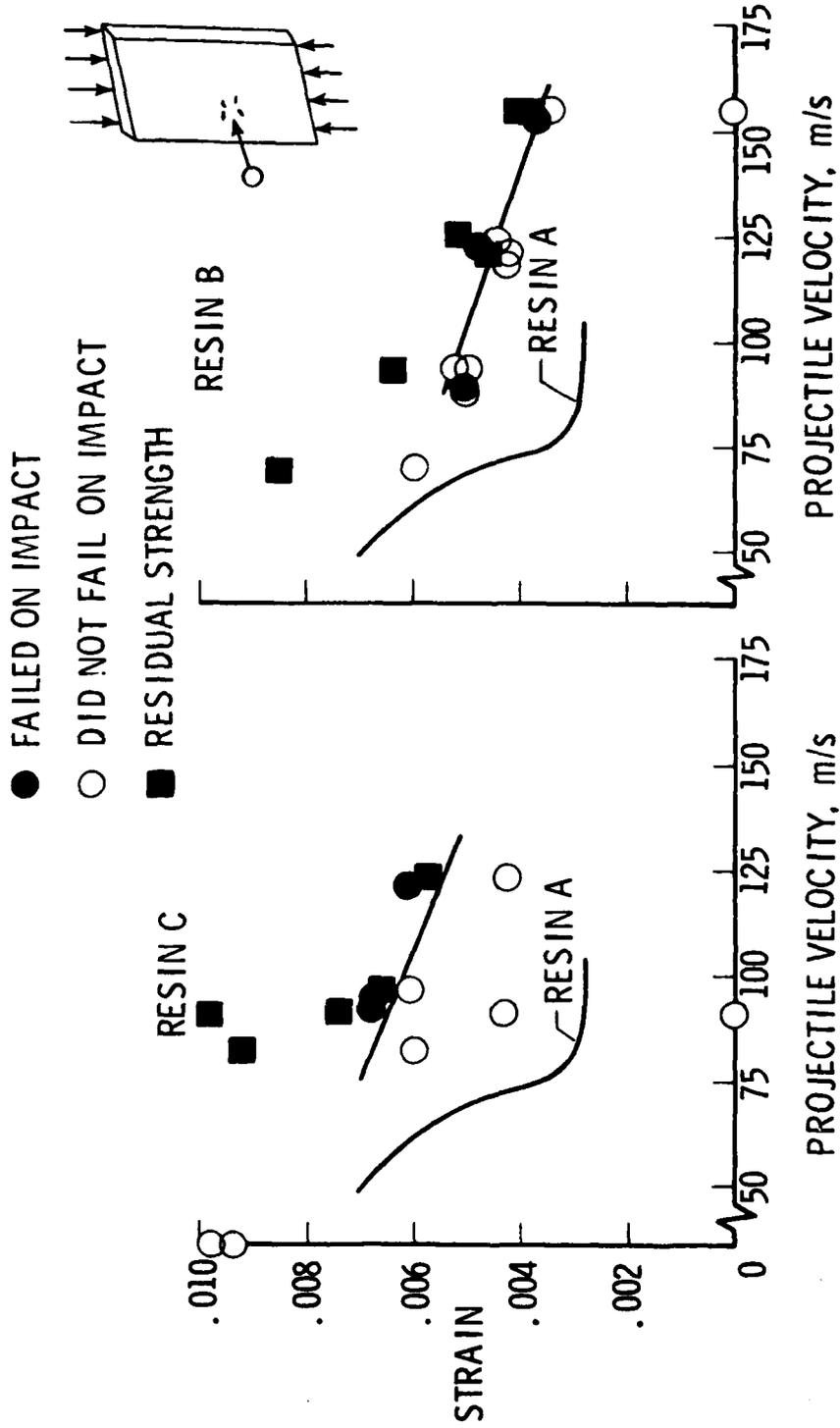
MATERIAL CHARACTERISTICS - MATRIX RESINS

EFFECT OF RESIN ON IMPACT DAMAGE AREA

PROJECTILE IMPACT
48-PLY LAMINATE

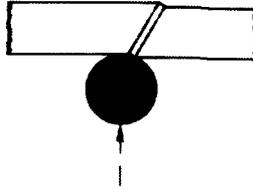


MATERIAL CHARACTERISTICS — MATRIX RESINS IMPACT IN COMPRESSION LOADED 48 PLY ORTHOTROPIC LAMINATES



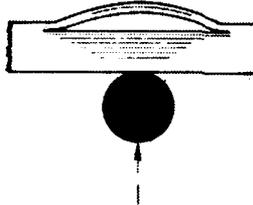
MATERIAL CHARACTERISTICS — MATRIX RESINS
IMPACT INITIATED COMPRESSION FAILURE MODES

TRANSVERSE SHEAR

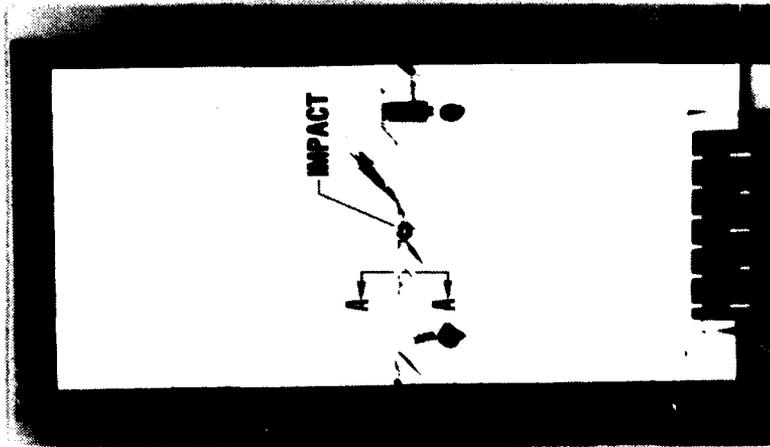


DAMAGE-TOLERANT RESIN

DELAMINATION

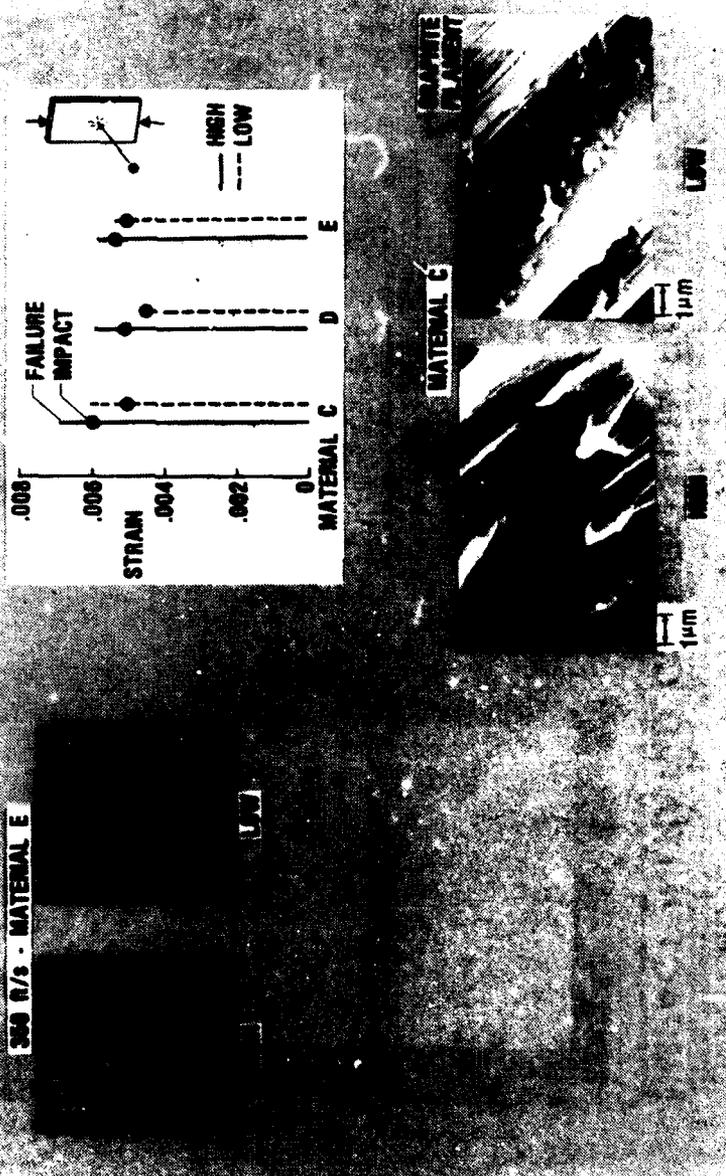


MATERIAL 1 (5206)



A-A

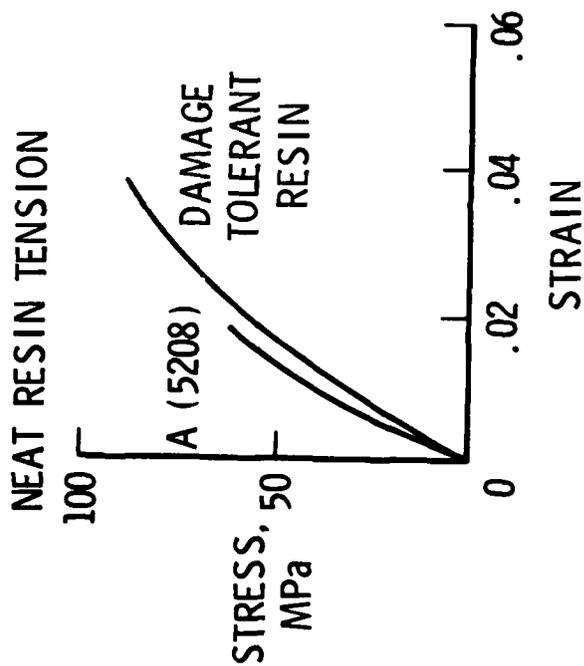
MATERIAL CHARACTERISTICS — MATRIX RESINS EFFECT OF RESIN VOLUME FRACTION



MATERIAL CHARACTERISTICS — MATRIX RESINS

DAMAGE TOLERANT RESIN PROPERTIES

MATERIAL	GENERIC CHEMISTRY			ADDITIVES
	BASE EPOXY	HARDENER		
(A)	(MY-720	+ AROMATIC AMINE	+)	—)
B	BISPHENOL A	+ ALIPHATIC AMINE	+)	THERMOPLASTIC
C	BISPHENOL A	+ ALIPHATIC AMINE	+)	VINYL MODIFIER
D	BISPHENOL A	+ ACIPHATIC AMINE	+)	THERMOPLASTIC
E	BISPHENOL A	+ NONAROMATIC AMINE	+)	ELASTOMER
F	BISPHENOL A	+ DILYANAMIDE	+)	ELASTOMER

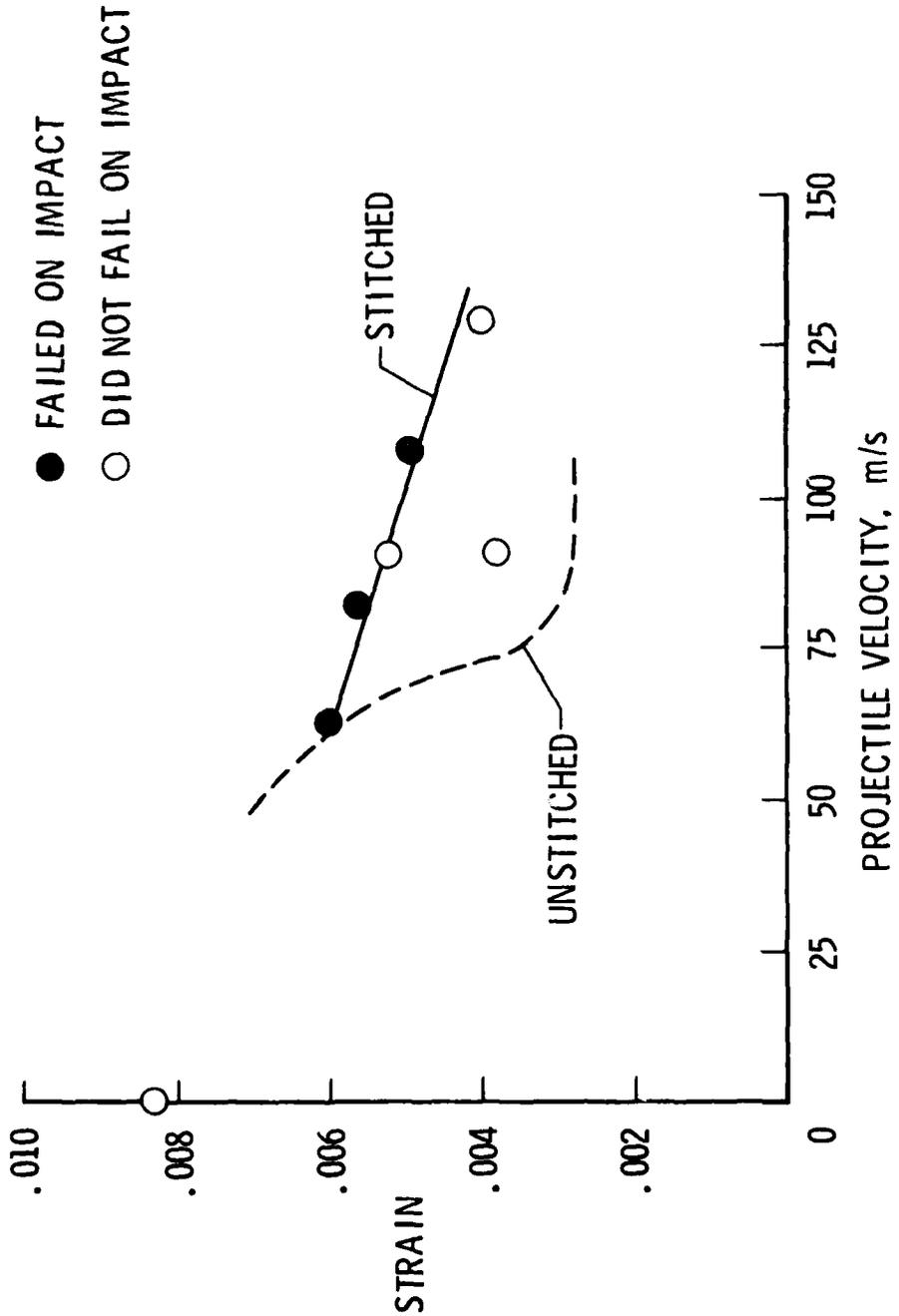


- DESIRABLE RESIN PROPERTIES
- TENSION STRENGTH > 70 MPa
 - TENSION STRAIN > 4%
 - TENSION MODULUS > 3 GPa

RESIN VOLUME FRACTION ≥ 40%

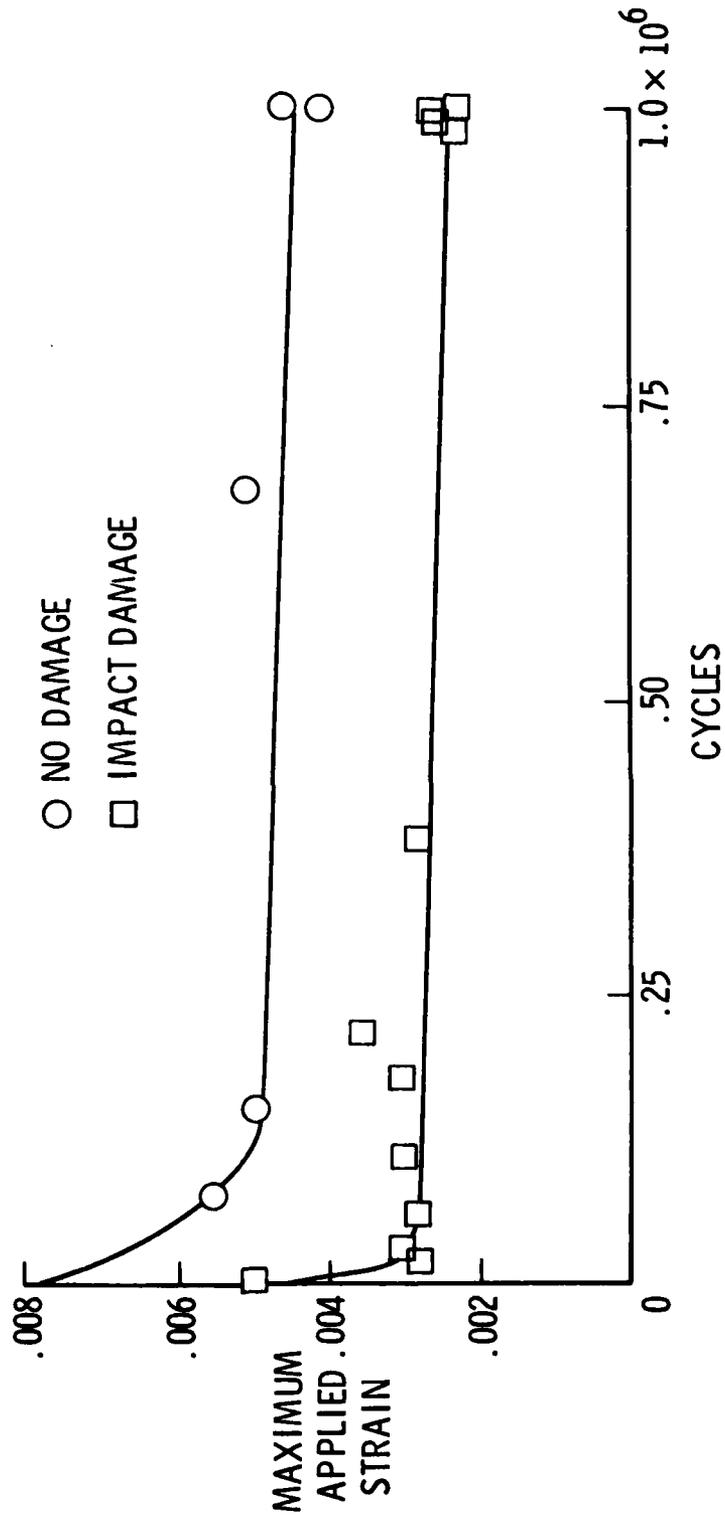
MATERIAL CHARACTERISTICS -- TRANSVERSE REINFORCEMENT

IMPACT TESTS ON MATERIAL A

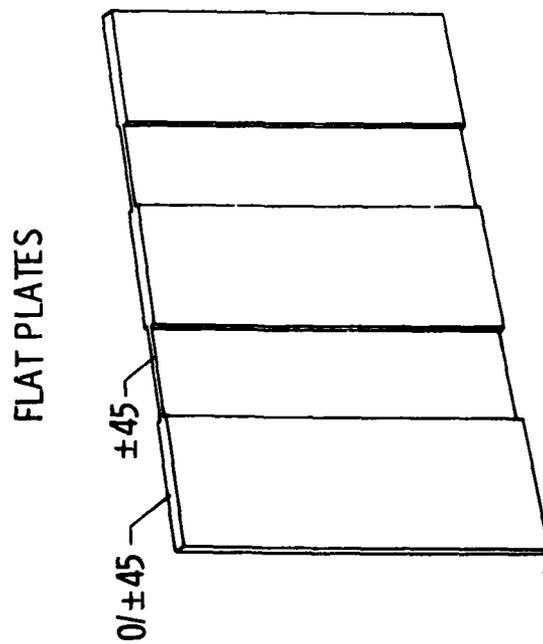
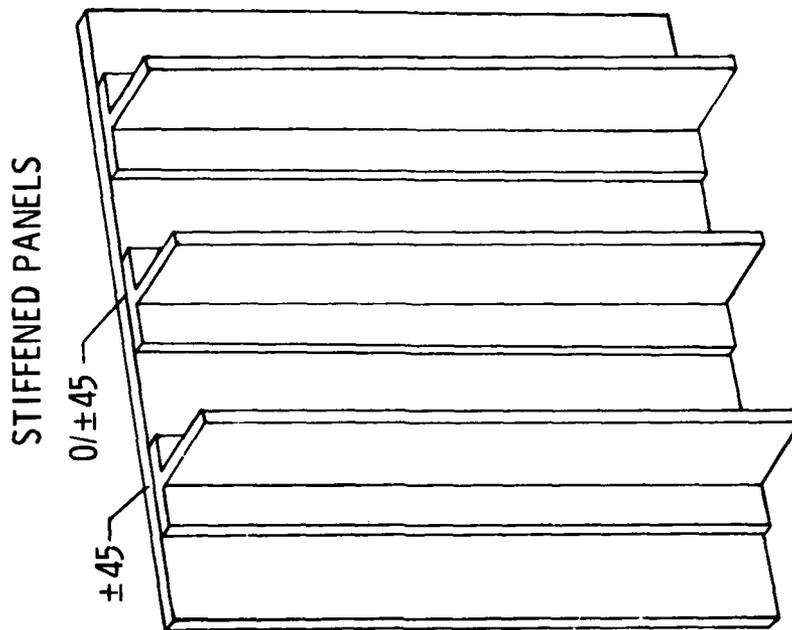


MATERIAL CHARACTERISTICS - TRANSVERSE REINFORCEMENT

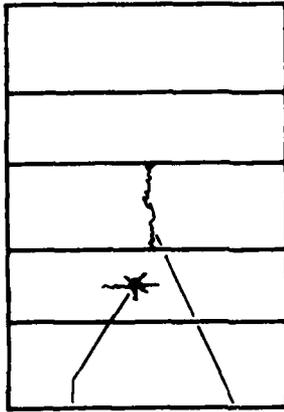
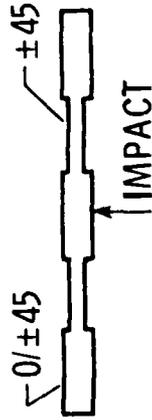
CYCLIC COMPRESSION LOADING OF STITCHED PANELS



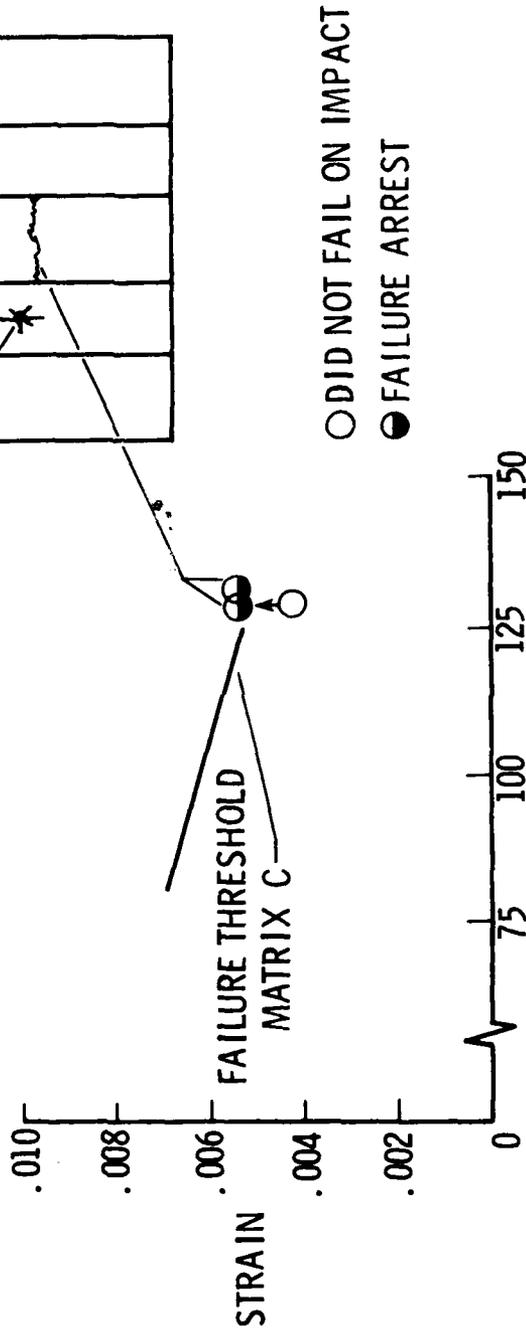
CONFIGURATION DETAILS -- DISCRETE STIFFNESS DESIGN



CONFIGURATION DETAILS – DISCRETE STIFFNESS DESIGN

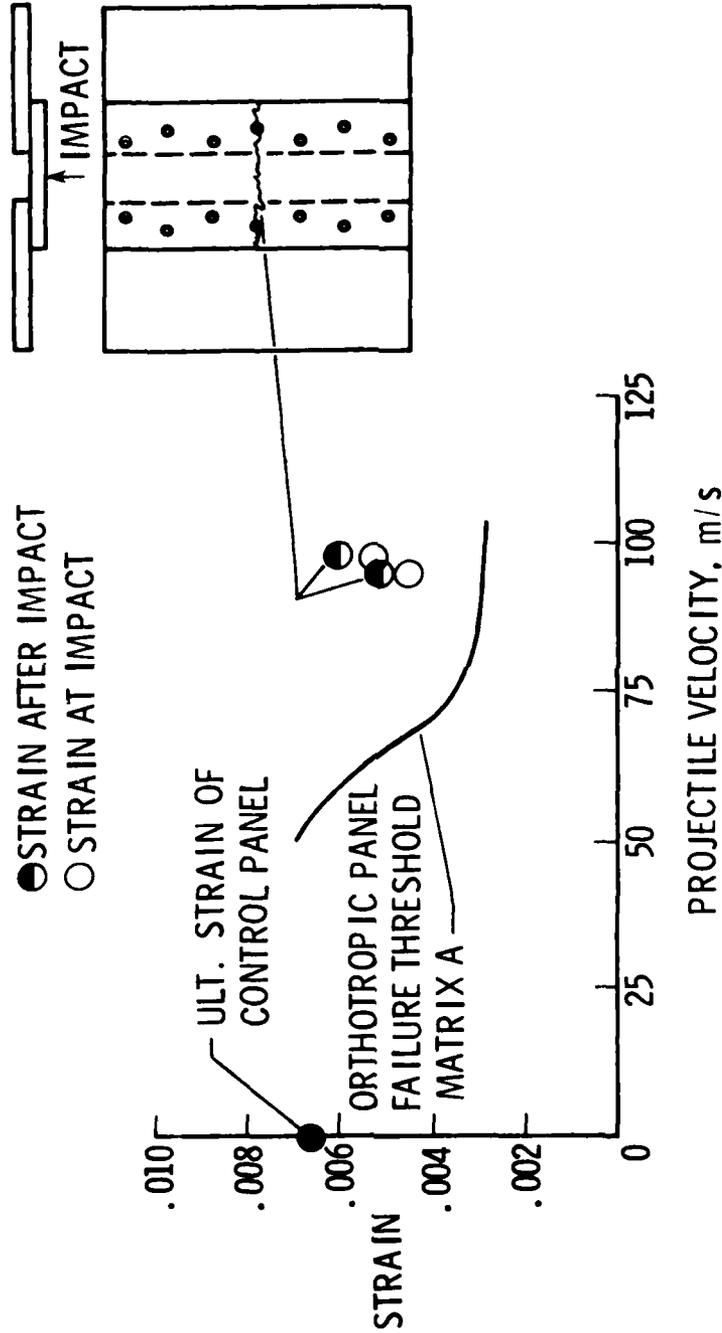


PRIOR DAMAGE
EASILY DETECTABLE

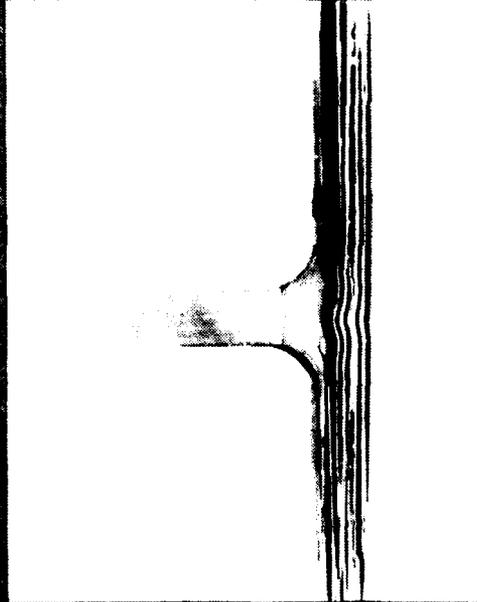


○ DID NOT FAIL ON IMPACT
● FAILURE ARREST

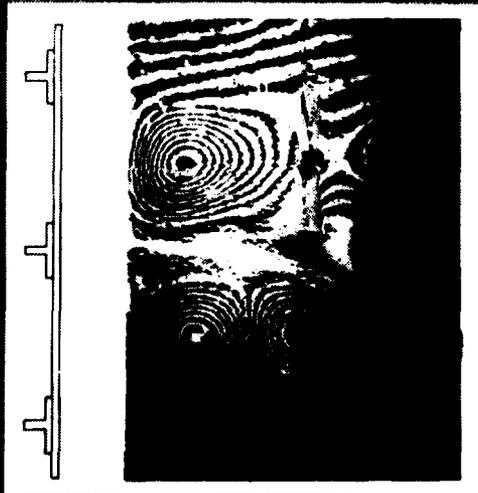
CONFIGURATION DETAILS -- MECHANICAL FASTENING



CONFIGURATION DETAILS — CROSS-SECTION TAILORING



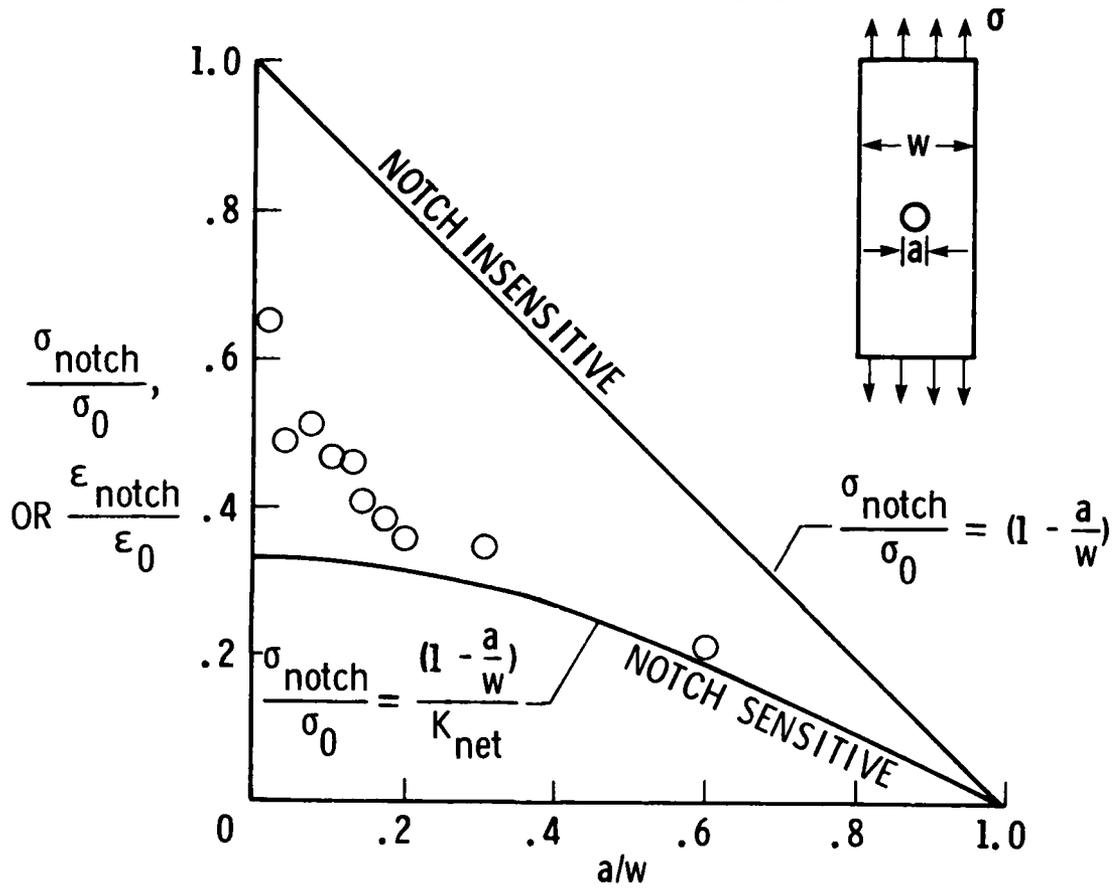
INTEGRAL STIFFENER



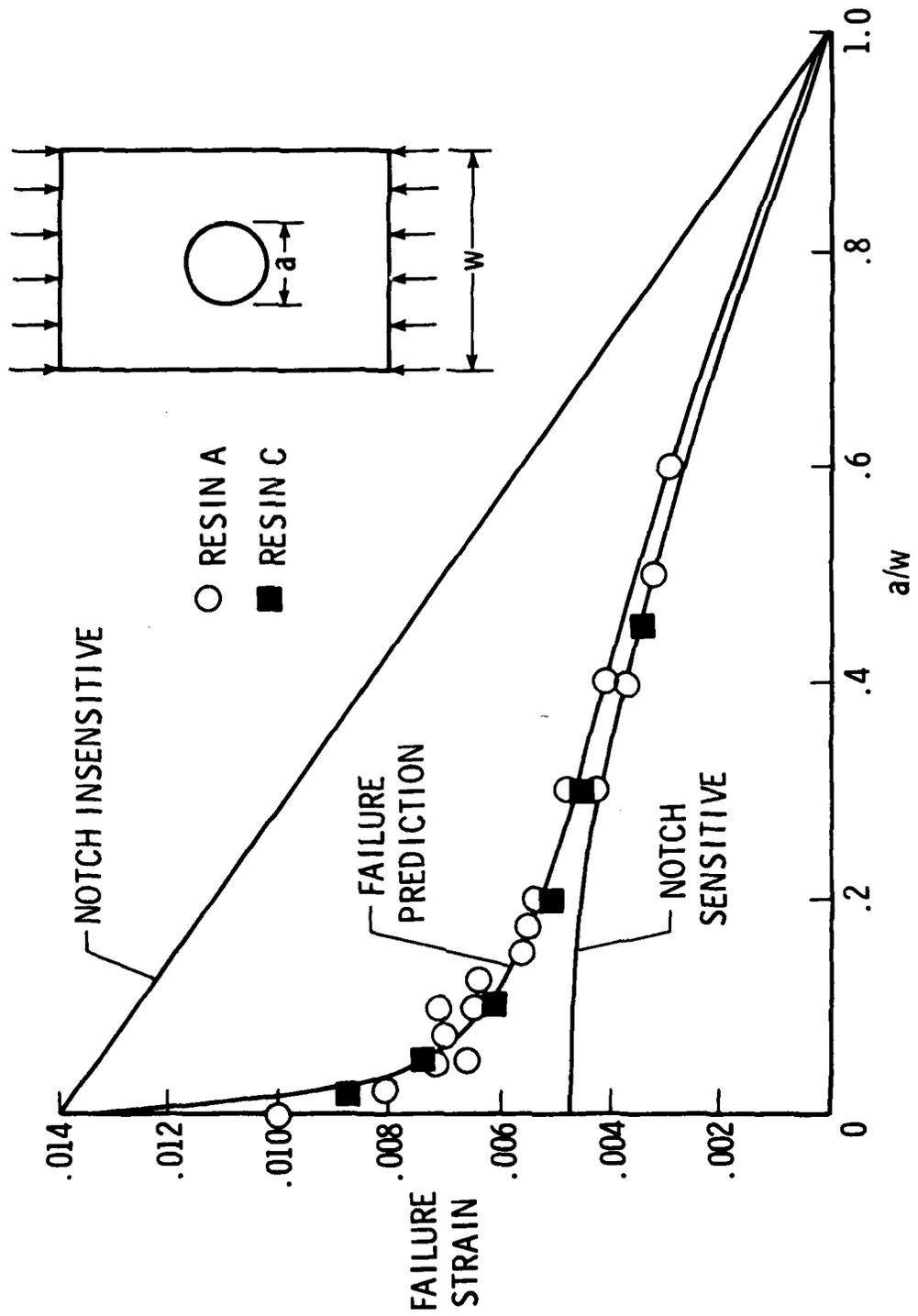
ATTACHED STIFFENER

DESIGN FOR DAMAGE — FAILURE PREDICTION

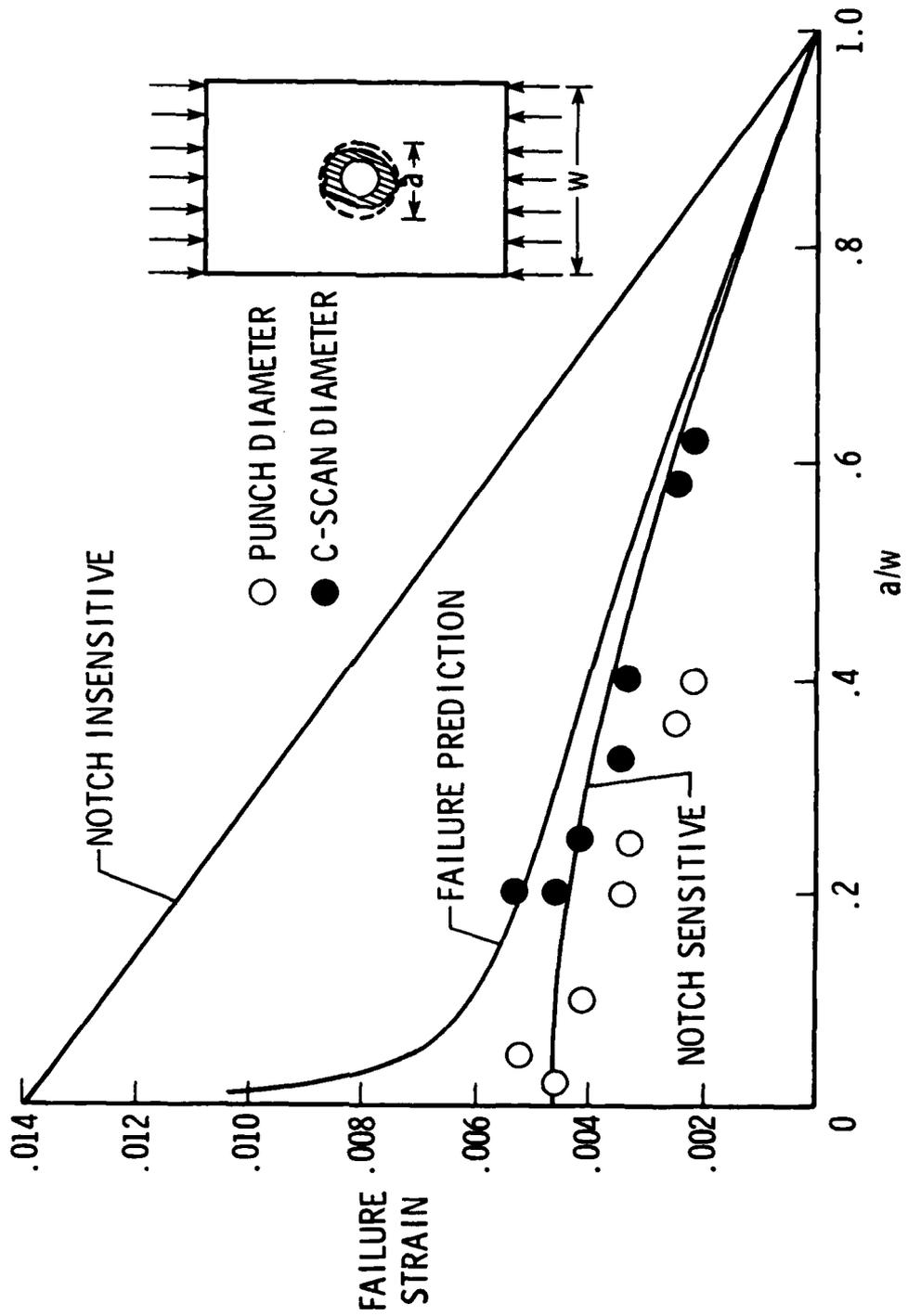
LIMITING VALUES FOR FAILURE



DESIGN FOR DAMAGE - FAILURE PREDICTION



DESIGN FOR DAMAGE – FAILURE PREDICTION



SUMMARY

- A NUMBER OF MATRIX MATERIALS HAVE BEEN EVALUATED AND NEAT RESIN REQUIREMENTS FOR A DAMAGE TOLERANT SYSTEM HAVE BEEN DEFINED
- CONFIGURATION ASPECTS CAPABLE OF CONTROLLING GROWTH AND/OR ARRESTING DAMAGE PROPAGATION HAVE BEEN EVALUATED
- PRELIMINARY STUDIES HAVE BEEN CONDUCTED TO DEVELOP FAILURE PREDICTION TECHNIQUES TO ALLOW CONSIDERATION OF DAMAGE TOLERANCE IN THE DESIGN PHASE
- HIGH DESIGN ULTIMATE STRAINS IN COMPOSITE COMPRESSION STRUCTURES WILL BE ACHIEVABLE THROUGH A COMBINATION OF IMPROVED MATERIALS AND DESIGN CONSIDERATIONS

AEROELASTIC TAILORING
OF
COMPOSITES

W. A. ROGERS
GENERAL DYNAMICS
FORT WORTH DIVISION

AND

M. H. SHIRK
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
FLIGHT DYNAMICS LABORATORY

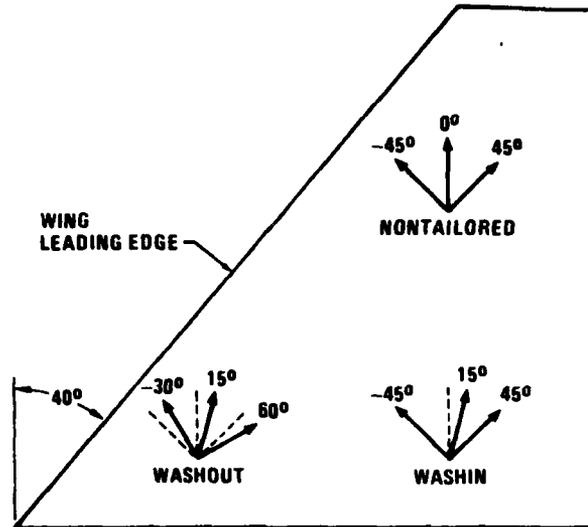
OBJECTIVES

- GENERATE WIND TUNNEL TEST DATA USING STATIC AEROELASTIC AND FLUTTER MODELS TO:
 - EVALUATE CURRENT ANALYTICAL PROCEDURES USED TO PREDICT AEROELASTIC TAILORING BENEFITS
 - DEVELOP AEROELASTIC AND FLUTTER MODEL SCALING AND FABRICATION TECHNIQUES
- DEMONSTRATE BENEFITS ATTAINABLE THROUGH AEROELASTIC TAILORING
 - REDUCED DRAG AT MANEUVER CONDITIONS (WASHOUT DESIGN)
 - INCREASED LIFT-CURVE SLOPE (WASHIN DESIGN)

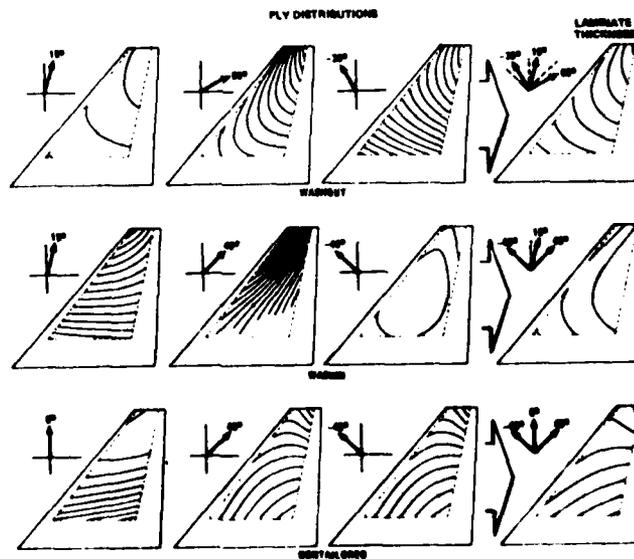
CONCLUSIONS

- AEROELASTIC TAILORING DESIGN OBJECTIVES WERE MET FOR EACH OF THREE TAILORED WINGS
- WASHOUT WING PRODUCED SIGNIFICANT REDUCTION IN TRANSONIC DRAG DUE TO LIFT
- WASHIN WING PROVIDED INCREASED LIFT-CURVE SLOPE
- A COMPREHENSIVE SET OF FORCE, PRESSURE, AND DEFLECTION DATA WERE OBTAINED IN THE WIND TUNNEL FOR THE AEROELASTIC MODELS FOR MACH 0.6 TO 1.2
- BENEFICIAL DYNAMIC CHARACTERISTICS OF TAILORING WERE DEMONSTRATED THROUGH WIND TUNNEL FLUTTER TESTS

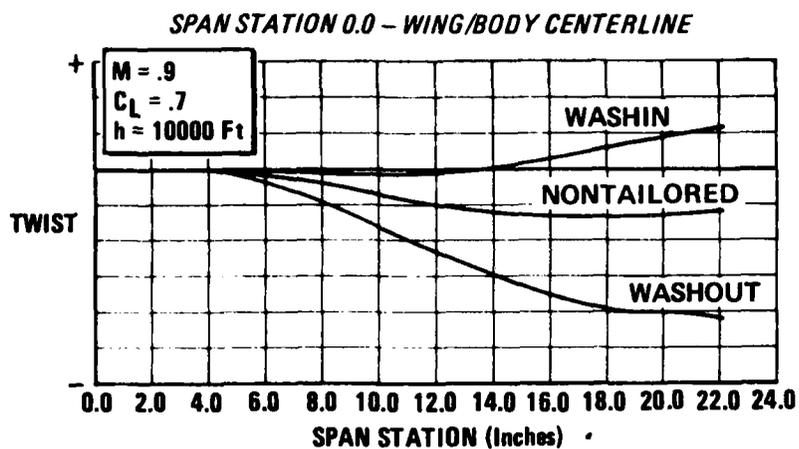
PLY ORIENTATIONS FOR AEROELASTIC DESIGNS



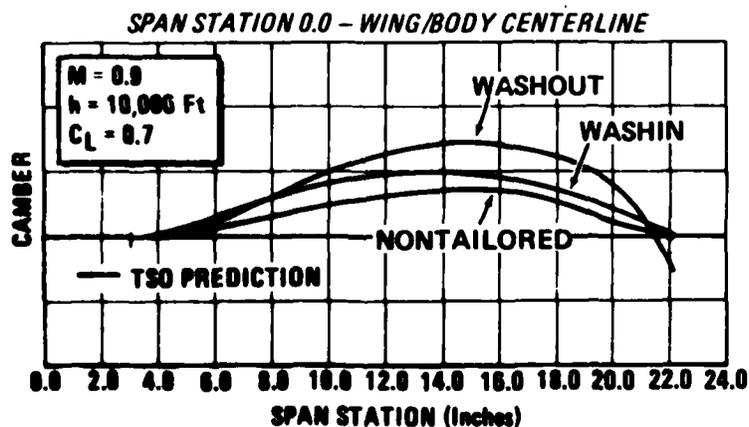
PLY DISTRIBUTIONS FOR FULL SCALE DESIGNS



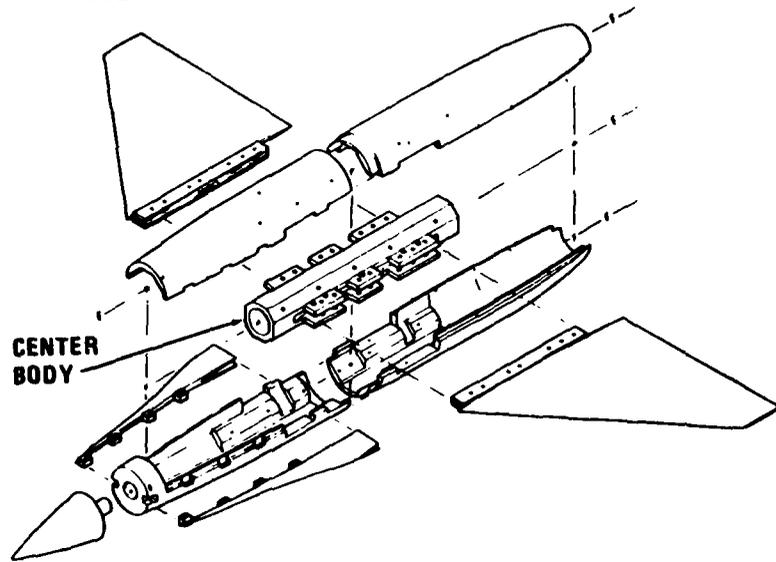
MODEL TWIST DISTRIBUTIONS AT DESIGN CONDITION



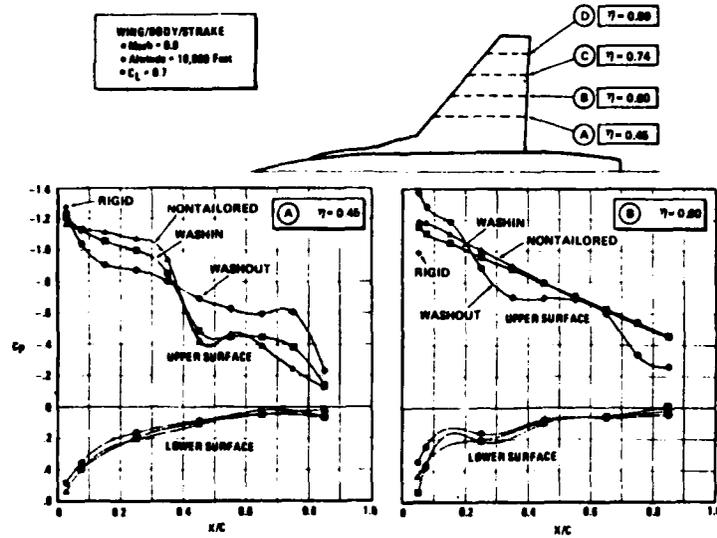
MODEL CAMBER DISTRIBUTIONS AT DESIGN CONDITION



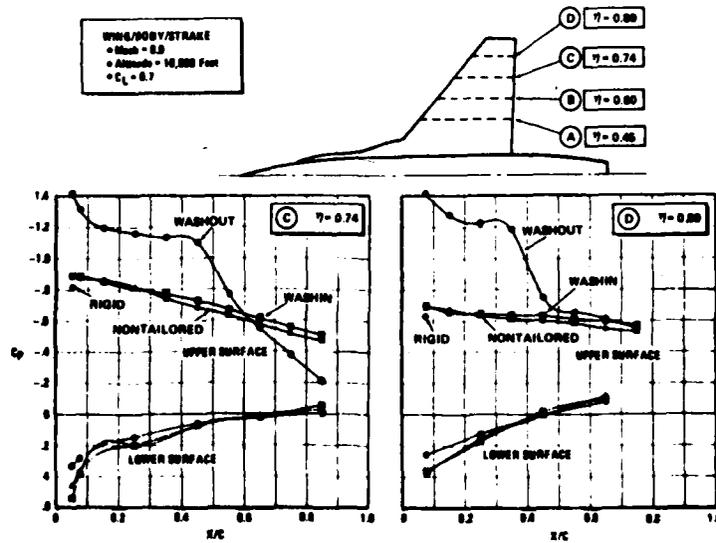
AEROELASTIC WIND TUNNEL MODEL



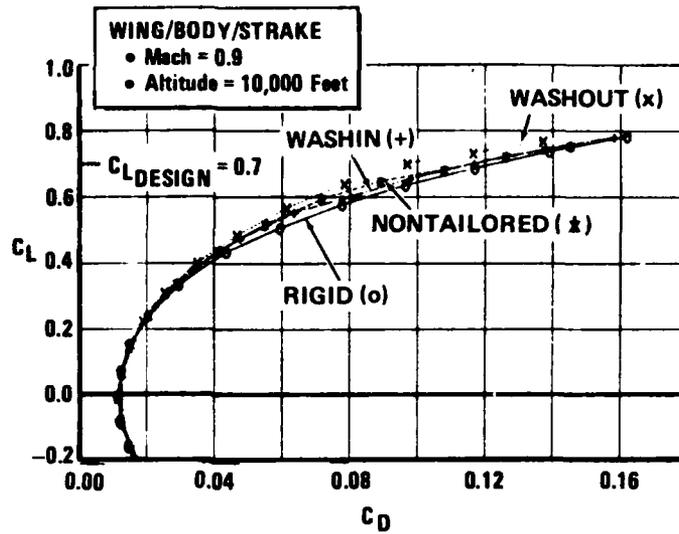
PRESSURE DISTRIBUTIONS AT DESIGN CONDITION



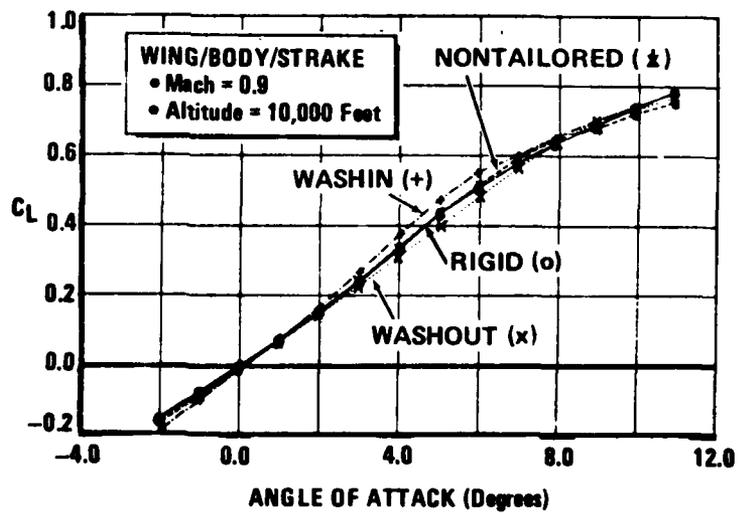
PRESSURE DISTRIBUTIONS AT DESIGN CONDITION (Cont'd)



DRAG CHARACTERISTICS AT DESIGN CONDITION



LIFT CHARACTERISTICS AT DESIGN CONDITION

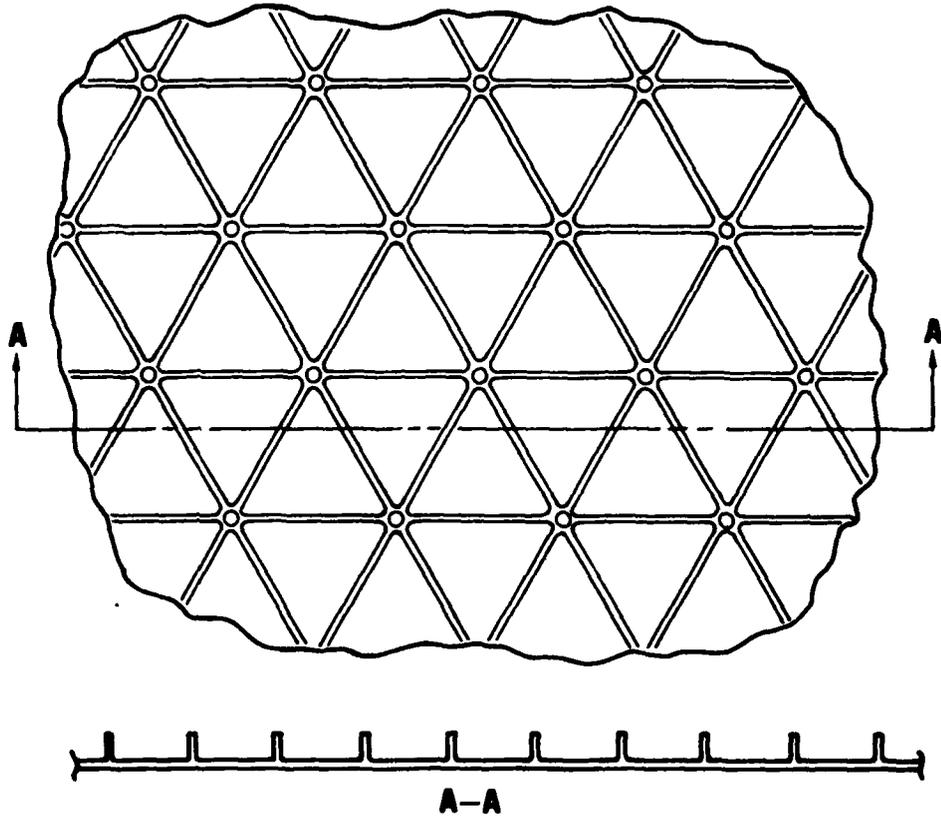


**DAMAGE TOLERANCE OF CONTINUOUS FILAMENT
ISOGRID STRUCTURES**

**Lawrence W. Rehfield and Ambur D. Reddy
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332**



This work was sponsored by AFOSR under Grant AFOSR-81-0056



ISOGRID GEOMETRIC CONFIGURATION

DAMAGE TOLERANCE

A STRUCTURE IS DAMAGE TOLERANT IF IT IS ABLE TO PERFORM ITS MISSION AFTER SUSTAINING A PRESCRIBED FORM OF DAMAGE.

OBJECTIVES

INVESTIGATE THE EFFECT OF RIB DAMAGE ON

- . COMPRESSIVE BUCKLING BEHAVIOR
- . DYNAMIC BEHAVIOR

SUMMARY OF PREVIOUS WORK

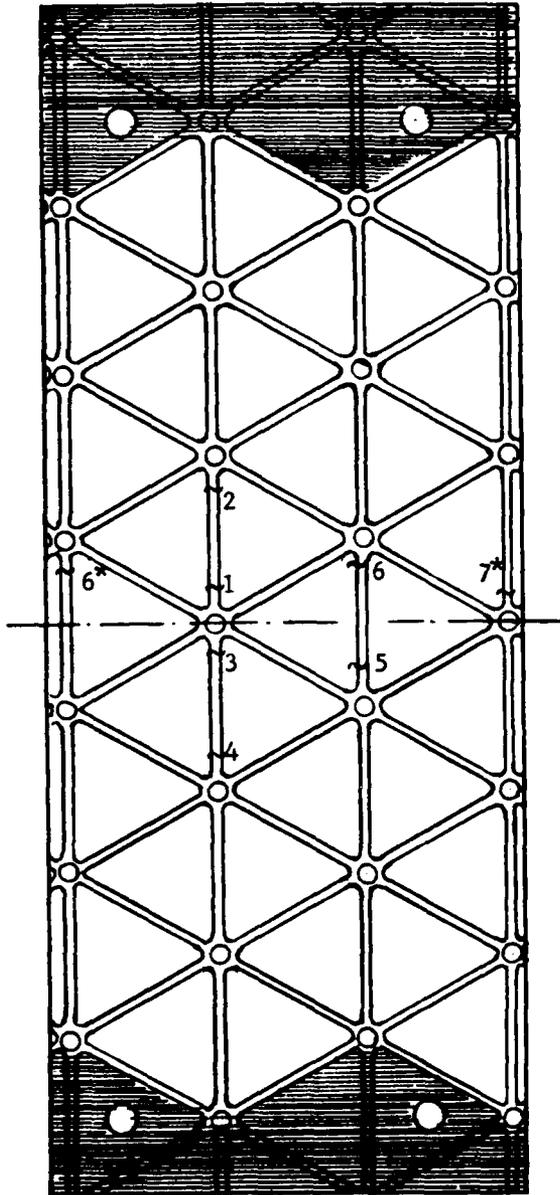
- . DESIGN AND MANUFACTURE OF FLAT PANELS
- . COMPRESSIVE BUCKLING TESTS OF LARGE AND SMALL
FLAT PANELS AS WIDE COLUMNS
- . EXTENSIVE ELEMENT TEST PROGRAM
- . CORRELATION STUDY

BENDING FAILURE MODE

RIB FRACTURES AT THE TENSION SURFACE NEAR A NODE. CRACK PROPAGATES THROUGHOUT THE RIB DEPTH TO THE SKIN. THEN DISBONDING OCCURS.

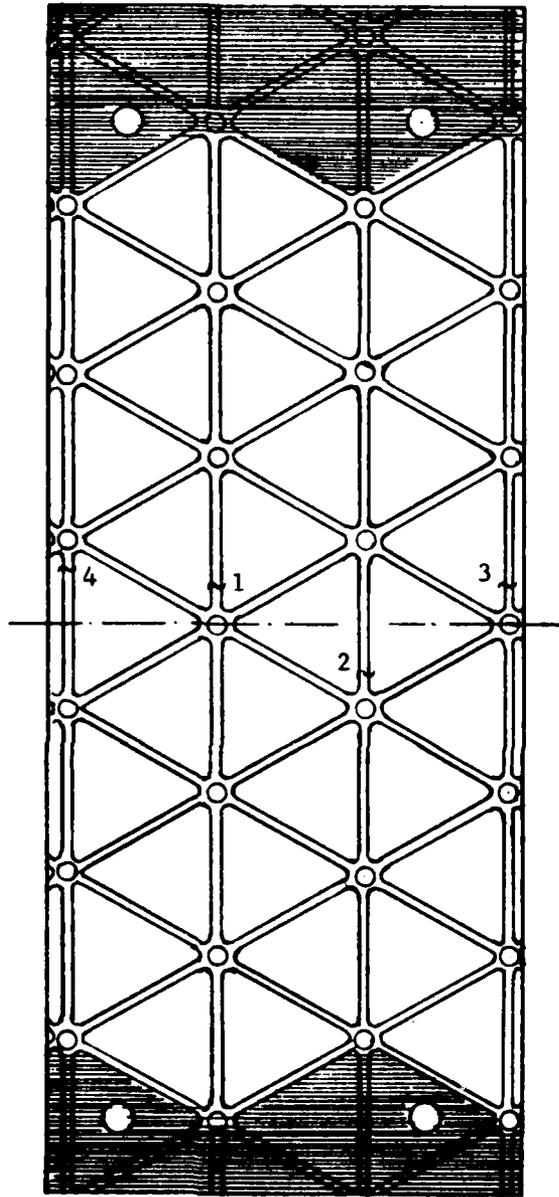
OVERVIEW

- BUCKLING RESISTANCE IS ESTABLISHED FOR THE UNDAMAGED STRUCTURE
- BENDING FAILURE IS SIMULATED BY RIB BREAKS NEAR NODES
- BUCKLING RESISTANCE DEGRADATION WITH PROGRESSIVE DAMAGE DETERMINED
- DYNAMIC TEST DATA AT EACH DAMAGE LEVEL GENERATED



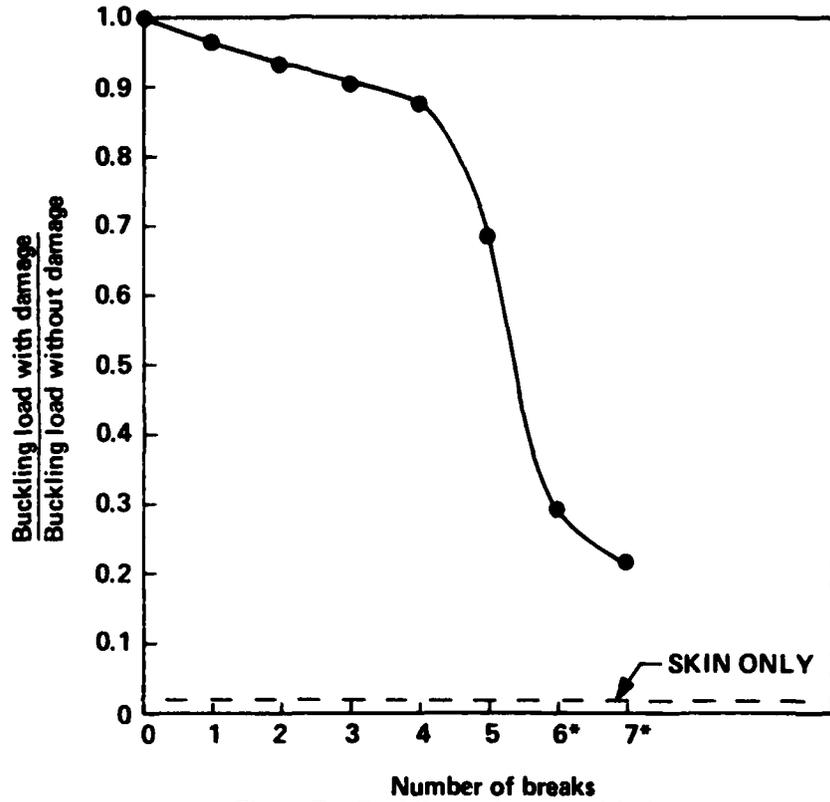
~ Denotes rib break.
Numbers indicate sequence
of break creation

SMALL PANEL - SERIES FAILURE

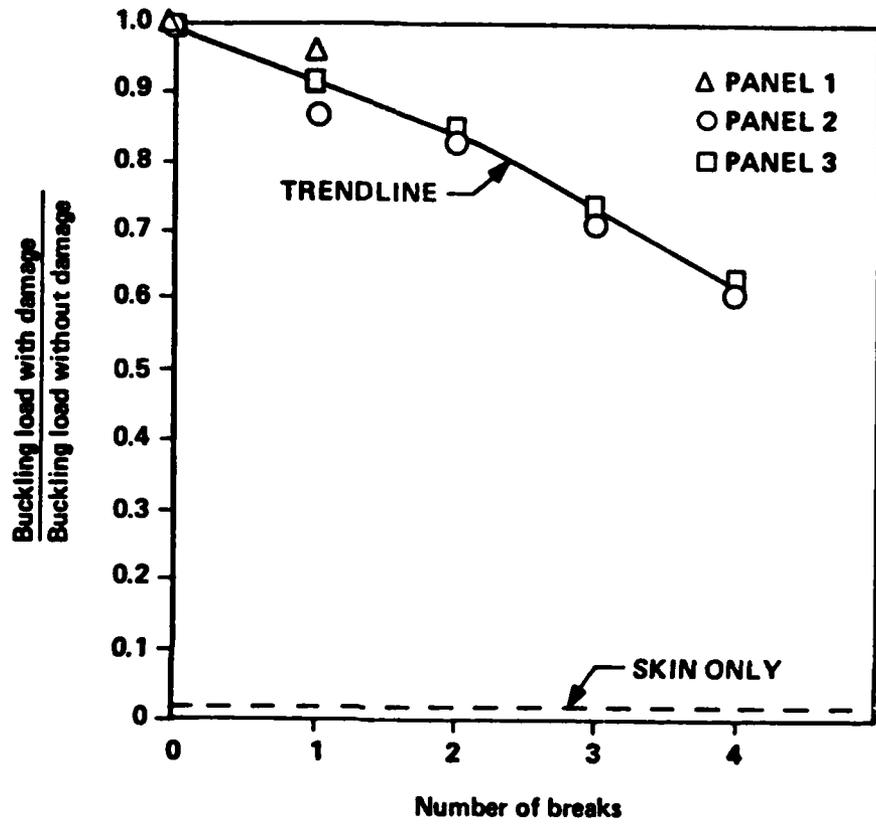


~ Denotes rib break.
Numbers indicate sequence of
break creation.

SMALL PANEL - PARALLEL FAILURE



Number of breaks
Figure 7. Buckling resistance with damage—
Small panel



Buckling Resistance with Damage - Small Panel

CONCLUSIONS

- o A HIGH DEGREE OF DAMAGE TOLERANCE IS
DEMONSTRATED.

- o FINITE ELEMENT SIMULATIONS OF BEHAVIOR
OF DAMAGED PANELS AGREE WITH EXPERIMENTAL
OBSERVATIONS.

AFWAL-TR-82-4007

SPACE ENVIRONMENTAL EFFECTS
ON POLYMER MATRIX COMPOSITES

BY

R. C. TENNYSON, B. A. W. SMITH AND D. MORISON

UNIVERSITY OF TORONTO
INSTITUTE FOR AEROSPACE STUDIES
TORONTO, ONTARIO, CANADA

PROGRAM OBJECTIVES

1. DETERMINE THE EFFECT OF SPACE ENVIRONMENT ON THE MECHANICAL AND PHYSICAL PROPERTIES OF POLYMER MATRIX COMPOSITE MATERIALS AS A FUNCTION OF EXPOSURE TIME BY MEANS OF IN-SITU LABORATORY SIMULATION.
2. EVALUATE THE EFFECTS OF GROUND-BASED ACCELERATED TESTING IN SPACE SIMULATORS PERTAINING TO THERMAL CYCLING AND RADIATION DAMAGE.
3. OBTAIN TEST DATA FROM OUR LDEF SATELLITE COMPOSITE MATERIALS EXPERIMENT FOR COMPARISON WITH 1 AND 2.

CONCLUSIONS

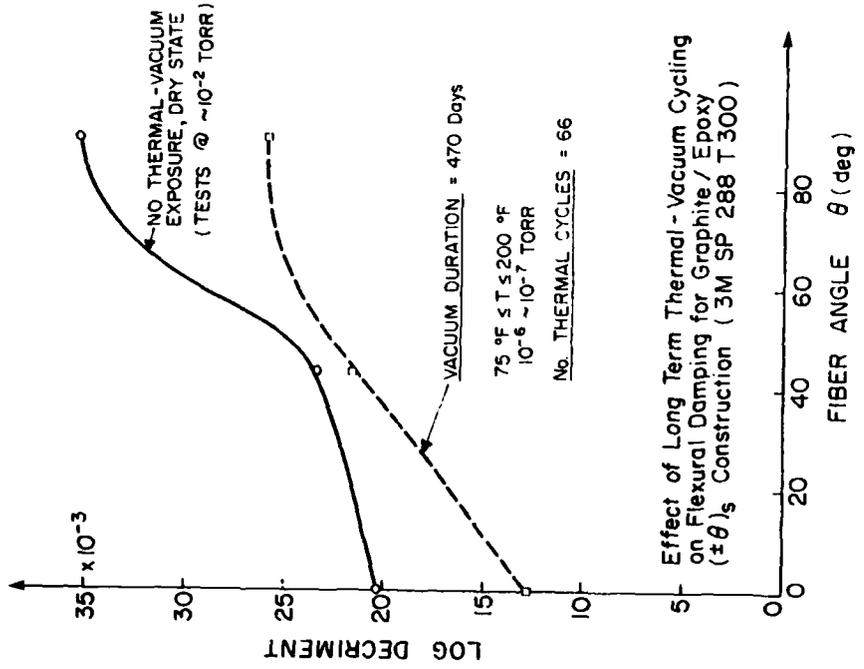
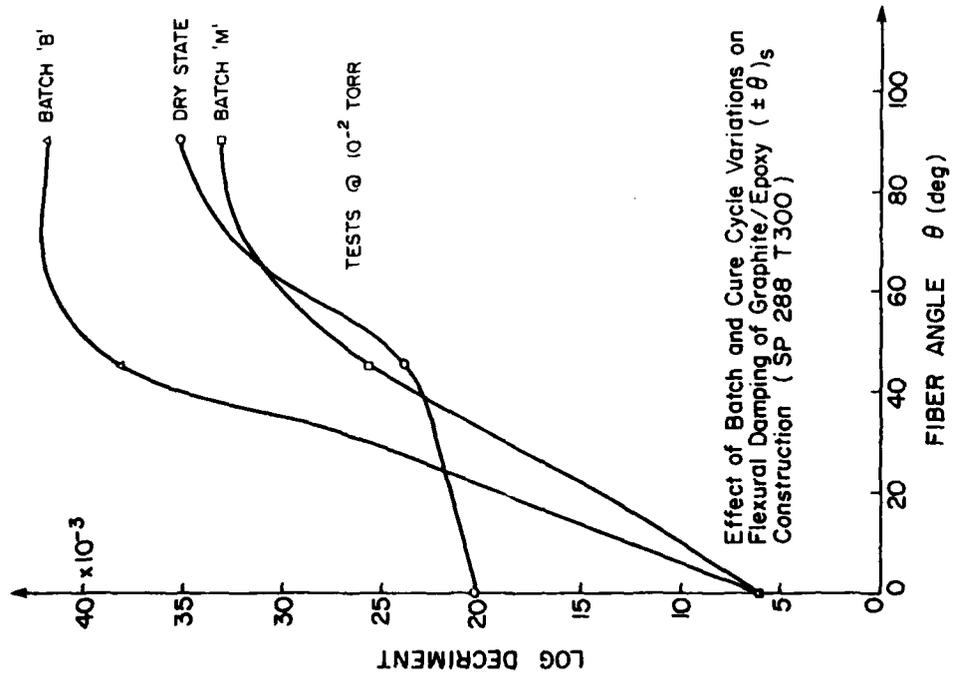
COMPARED TO AMBIENT CONDITIONS, THE FOLLOWING EFFECTS HAVE BEEN OBSERVED:

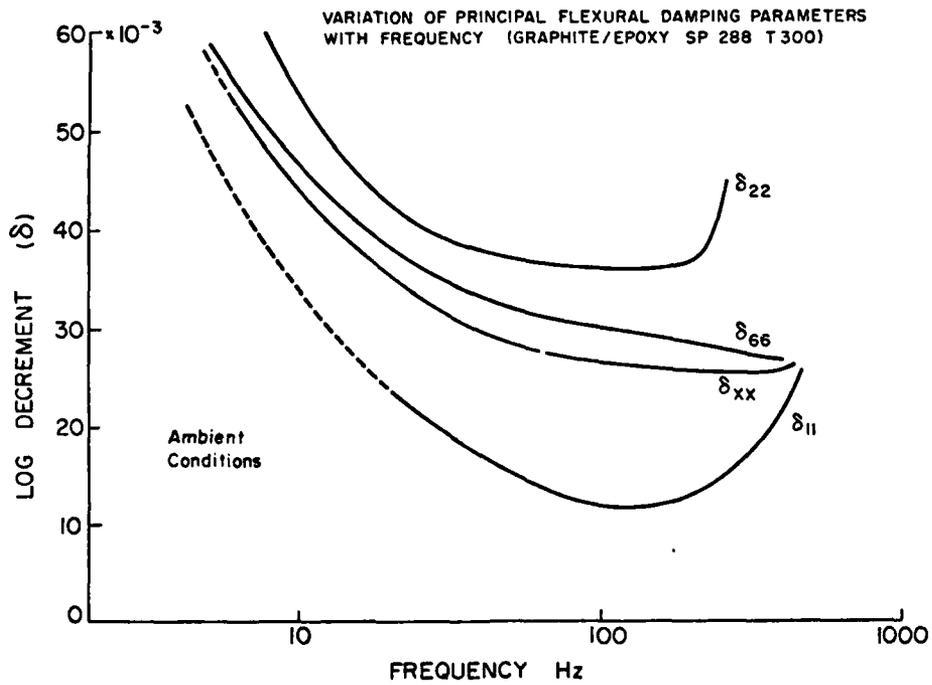
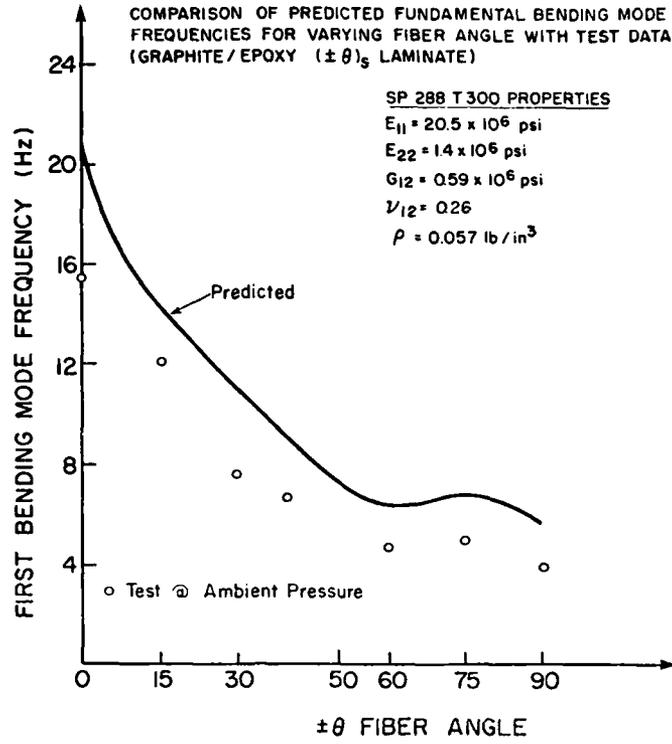
1. HARD VACUUM ($\sim 10^{-6}$ TORR)
 - (A) MATRIX STIFFNESS (E_{22}) AND TENSILE STRENGTH (Y) INCREASE OVER A WIDE TEMPERATURE RANGE;
 - (B) MATRIX CREEP COMPLIANCE (S_{22}) REDUCES;
 - (C) CTE CHANGES DEPENDING ON LAMINATE CONFIGURATION;
 - (D) MATERIAL DAMPING CHANGES, DEPENDING ON LAMINATE CONFIGURATION, WITH PRINCIPAL VALUES (β_{11} , β_{22} , β_{66}) SHOWING A DECREASE.

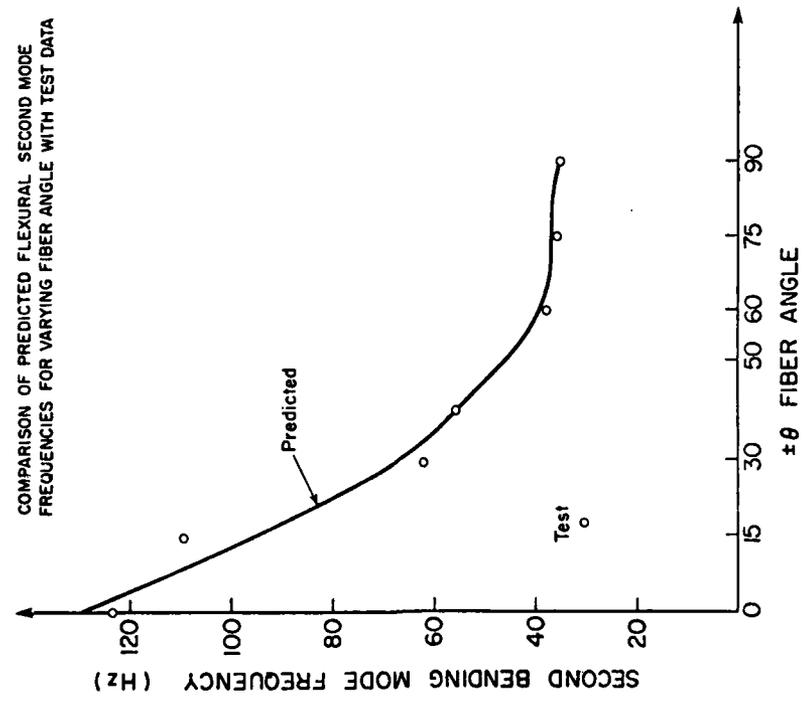
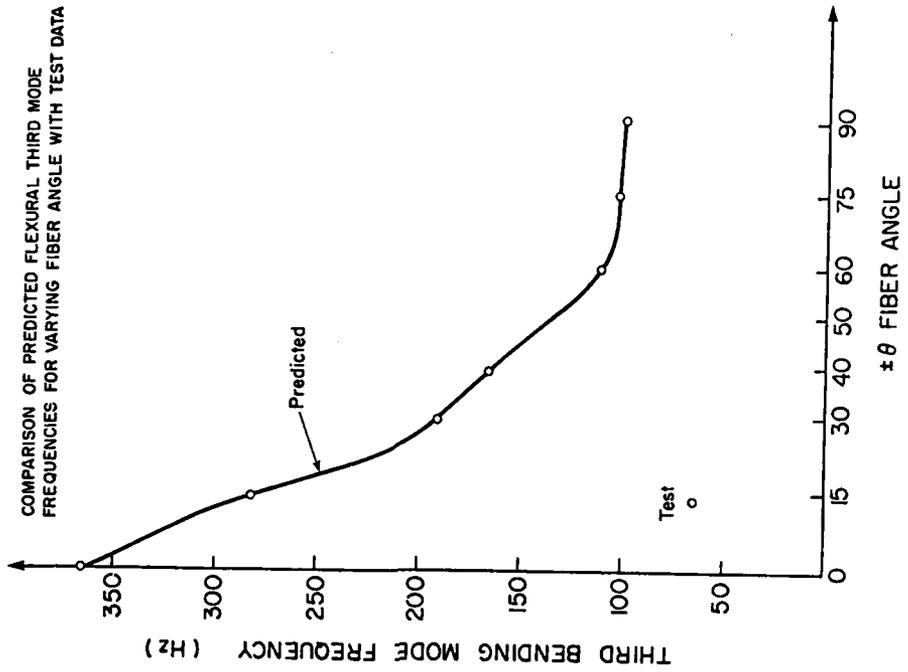
2. COMBINED U.V. RADIATION IN HARD VACUUM (~ 180 E.S.D. @ 10^{-7} TORR)
MATRIX STIFFNESS, CREEP COMPLIANCE AND CTE SHOW NO SIGNIFICANT U.V. EFFECT UP TO ~ 180 E.S.D.

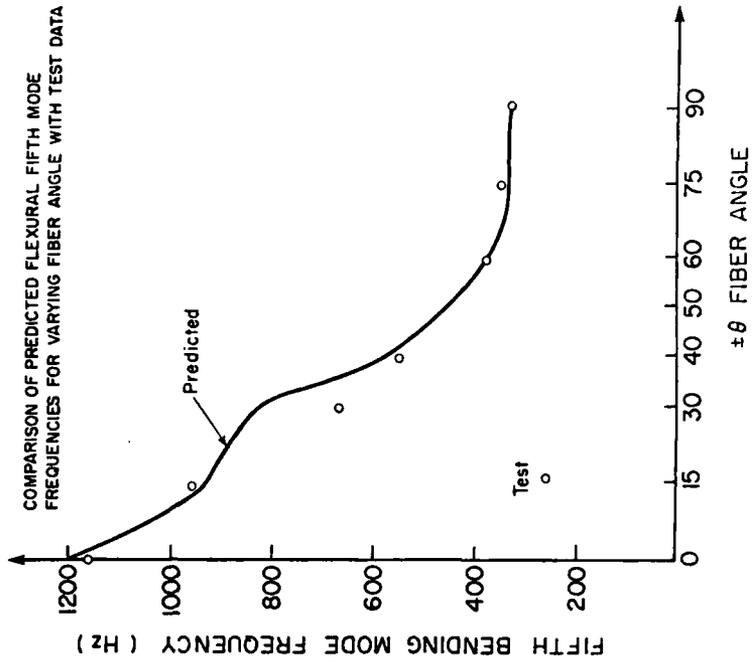
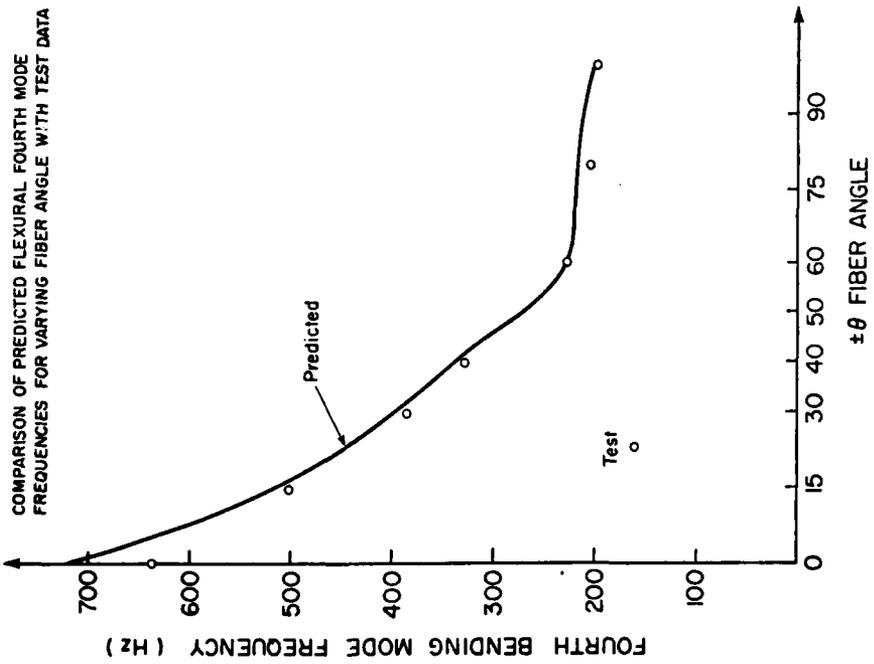
3. THERMAL-VACUUM CYCLING
 - (A) MATRIX STIFFNESS AND TENSILE STRENGTH ARE REDUCED OVER A WIDE TEMPERATURE RANGE;
 - (B) CTE DRIFT WITH INCREASING NUMBERS OF T/C.

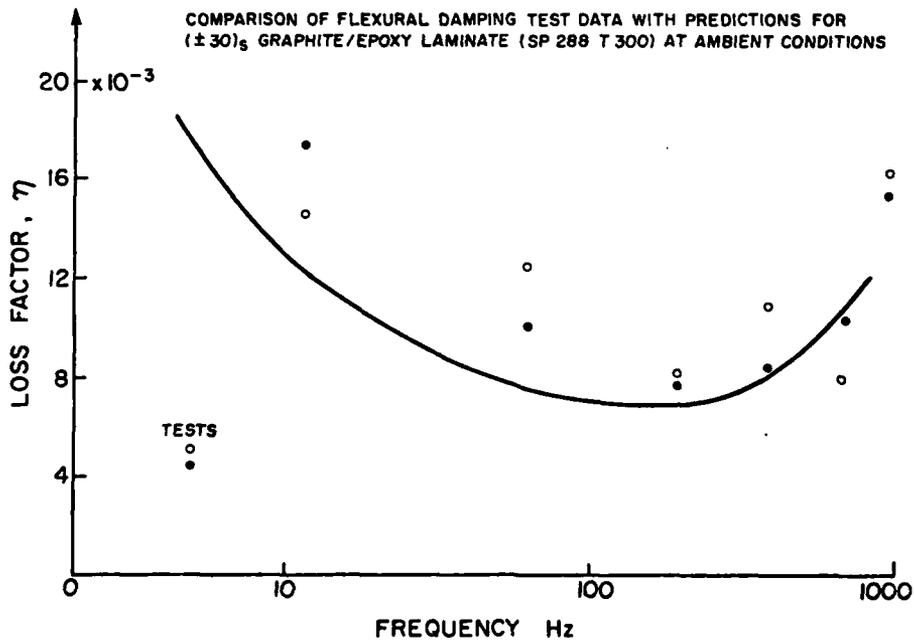
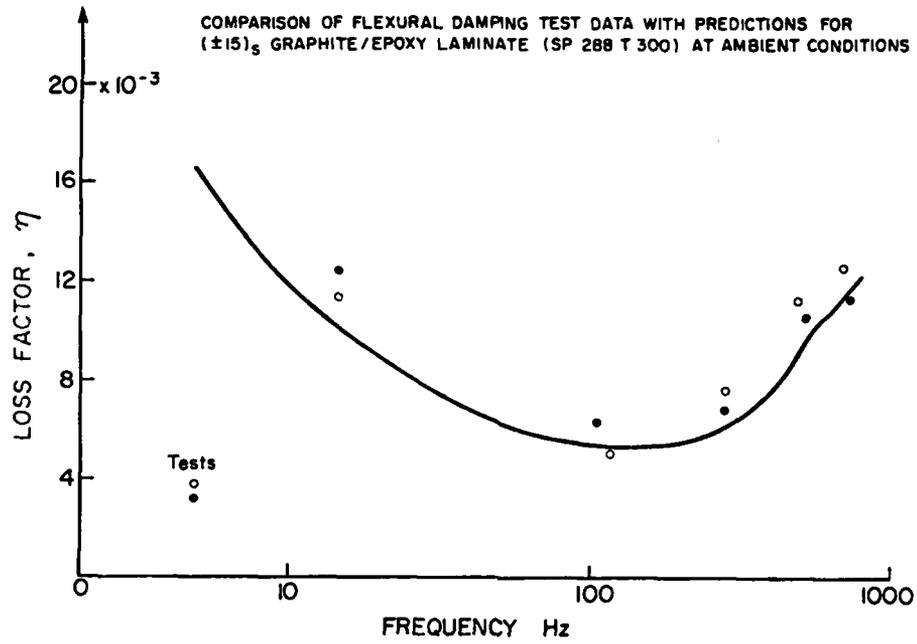
4. ANALYSIS
LAMINATE MODELS ARE QUITE ACCURATE IN PREDICTING CTE, DAMPING, CREEP AND STRENGTH OF ARBITRARY LAMINATE CONFIGURATIONS BASED ON PRINCIPAL MATERIAL PROPERTY DATA OBTAINED UNDER DIFFERENT ENVIRONMENTAL CONDITIONS.

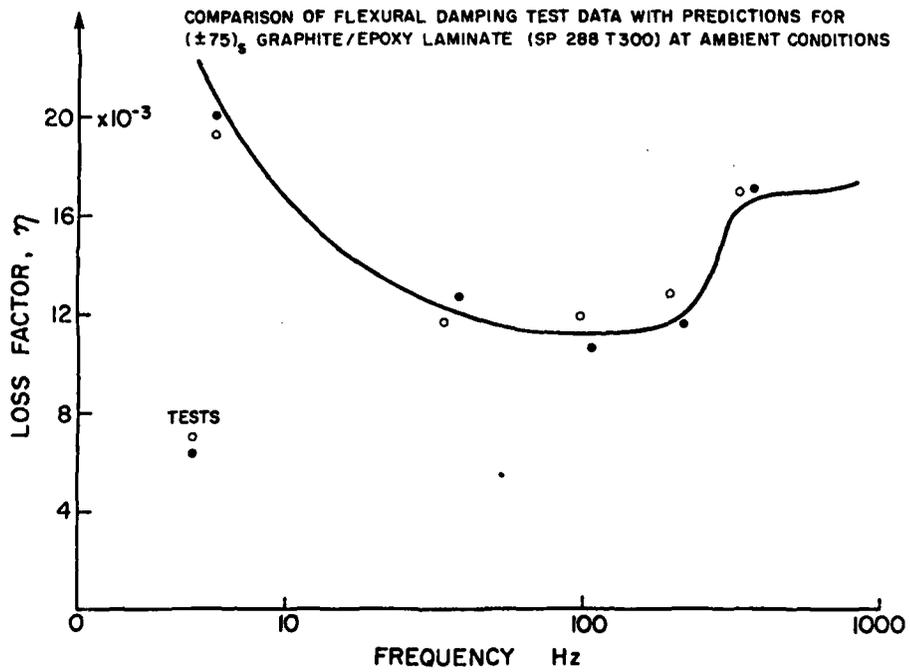
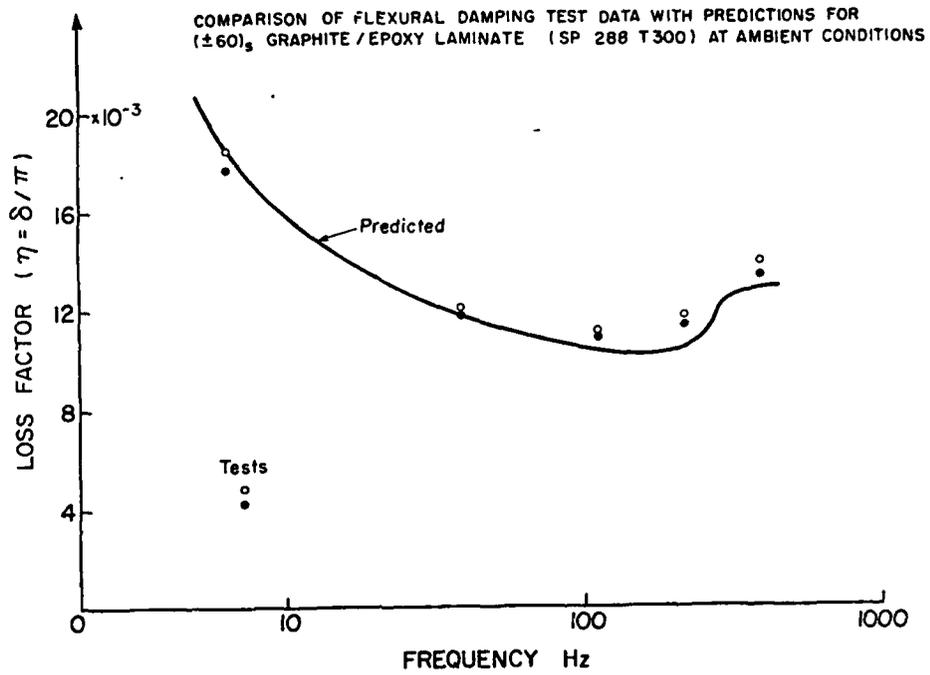




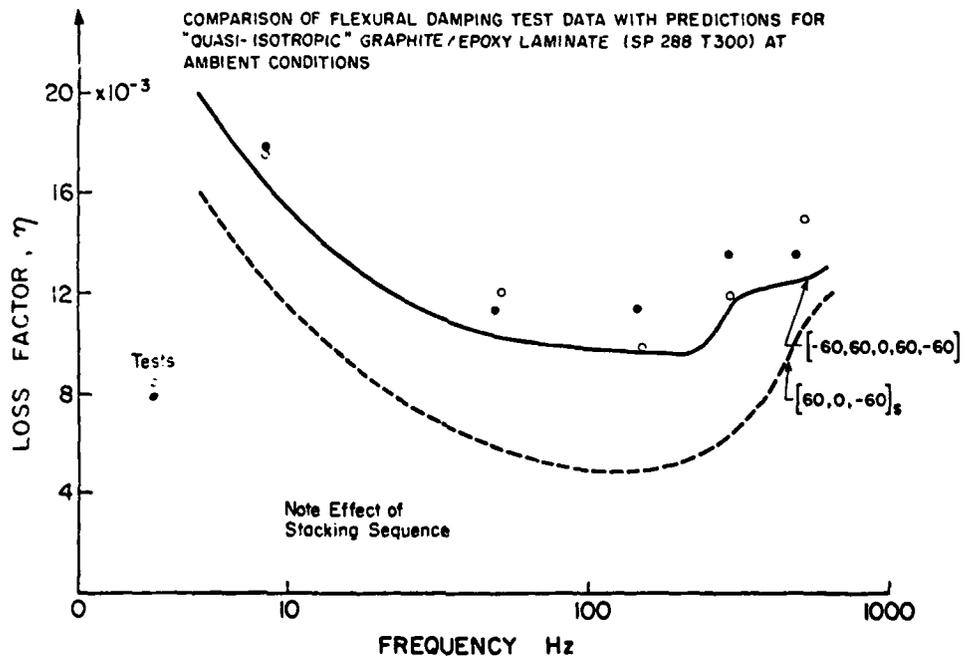
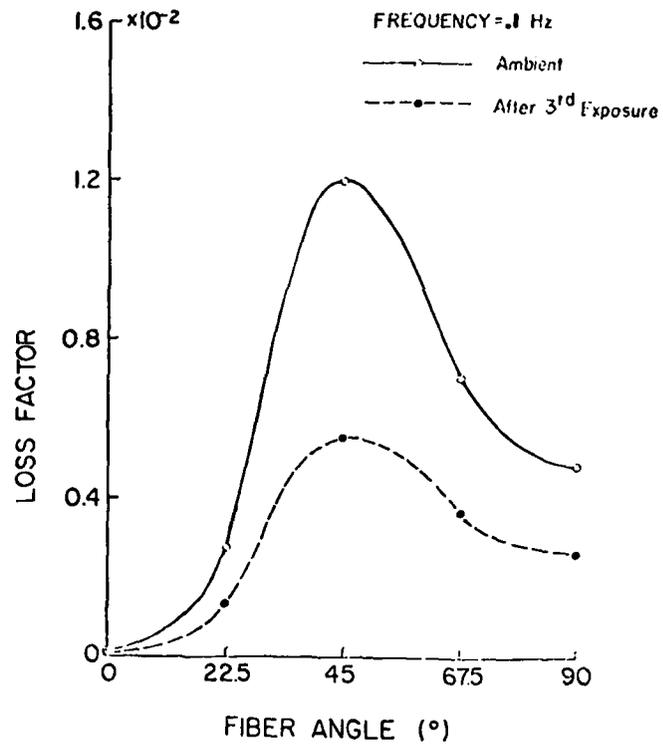




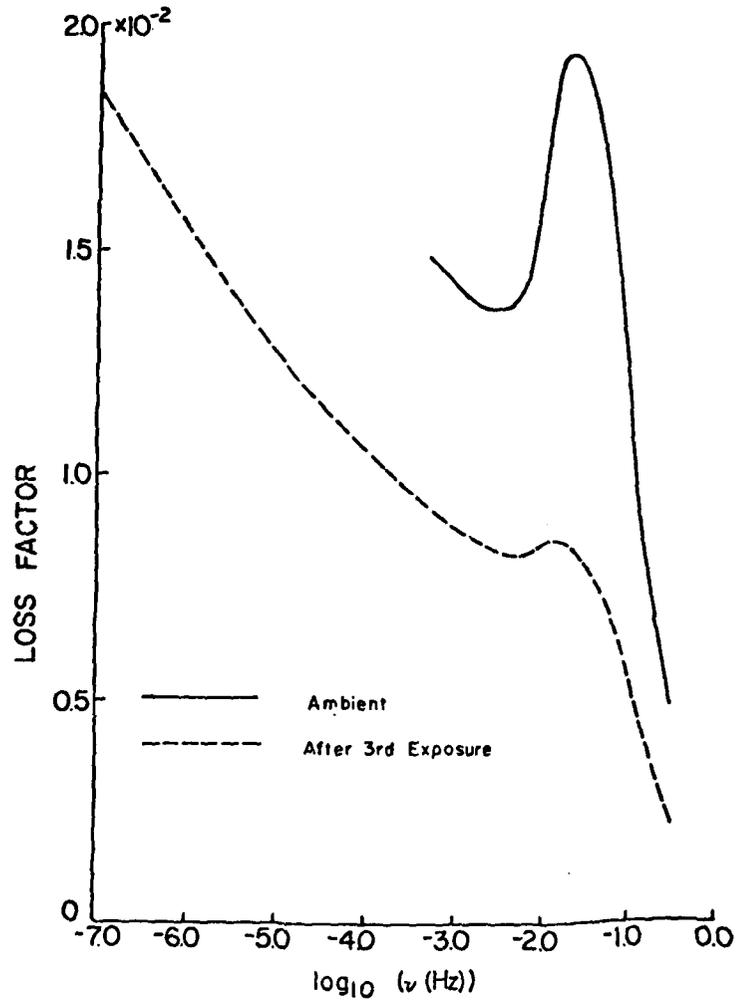


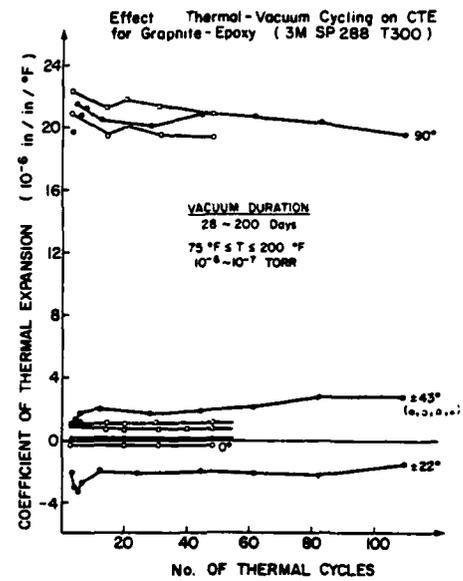
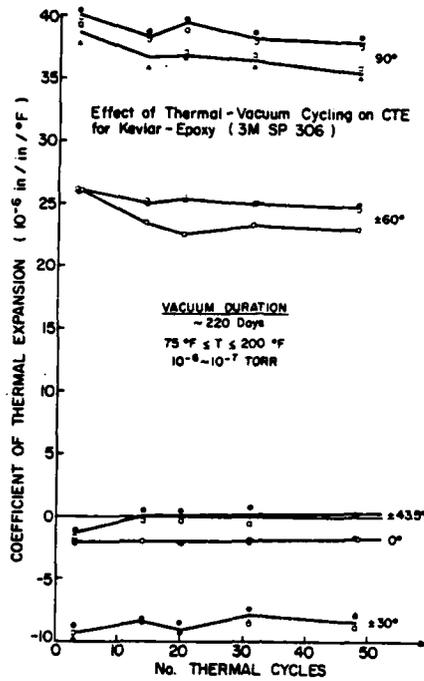


PREDICTED LOSS FACTORS OF SYMMETRIC
BALANCED GRAPHITE/EPOXY LAMINATES

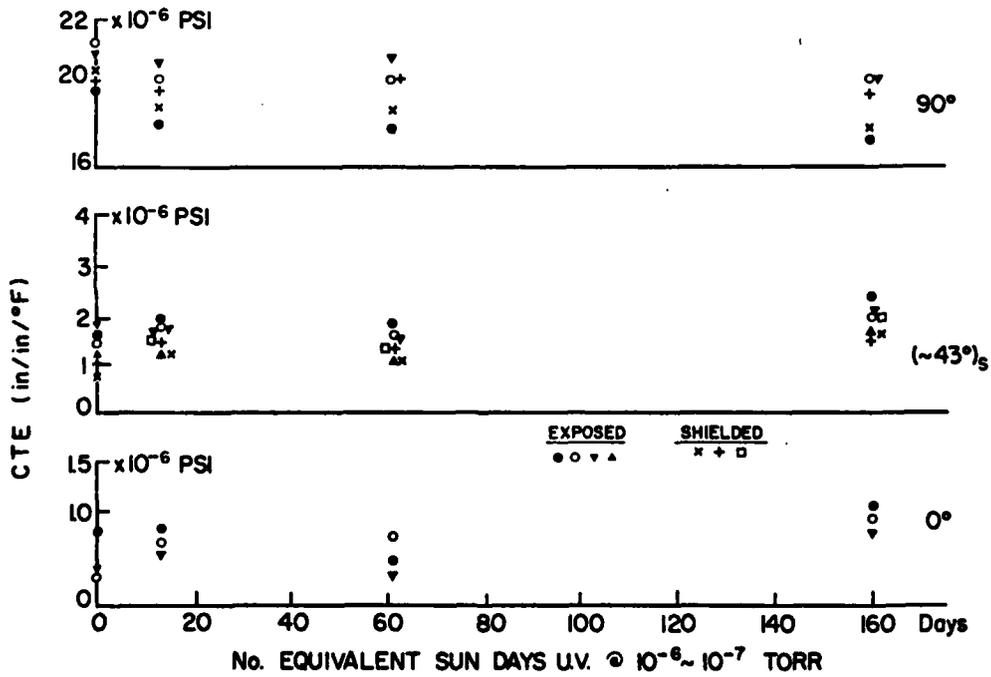


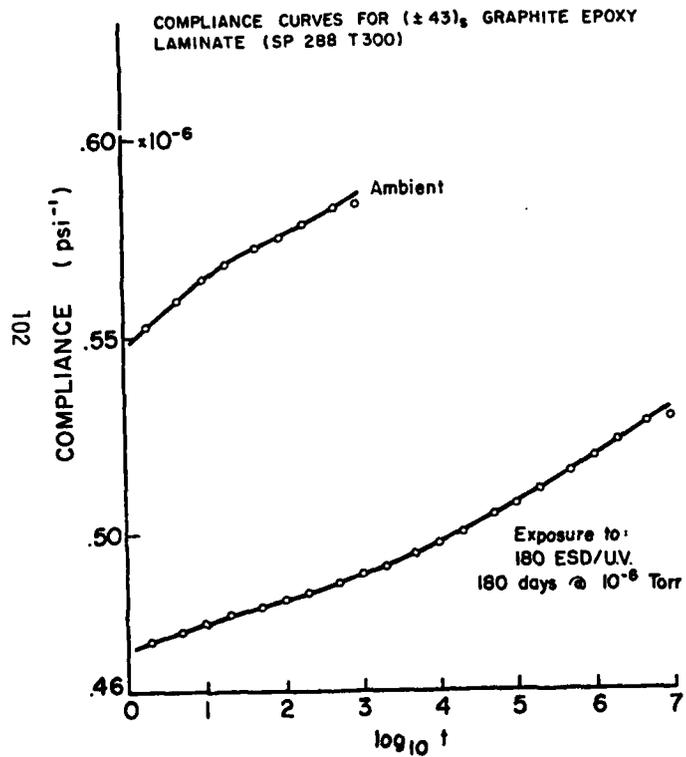
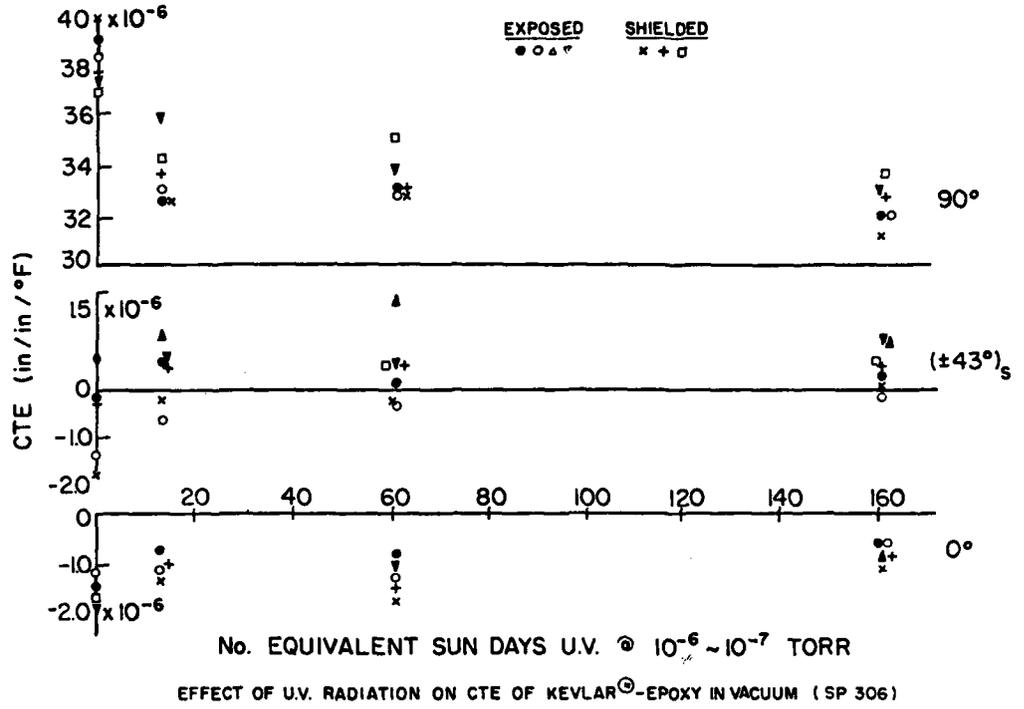
LOSS FACTORS PREDICTED FOR $(\pm 45^\circ)_s$ GRAPHITE/
EPOXY LAMINATE

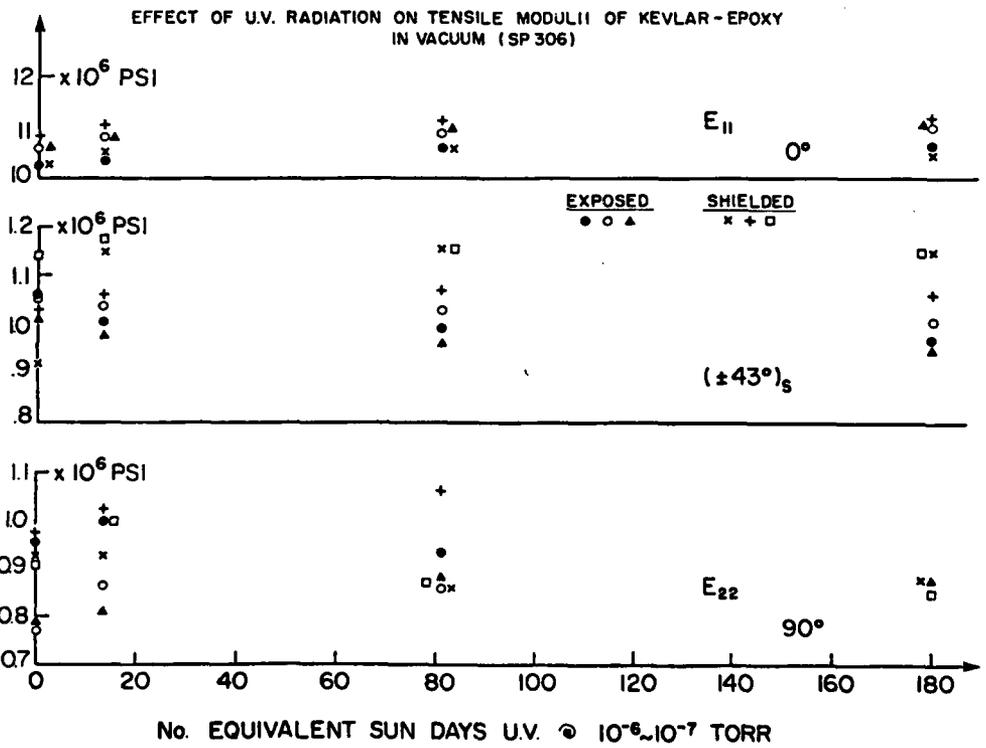
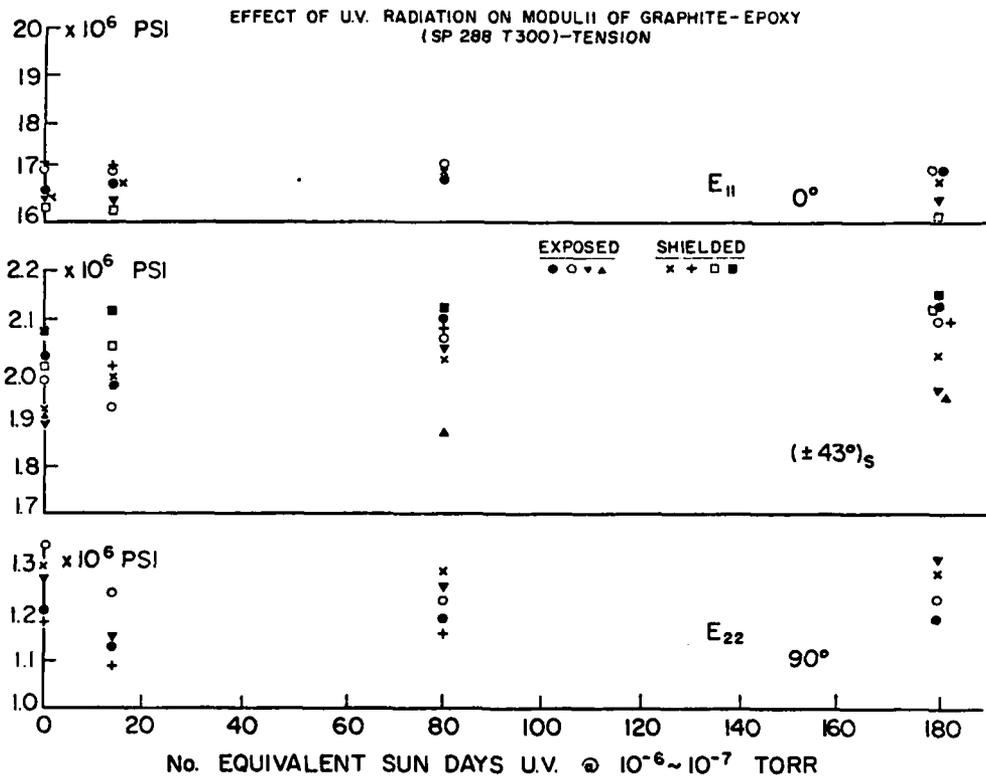




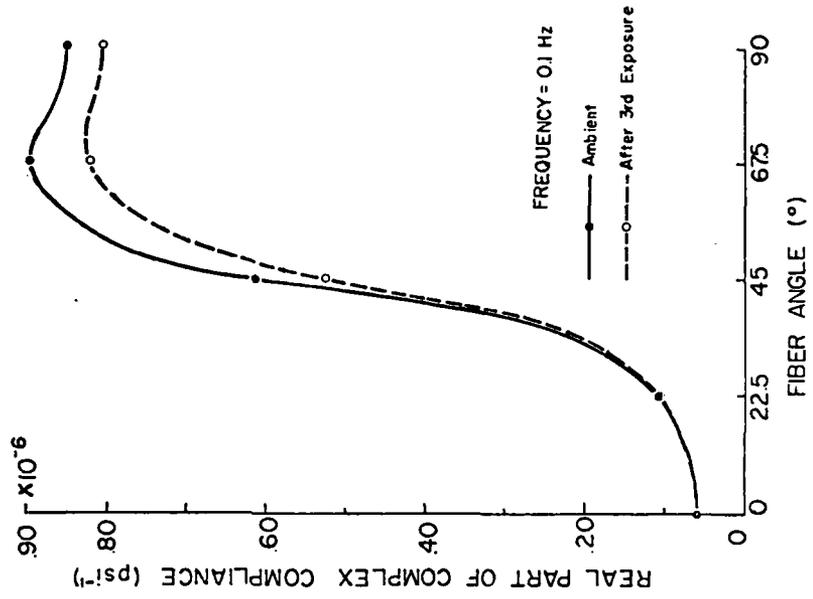
EFFECT OF U.V. RADIATION ON CTE OF GRAPHITE-EPOXY IN VACUUM (SP 288 T 300)



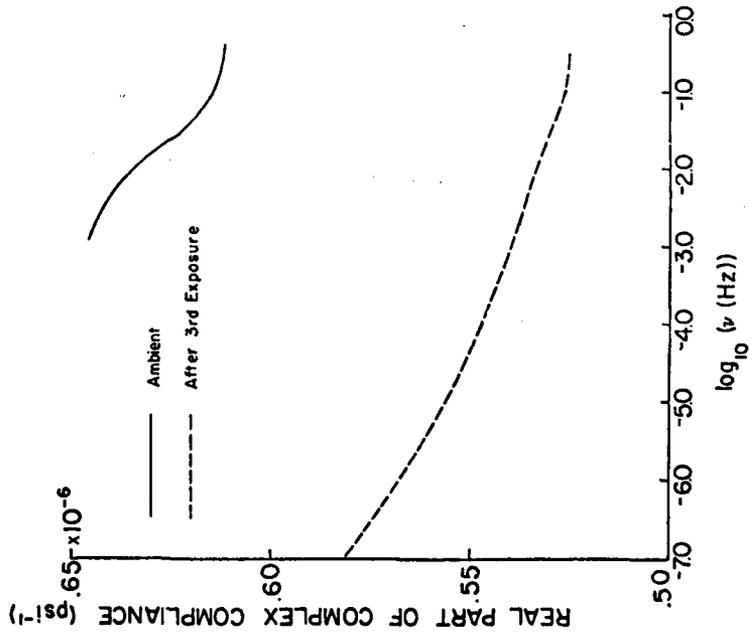




REAL PART OF COMPLEX COMPLIANCE PREDICTED FOR SYMMETRIC BALANCED GRAPHITE/EPOXY LAMINATES



REAL PART OF COMPLEX COMPLIANCE PREDICTED FOR (±45°) GRAPHITE/EPOXY LAMINATE



AFWAL-TR-82-4007

STUDY OF BUCKLING, POSTBUCKLING BEHAVIOR
AND VIBRATION OF LAMINATED COMPOSITE PLATES

by

Arthur W. Leissa

Department of Engineering Mechanics

Ohio State University

Columbus, Ohio

OBJECTIVES

1. To collect the literature dealing with buckling, postbuckling behavior and vibration of flat and curved composite panels.
2. To digest, summarize, organize and integrate useful knowledge found.
3. To extend analytical procedures and results found by means of simple computer programs to provide additional useful information.
4. To write a monograph dealing with buckling and postbuckling behavior of composite panels.
5. To write a survey paper summarizing the literature of composite panel vibrations.
6. To determine problem areas where further research is needed.

Uncoupled Equation of Plate Vibration
and Buckling (Symmetric Laminates)

$$\begin{aligned}
 & D_{11} \frac{\partial^4 w}{\partial x^4} + 4D_{16} \frac{\partial^4 w}{\partial x^3 \partial y} + 2(D_{12} + D_{66}) \frac{\partial^4 w}{\partial x^2 \partial y^2} \\
 & + 4D_{26} \frac{\partial^4 w}{\partial x \partial y^3} + D_{22} \frac{\partial^4 w}{\partial y^4} + \rho \frac{\partial^2 w}{\partial t^2} \\
 = & N_x \frac{\partial^2 w}{\partial x^2} + 2N_{xy} \frac{\partial^2 w}{\partial x \partial y} + N_y \frac{\partial^2 w}{\partial y^2}
 \end{aligned}$$

where:

$$D_{ij} \equiv \int_{-h/2}^{h/2} C_{ij}^{(k)} z^2 dz, \quad \rho \equiv \int_{-h/2}^{h/2} \rho^{(k)} dz$$

For the k th layer:

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{16} \\ C_{12} & C_{22} & C_{26} \\ C_{16} & C_{26} & C_{66} \end{bmatrix} \begin{bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{bmatrix}$$

Coupled Equations of Plate Vibration
and Buckling (Unsymmetric Laminates)

$$\begin{bmatrix} L_{11} & L_{12} & L_{13} \\ L_{21} & L_{22} & L_{23} \\ L_{31} & L_{32} & L_{33} \end{bmatrix} \begin{bmatrix} u \\ v \\ w \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

where:

$$L_{11} = A_{11} \frac{\partial^2}{\partial x^2} + 2A_{16} \frac{\partial^2}{\partial x \partial y} + A_{66} \frac{\partial^2}{\partial y^2} - \rho \frac{\partial^2}{\partial t^2}$$

$$L_{22} = A_{66} \frac{\partial^2}{\partial x^2} + 2A_{26} \frac{\partial^2}{\partial x \partial y} + A_{22} \frac{\partial^2}{\partial y^2} - \rho \frac{\partial^2}{\partial t^2}$$

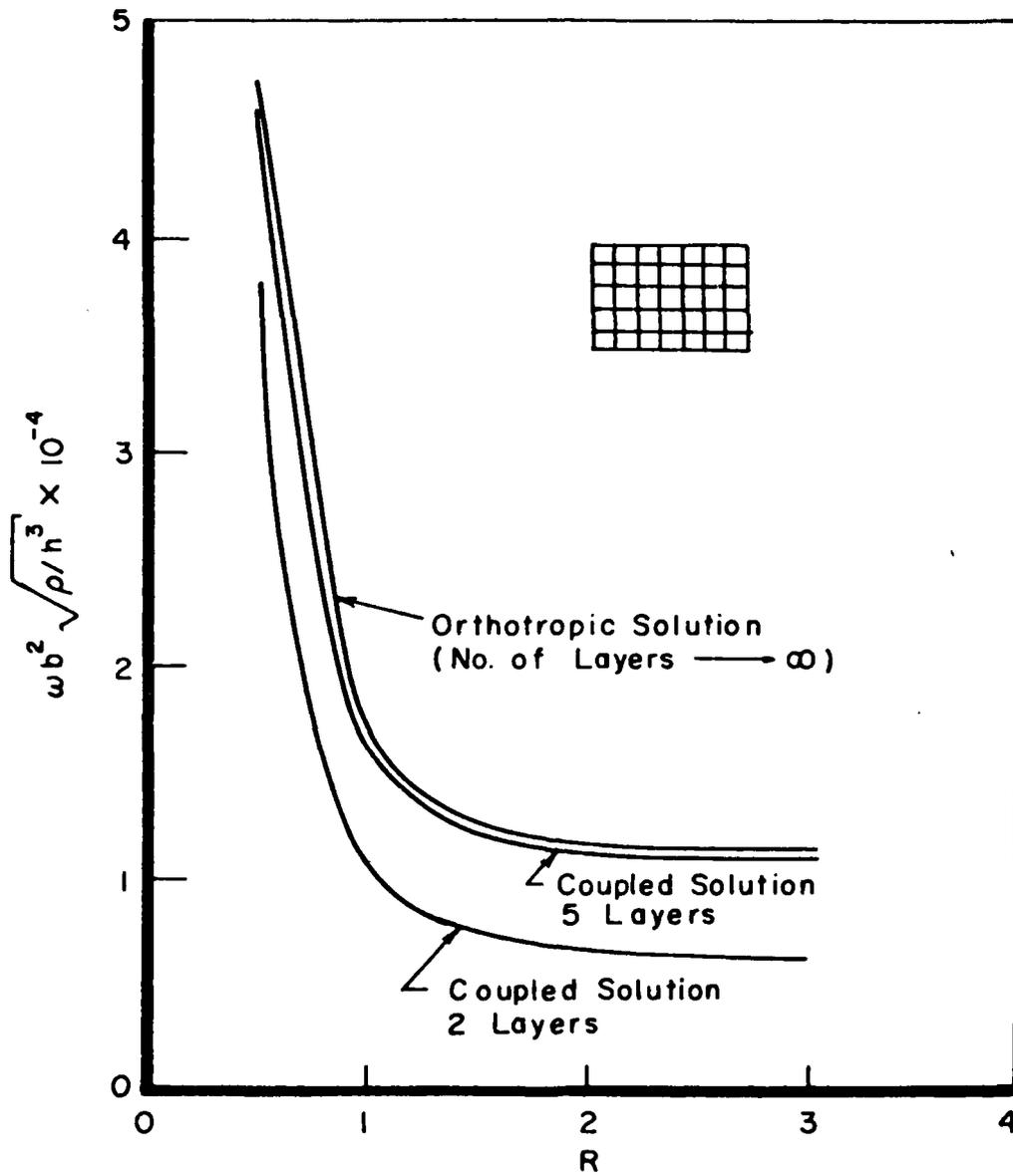
$$\begin{aligned} L_{33} = & D_{11} \frac{\partial^4}{\partial x^4} + 4D_{16} \frac{\partial^4}{\partial x^3 \partial y} + 2(D_{12} + D_{66}) \frac{\partial^4}{\partial x^2 \partial y^2} \\ & + 4D_{26} \frac{\partial^4}{\partial x \partial y^3} + D_{22} \frac{\partial^4}{\partial y^4} - \left(N_x \frac{\partial^2}{\partial x^2} \right. \\ & \left. + 2N_{xy} \frac{\partial^2}{\partial x \partial y} + N_y \frac{\partial^2}{\partial y^2} \right) - \rho \frac{\partial^2}{\partial t^2} \end{aligned}$$

$$L_{12} = L_{21} = A_{16} \frac{\partial^2}{\partial x^2} + (A_{12} + A_{66}) \frac{\partial^2}{\partial x \partial y} + A_{26} \frac{\partial^2}{\partial y^2}$$

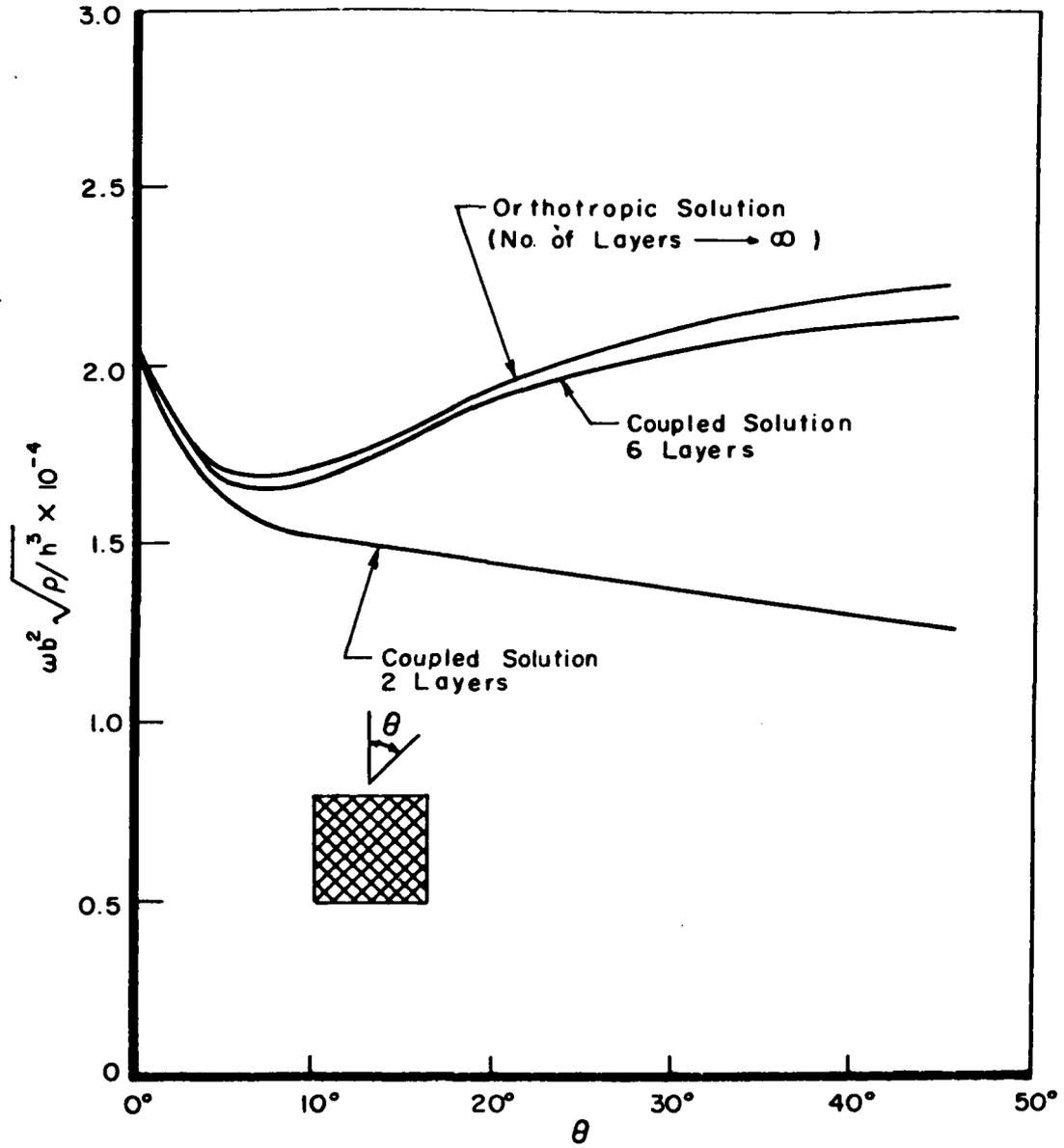
$$\begin{aligned} L_{13} = L_{31} = & -B_{11} \frac{\partial^3}{\partial x^3} - 3B_{16} \frac{\partial^3}{\partial x^2 \partial y} - (B_{12} + 2B_{66}) \frac{\partial^3}{\partial x \partial y^2} \\ & - B_{26} \frac{\partial^3}{\partial y^3} \end{aligned}$$

$$\begin{aligned} L_{23} = L_{32} = & -B_{16} \frac{\partial^3}{\partial x^3} - (B_{12} + 2B_{66}) \frac{\partial^3}{\partial x^2 \partial y} - 3B_{26} \frac{\partial^3}{\partial x \partial y^2} \\ & - B_{22} \frac{\partial^3}{\partial y^3} \end{aligned}$$

and where: $(A_{ij}, B_{ij}, D_{ij}) \equiv \int_{-h/2}^{h/2} C_{ij}^{(k)}(1, z, z^2) dz$



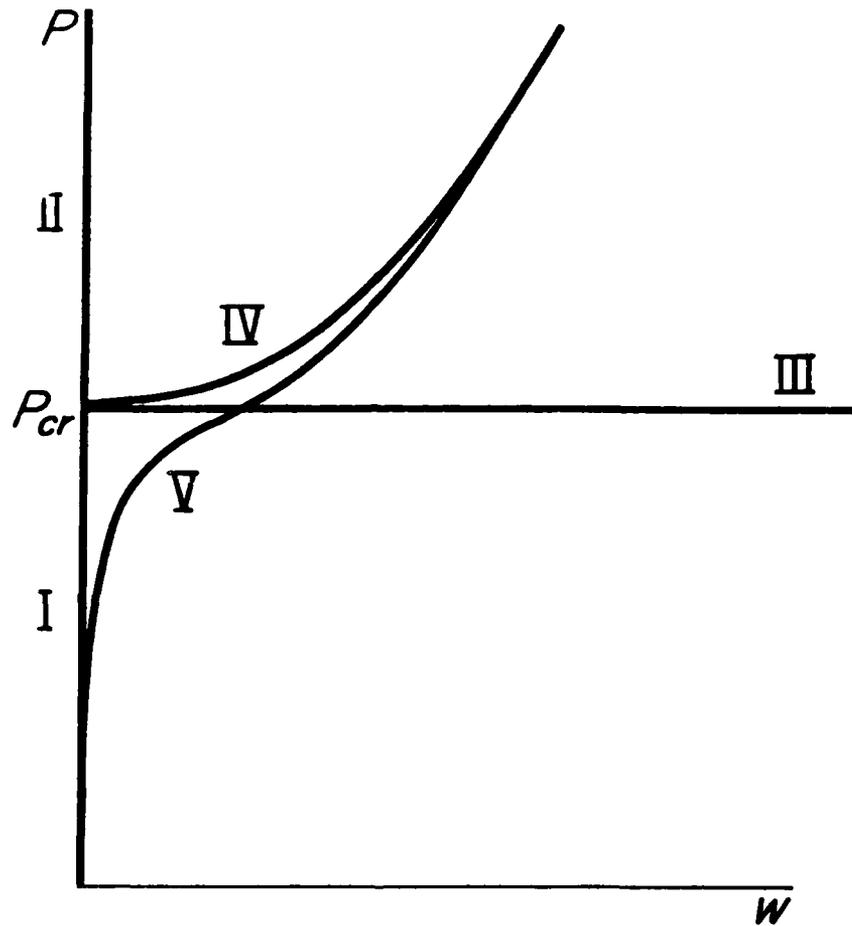
Fundamental Vibration Frequency as a Function of Aspect Ratio for a Simply-Supported Graphite-Epoxy Cross-Ply Plate



Fundamental Vibration Frequency as a Function of Angle-Ply Orientation for a Simply-Supported Graphite-Epoxy Square Plate

Complicating Effects in Vibrations of Laminated
Composite Plates

1. Inplane initial stresses
2. Large amplitude (nonlinear) transverse displacements
3. Shear deformation
4. Rotary inertia
5. Effects of surrounding media
6. Inplane nonhomogeneity
7. Variable thickness
8. Hygrothermal effects



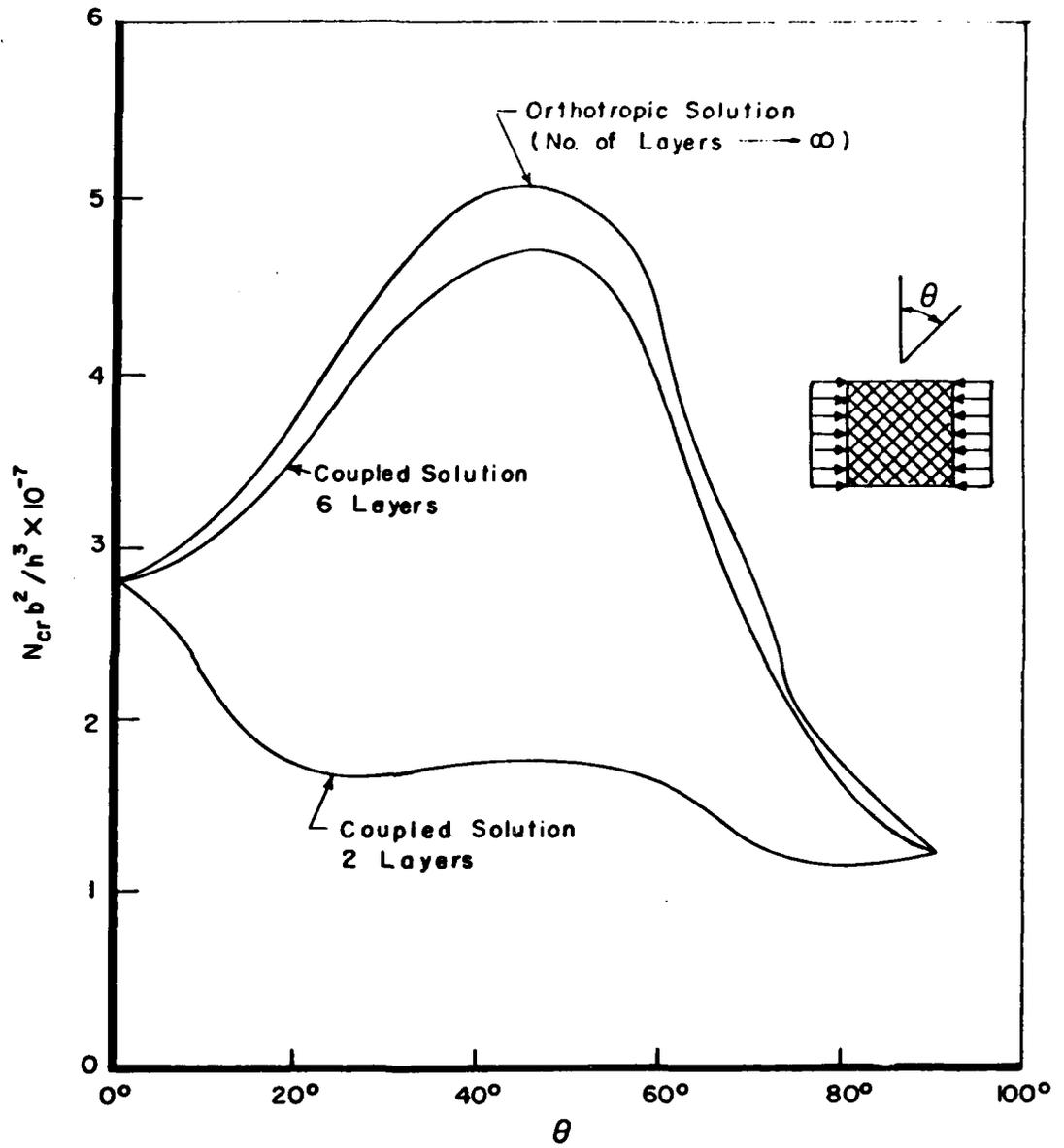
Load-displacement curves

BUCKLING AND POSTBUCKLING BEHAVIOR OF LAMINATED
COMPOSITE PLATES - ORGANIZATION OF SUBJECT

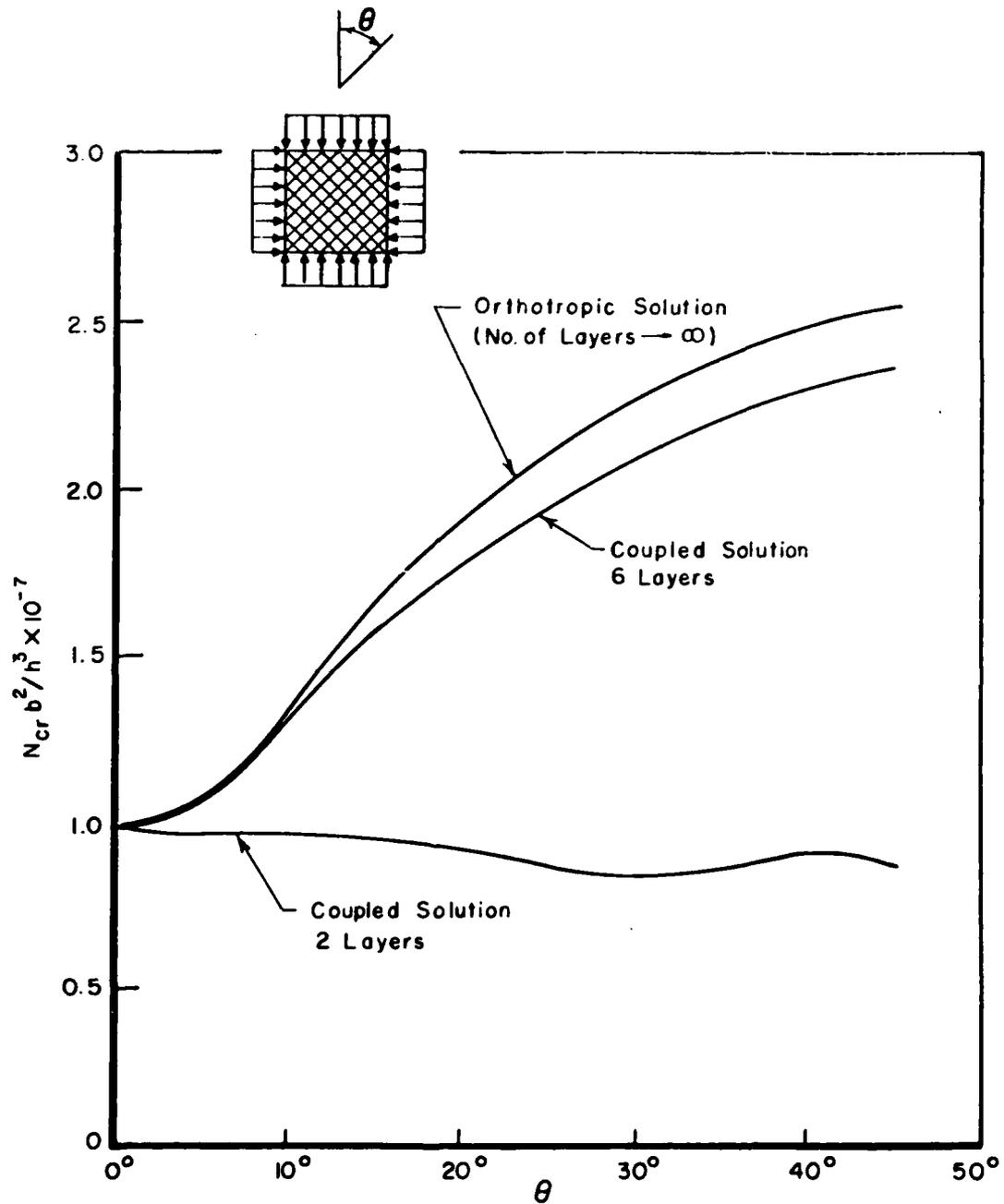
1. Classical Buckling Studies
 - a. Shape - rectangular, quadrilateral, etc.
 - b. Edge conditions - simply supported, clamped, free, elastically supported, intermittent support, point supports
 - c. Loads - constant or variable N_x , N_y , N_{xy}
 - d. Cutouts and cracks, stiffeners

2. Complicating Effects
 - a. Elastic foundation and other displacement-dependent transverse loads
 - b. Shear deformation
 - c. Variable thickness
 - d. Hygrothermal effects

3. Postbuckling and other Nonclassical Phenomena
 - a. Postbuckling
 - b. Imperfections
 - c. Parametric excitation
 - d. Follower forces
 - e. Inelastic buckling



Critical Buckling Load as a Function of Angle-Ply Orientation for Simply-Supported Graphite-Epoxy Square Plate Under Uniaxial Compression



Critical Buckling Load as a Function of Angle-Ply Orientation for Simply-Supported Graphite-Epoxy Square Plate Under Biaxial Compression

CONCLUSIONS TO DATE

1. The vibrations, buckling and postbuckling behavior of composite plates is a very complicated subject, more complicated than for homogeneous, isotropic plates.
2. The efficiency of composites for high performance design applications is being more widely demonstrated, and thus the need for accurate theoretical and experimental information is becoming increasingly important
3. Considerable progress in the rational analysis of laminated composite plates has been made in the past fifteen years, and a great deal of useful information has been published.
4. A monograph which digests, integrates and summarizes the available knowledge should be useful to designers, engineers and researchers.

AFWAL-TR-82-4007

DEPENDENCE OF FIBER-MATRIX FAILURE MODES
ON INTERPHASE PROPERTIES

BY

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MECHANICS AND SURFACE INTERACTIONS BRANCH
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WPAFB, OH 45433

OBJECTIVES:

- DETERMINE THE SURFACE CHEMISTRY TOPOGRAPHY AND MORPHOLOGY OF THE SURFACES OF GRAPHITE REINFORCING FIBERS
- DETERMINE THE MECHANISM BY WHICH SURFACE TREATMENTS (OXIDATIVE AND FINISHING) IMPROVE FIBER-MATRIX ADHESION
- DETERMINE THE BEHAVIOR OF THE FIBER-MATRIX INTERPHASE UNDER SHEAR LOADING

CONCLUSIONS

SURFACE TREATMENTS DO NOT INCREASE SURFACE AREA.

SURFACE TREATMENTS ADD OXYGEN TO THE FIBER SURFACE PROMOTING
BETTER FIBER MATRIX INTERACTION.

SURFACE TREATMENTS REMOVE ORIGINAL DEFECT LADEN FIBER
SURFACE AND LEAVE A STRUCTURALLY SOUNDER SURFACE.

SURFACE FINISHES PROMOTE BETTER ADHESION BY ACTING AS A
BRITTLE INNERLAYER BETWEEN FIBER AND MATRIX.

INTERFACIAL FAILURE MODES CHANGE FROM SLIDING TO INTERFACIAL
TO MATRIX WITH INCREASING FIBER-MATRIX ADHESION.

Surface Areas of A and HM Graphite Fibers

Fiber	Area (sq m/gm)
AU (VHT)	0.44
AU (AIR)	0.44
AS (VHT)	0.49
AS (AIR)	0.44
HMU (VHT)	0.51
HMS (VHT)	0.51
HMS (AIR)	0.51

ESCA Determination of Fiber Surface Composition

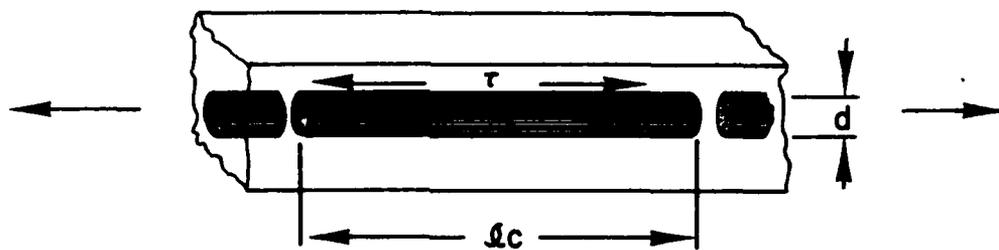
Fibers	C	O	Na	N	S
AU	86	9	3	2	-
AS	70	20	4	7	-
AS (300 C VHT)	72	18	6	3	-
AS (600 C VHT)	84	7	5	3	1
AS (750 C/H VHT)	94	3	1	1	1
HMU	95	5	-	-	-
HMS	89	9	-	-	-
HMS (300 C VHT)	97	3	-	-	-

Graphite Fiber Surface Free Energy Components

Fibers	γ^p (mJ/m)	γ^d (mJ/m)	γ (mJ/m)
AU	24	27	51
AS	30	26	56
AS (300 C VHT)	27	26	53
AS (750 C/H VHT)	12	32	44
HMU	8	33	41
HMS	21	28	49
HMS (300 C VHT)	13	30	43
Matrix			
Epon 828/mPDA	12	29	41

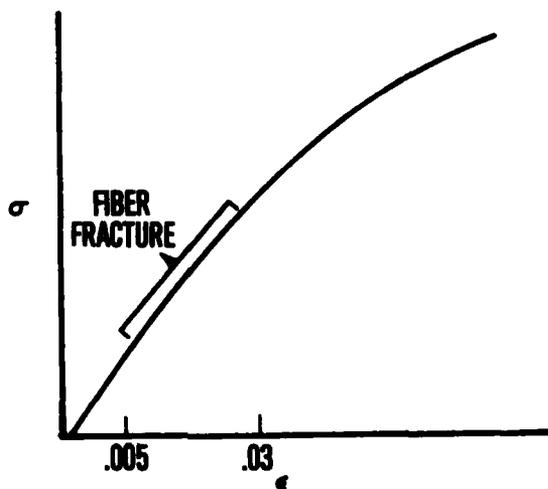
Interfacial Shear Strength

Fiber	(psi)
AU	3774
AS	10550
AS (300 C VHT)	9614
AS (750 C/H VHT)	8316
HMU	2090
HMS	3740
HMS (300 C VHT)	3032

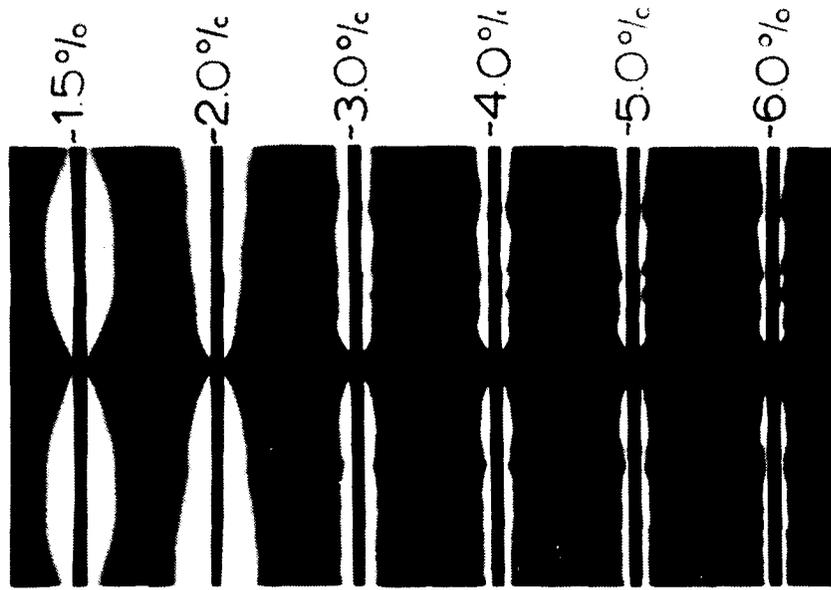


$$\tau = \frac{\sigma_f(d)}{2(l_c)}$$

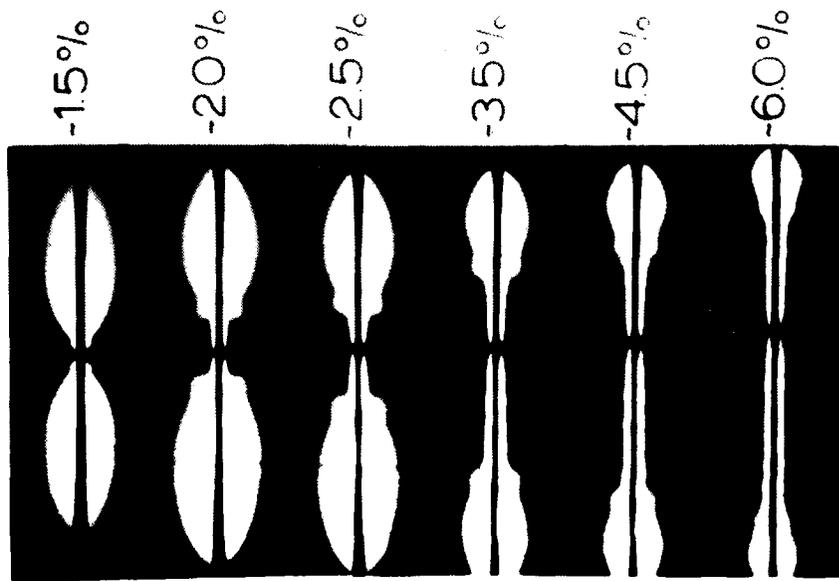
$$\tau = \frac{\sigma_f}{2\beta} \Gamma\left(1 - \frac{1}{\alpha}\right)$$

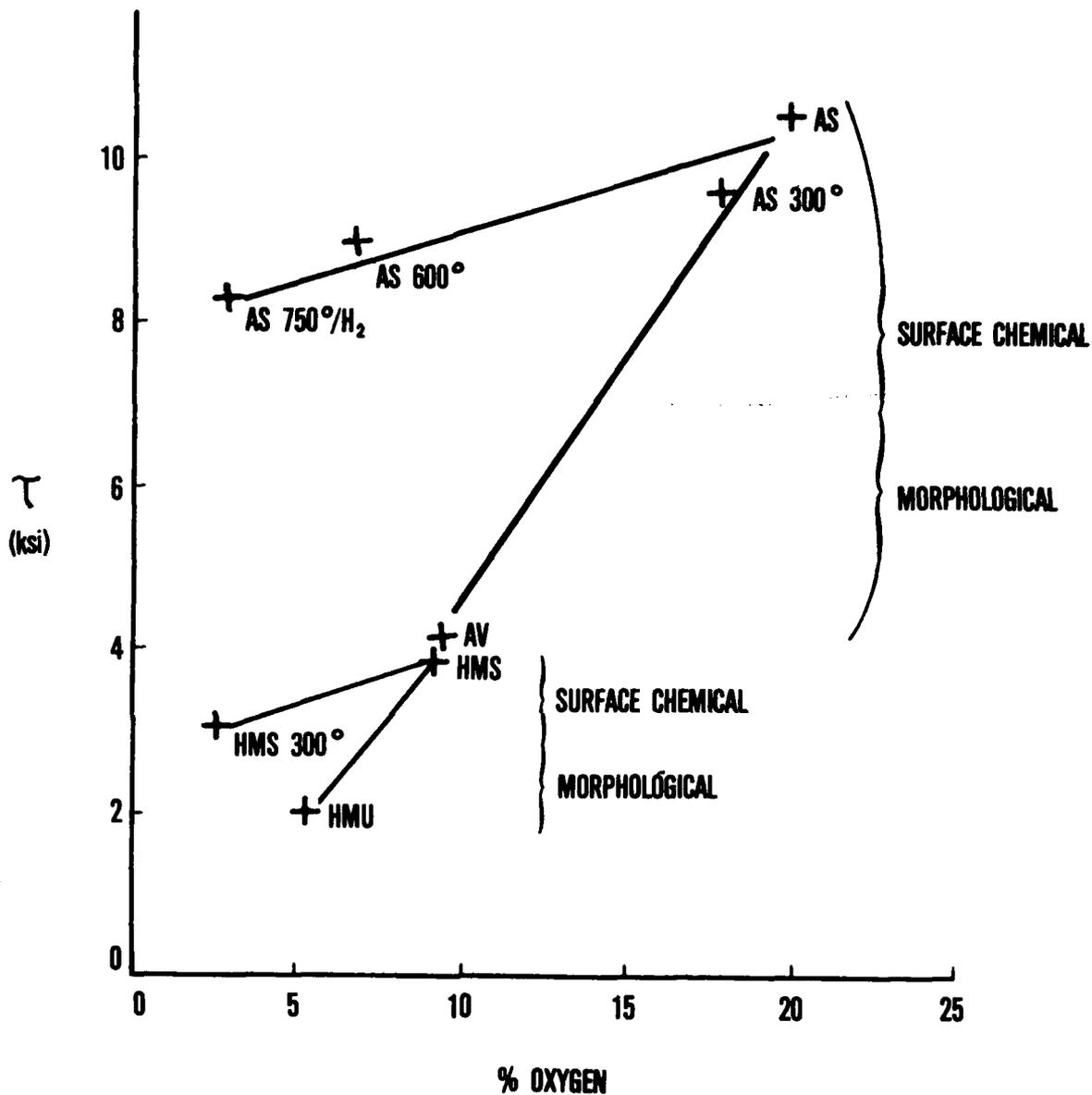


AU / EPON 828 - mPDA

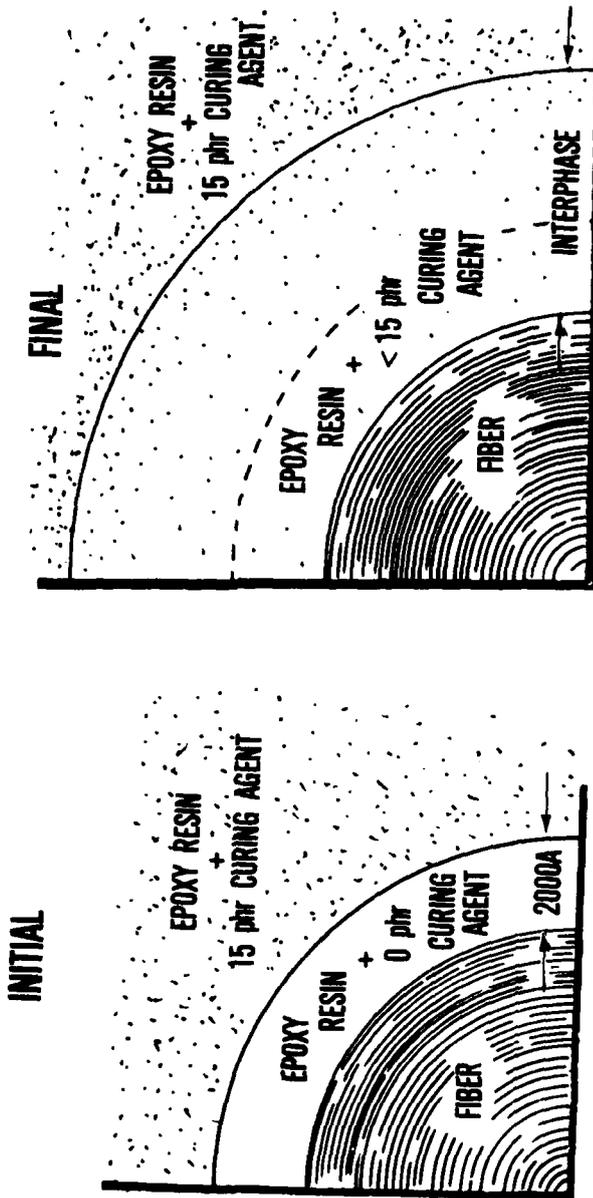


AS / EPON 828 - mPDA





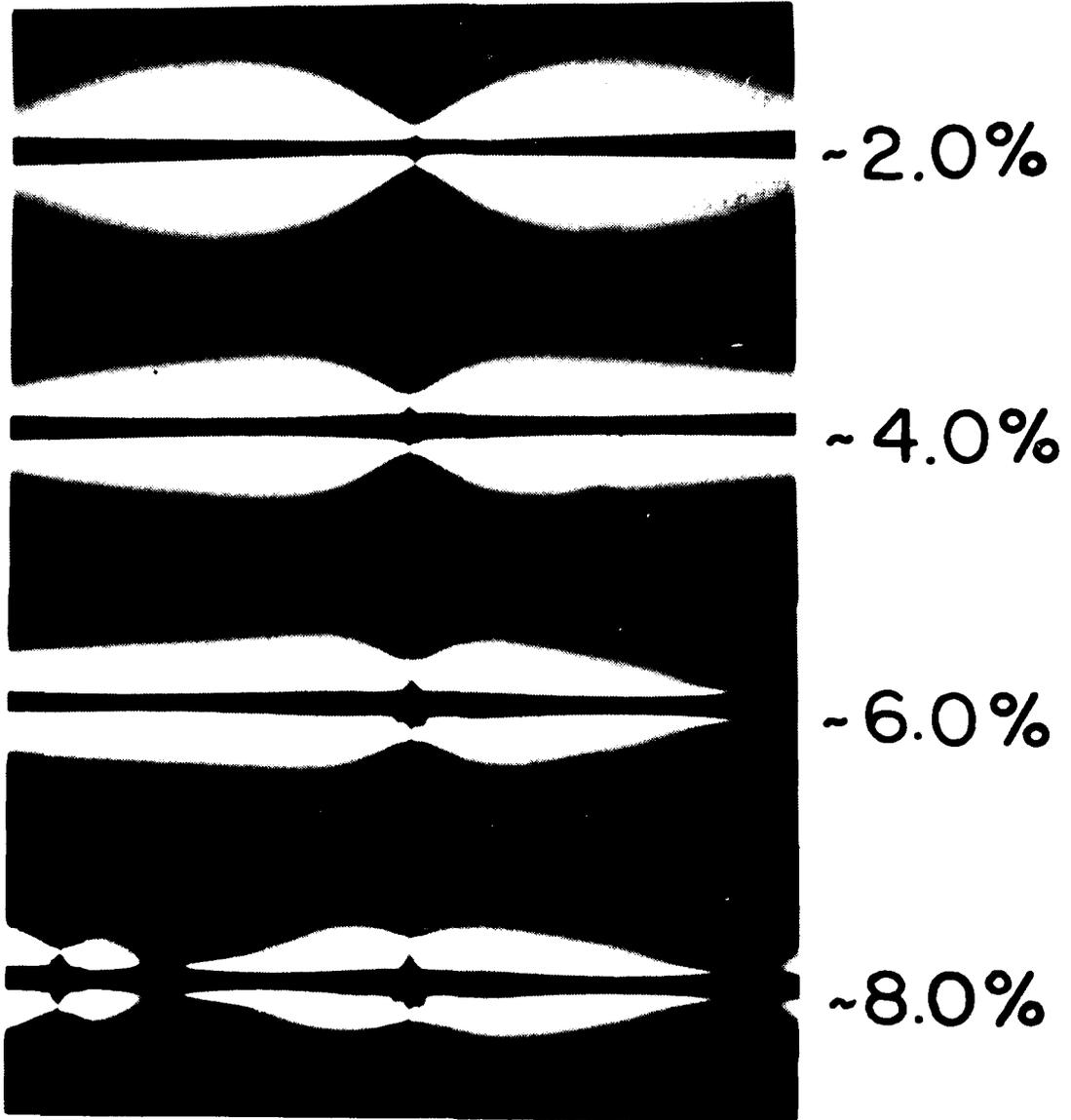
Interfacial Shear Strength as a Function of Percent Surface Oxygen



MECHANISM OF INTERPHASE DEVELOPMENT THROUGH APPLICATION OF A RESIN COATING

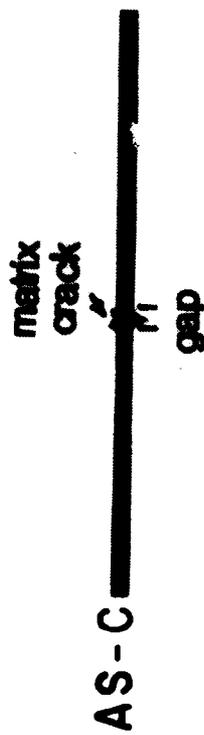
<u>FIBER</u>	<u>FRACTURE MODE</u>	<u>INTERFACIAL SHEAR STRENGTH</u>
AS-1	INTERFACIAL	45.0 MPa
AS-1C	MATRIX	57.1
AS-4	INTERFACIAL	30.6
AS-4C	MATRIX	38.6

ASI - C / EPON 828 - mPDA

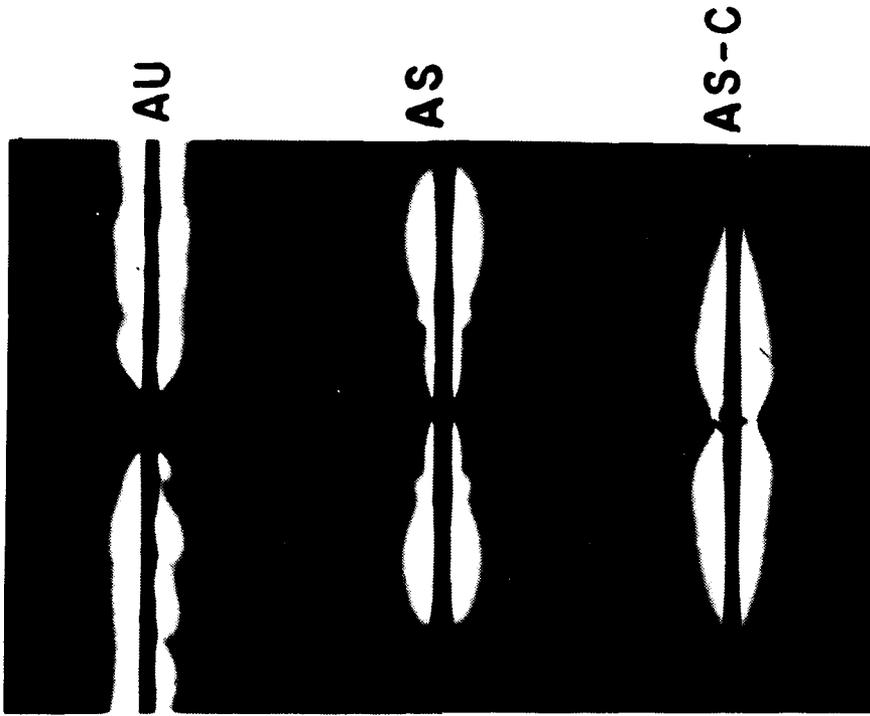


100 μ m

TRANSMITTED
LIGHT



POLARIZED
LIGHT



100 μm

Transmitted and Polarized Light Micrographs of AU, AS and ASC
Graphite Fibers in Epoxy under Strain

AFWAL-TR-82-4007

A METHOD FOR OPTIMIZATION OF COMPOSITE MATERIALS

N. BALASUBRAMANIAN
AFWAL/MLBM

OBJECTIVES

- TO SHOW THE INFLUENCE OF THE PROPERTIES OF CONSTITUENT MATERIALS ON THE FAILURE ENVELOPES OF LAMINATES.
- LAMINATE OPTIMIZATION - PREDICTION OF THE OPTIMUM LAMINATE FOR A GIVEN LOADING CONDITION
- TO OBTAIN FAILURE ENVELOPES FOR HYBRID COMPOSITES AND ILLUSTRATE THEIR USE IN OPTIMIZATION.

CONCLUSIONS

- WHEN LOADING CONDITIONS CORRESPOND TO THE FIRST AND THIRD QUADRANTS OF NORMAL STRESS RESULTANT SPACE, THE CONDITION OF HYDROSTATIC STRAIN ($\epsilon_1^o = \epsilon_2^o$) CAN BE USED TO SPECIFY THE PLY ORIENTATIONS AND THICKNESSES OF THE OPTIMUM LAMINATE. WHEN THIS CONDITION IS MET, ALL PLYS FAIL SIMULTANEOUSLY.
- IN THE CASE OF GLASS-EPOXY AND BORON-EPOXY, SIMULTANEOUS PLY FAILURE AND HENCE OPTIMIZATION (BY THE SIMPLE METHOD PROPOSED HERE) ARE POSSIBLE IN THE SECOND AND FOURTH QUADRANTS ALSO.
- SIMULTANEOUS PLY FAILURE AND LAMINATE OPTIMIZATION ARE POSSIBLE IN ALL FOUR QUADRANTS BY THE USE OF HYBRID COMPOSITES.

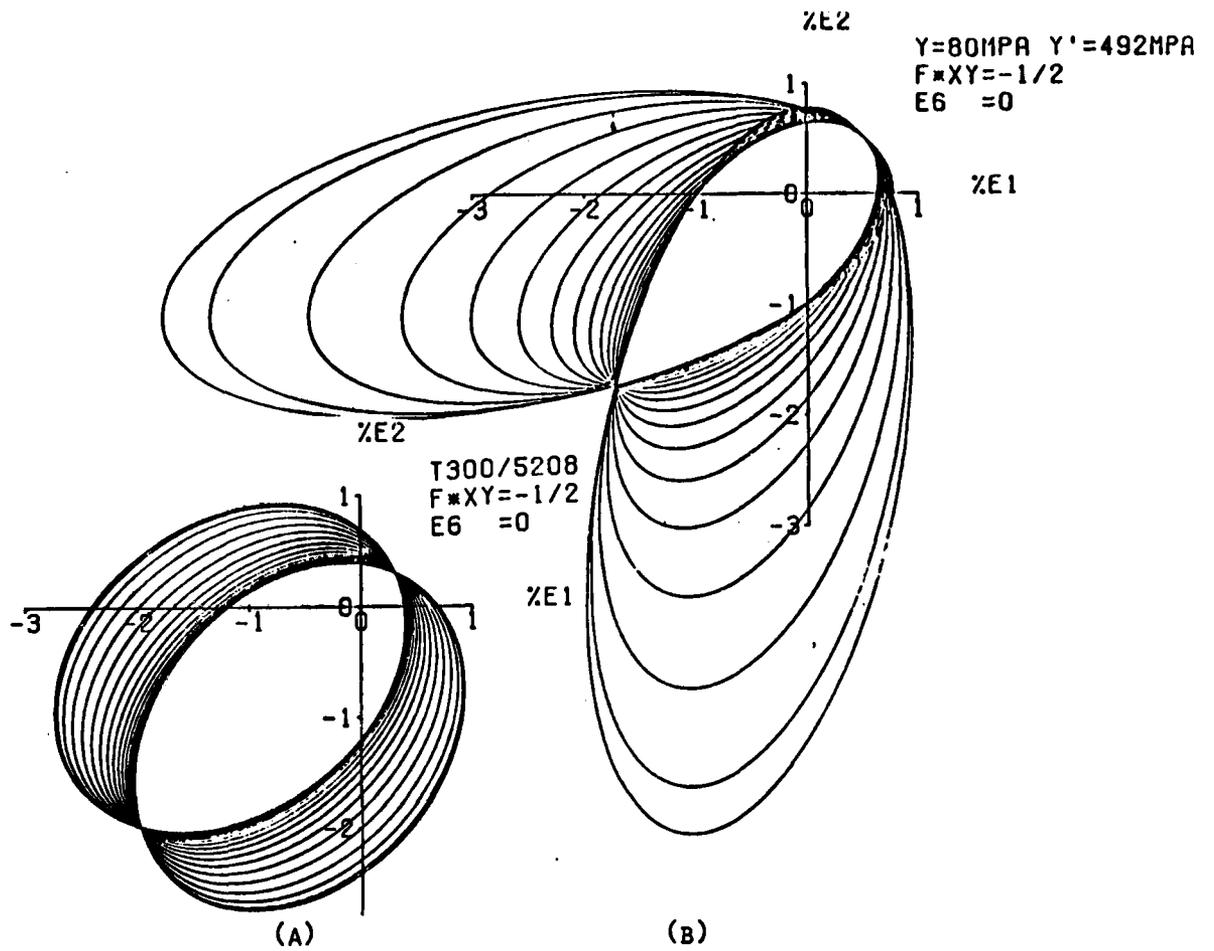


Figure 1. The Change in Failure Envelopes of Graphite-Epoxy Laminates (A) Due to the Improvement of Matrix Strength (B)

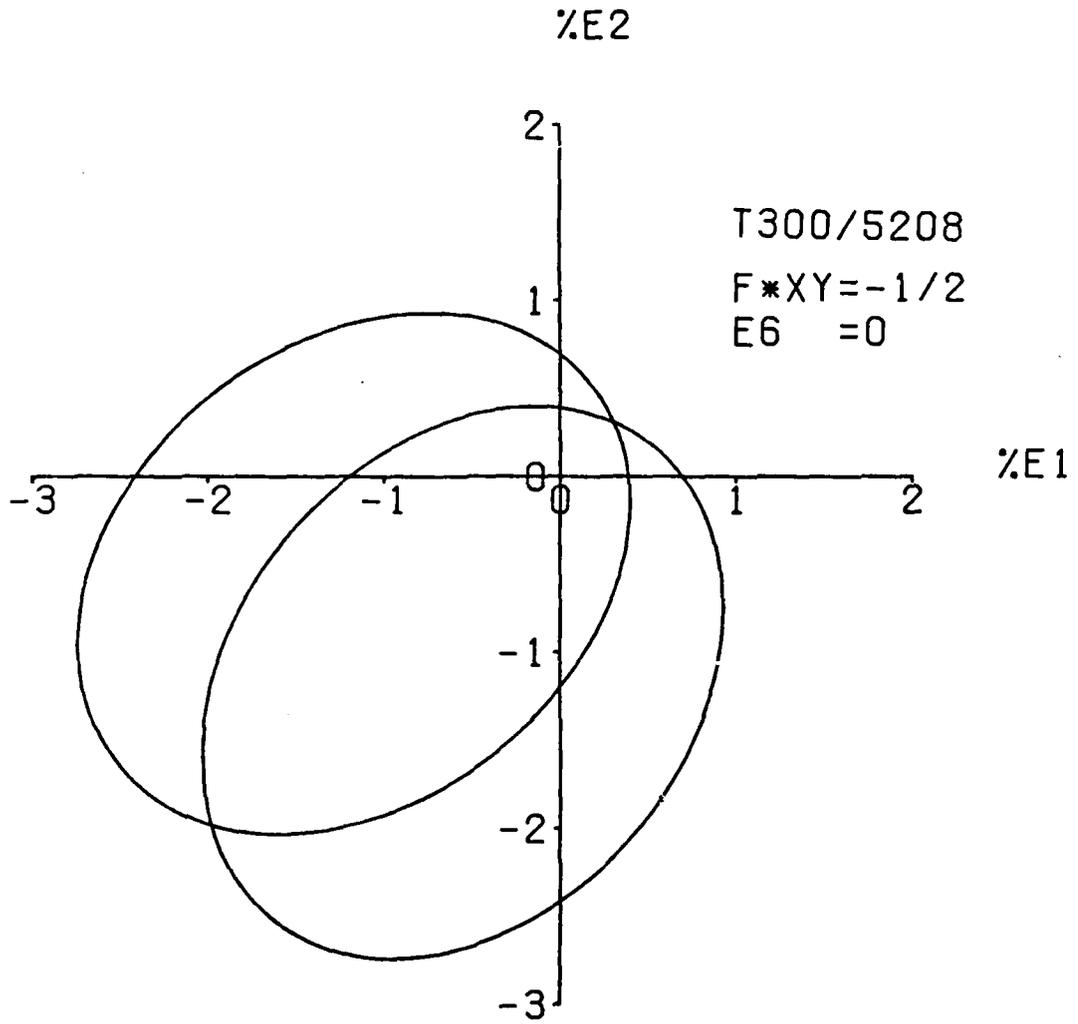


Figure 2. Failure Surfaces of Cross-Ply Laminates of Graphite-Epoxy

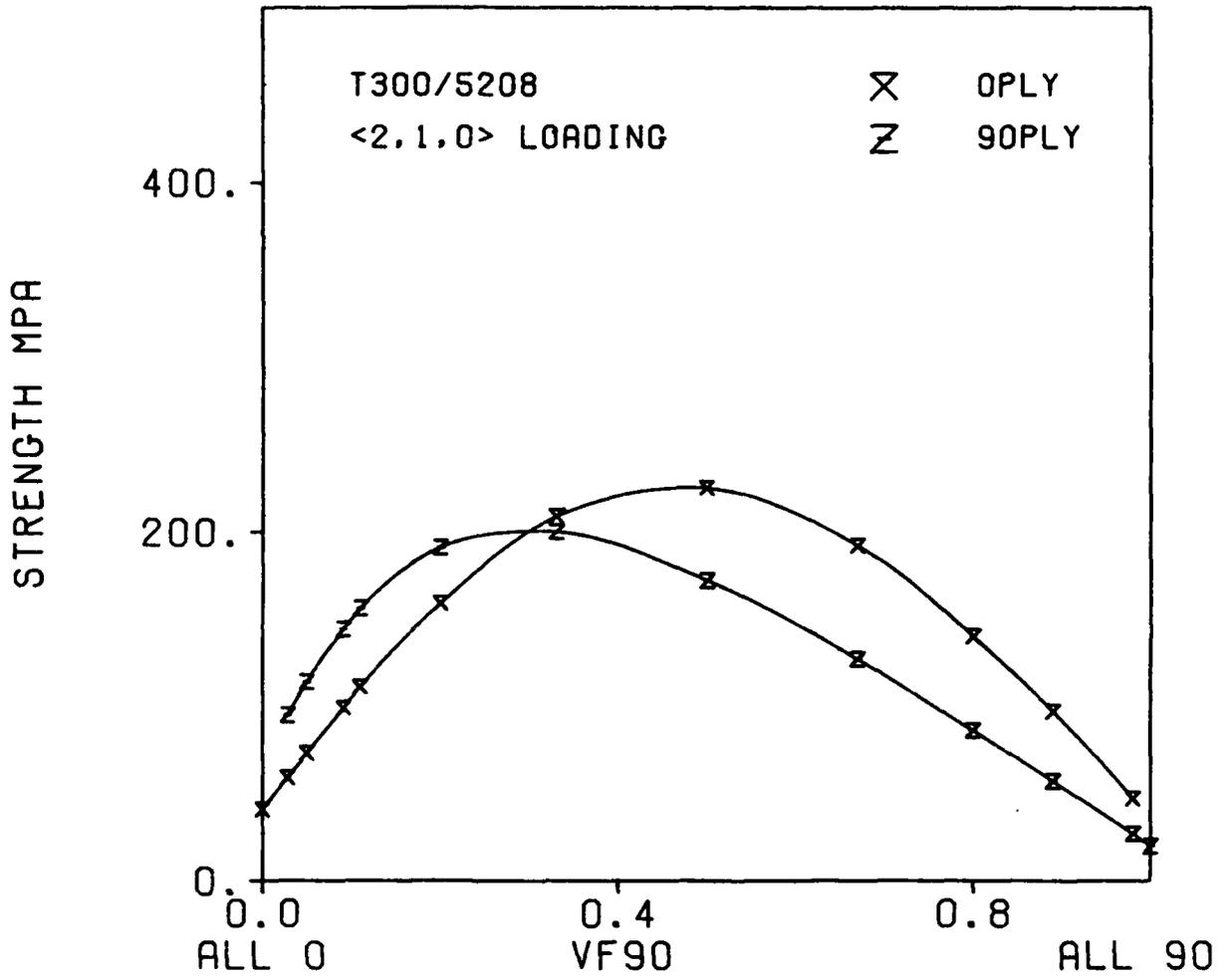


Figure 3. Ply Failure Stresses for Cross-Ply Laminates of Graphite-Epoxy for < 2, 1, 0 > Loading. In the Optimum Laminate the Strain Induced is Hydrostatic and the Plies Fail Simultaneously

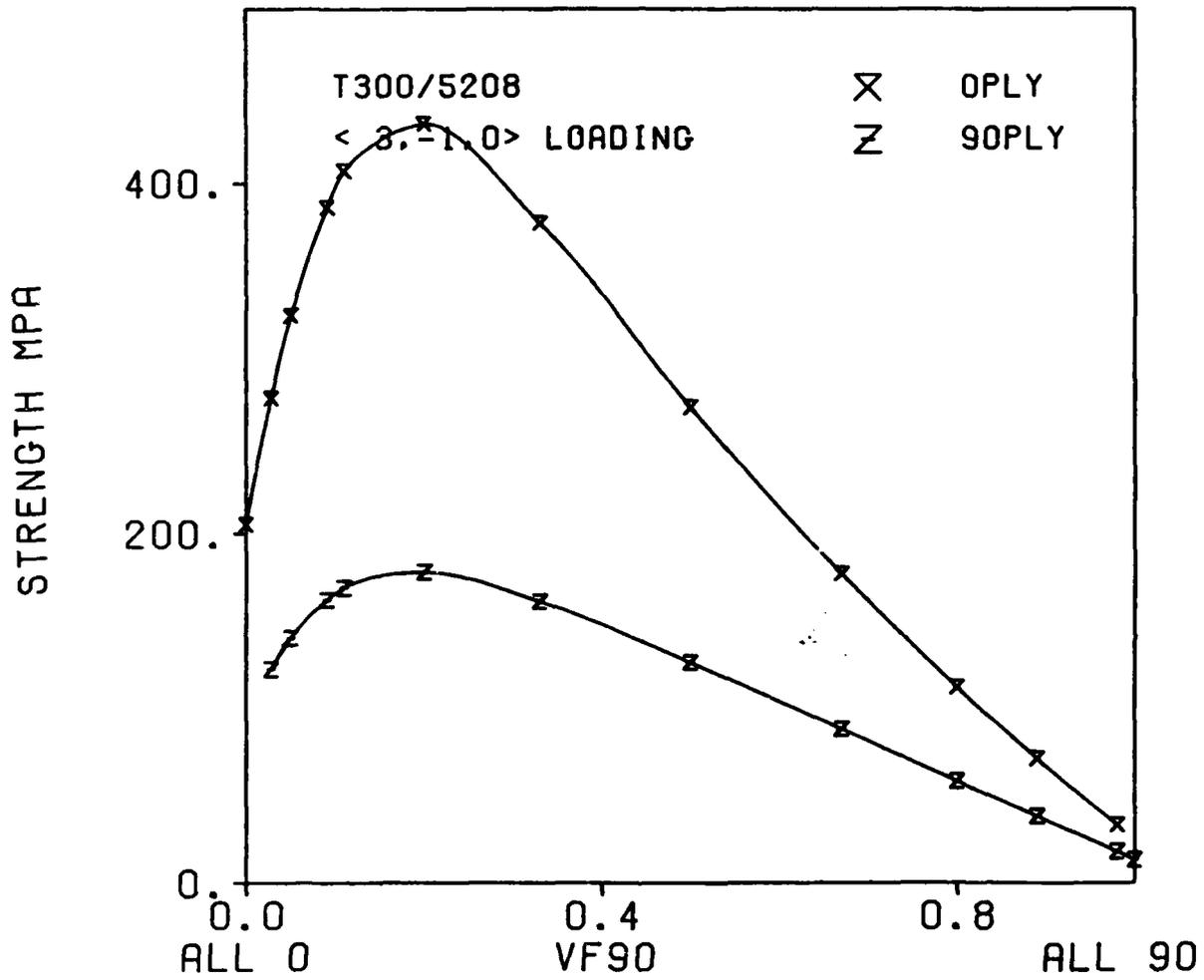


Figure 4. Ply Failure Stresses for Cross-Ply Laminates of Graphite-Epoxy for $\langle 3, -1, 0 \rangle$ Loading. A $[0_4/90]_s$ Laminate has the Maximum Value of FPF Strength

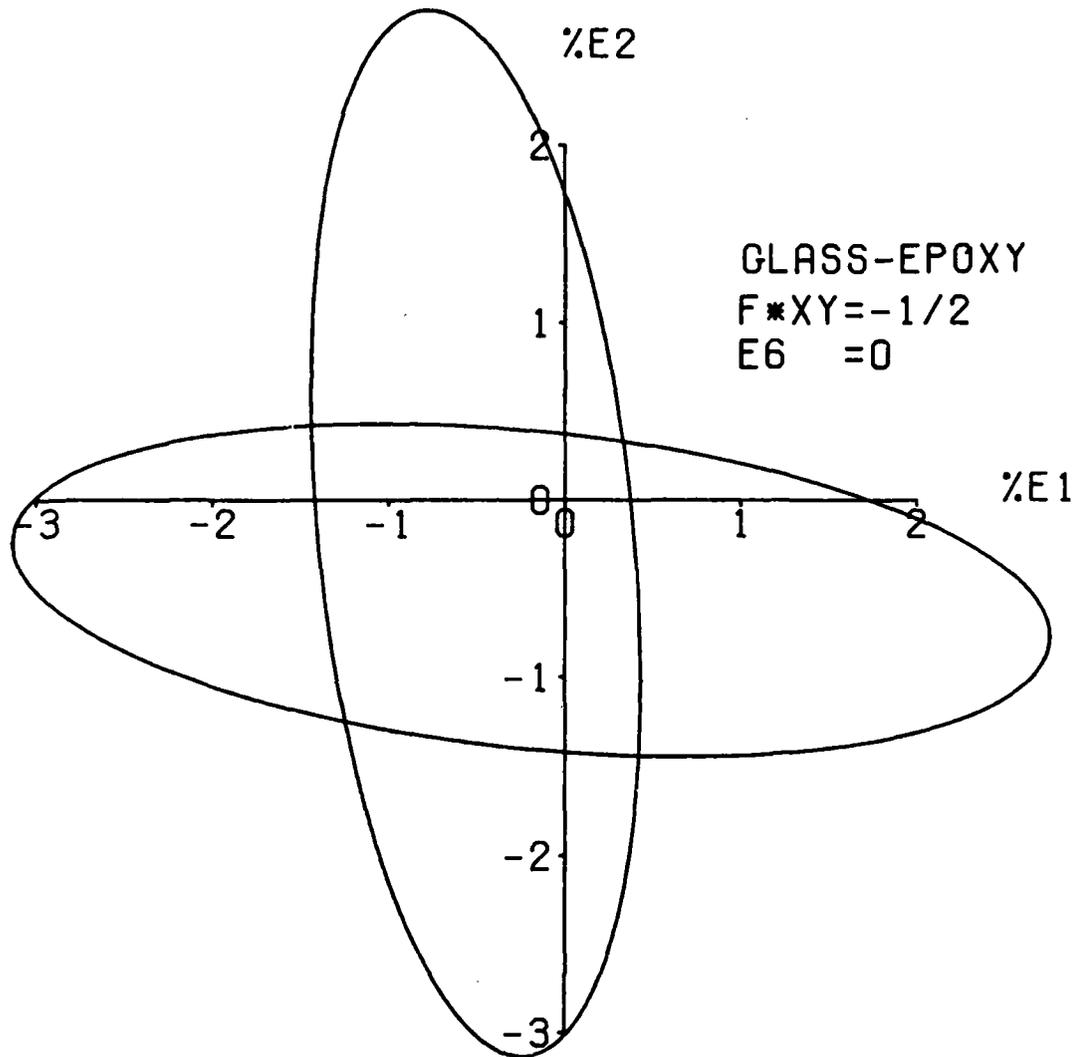


Figure 5. Failure Surfaces of Cross-Ply Laminates of Glass-Epoxy

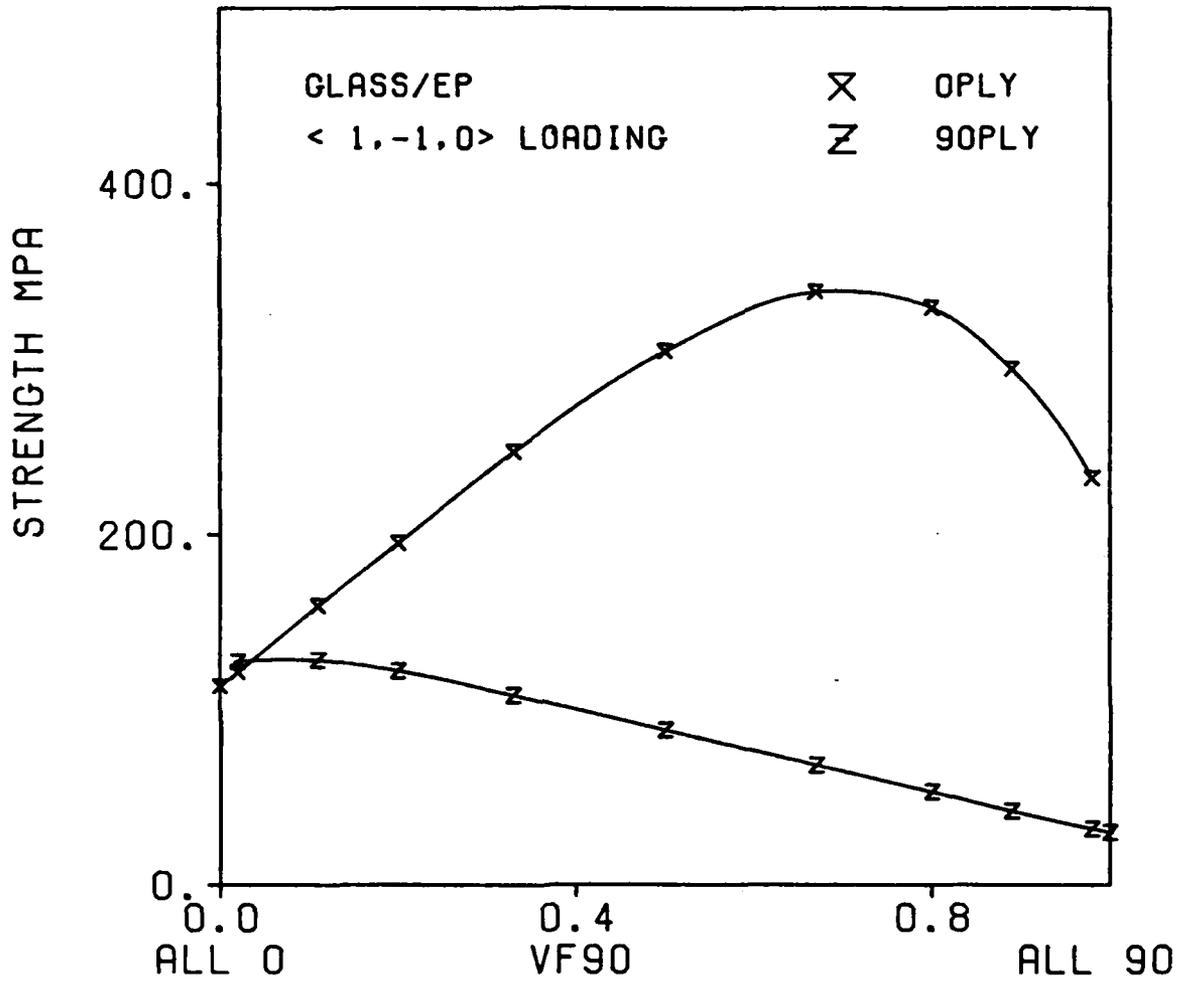


Figure 6. Ply Failure Stresses for Cross-Ply Glass-Epoxy Laminates for < 1, -1, 0 > Loading. Simultaneous Ply Failure Occurs in $[0_{20}/90]_S$ which has the Maximum Value of FPF Strength

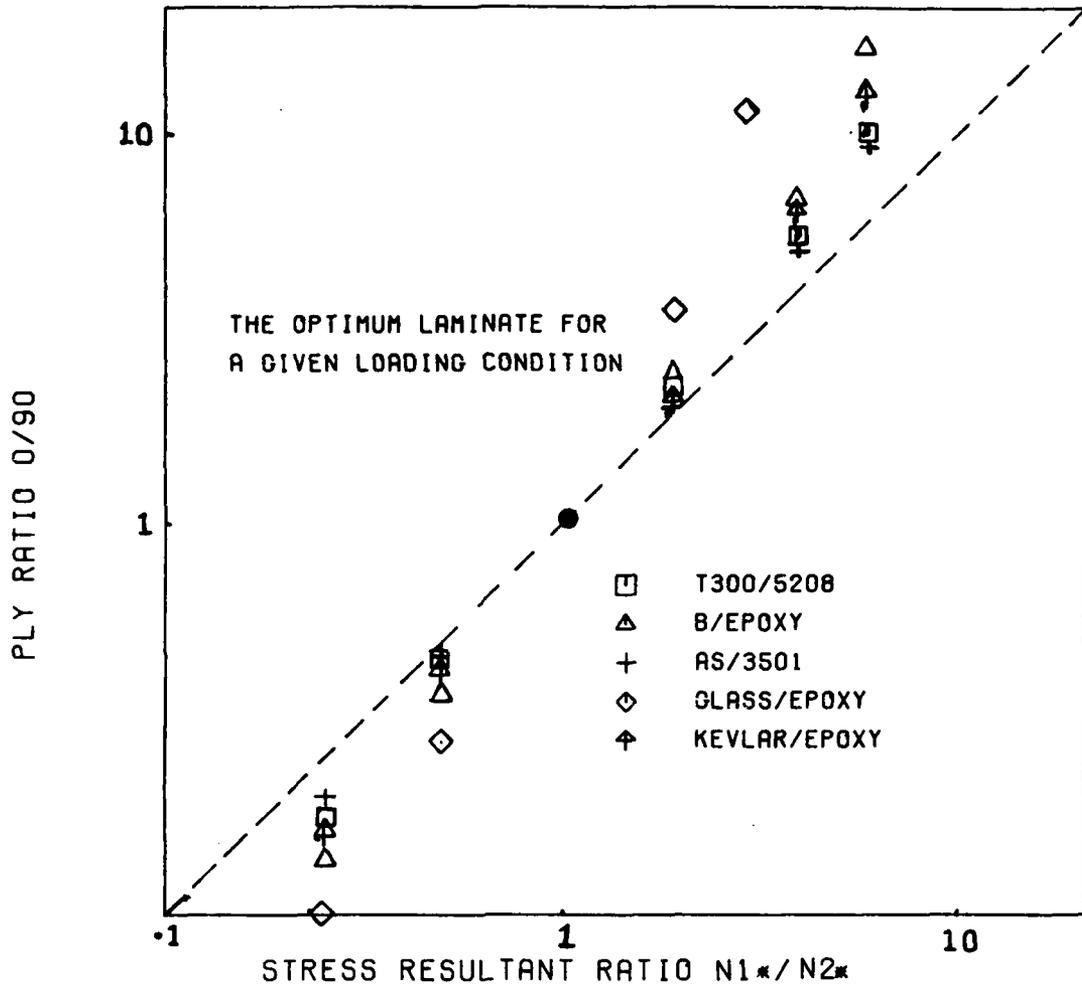


Figure 7. Laminate Optimization. The Predicted Ply Ratio of the Optimum Cross-Ply Laminate for a Given Loading Condition. The Dotted Line Corresponds to Netting Analysis

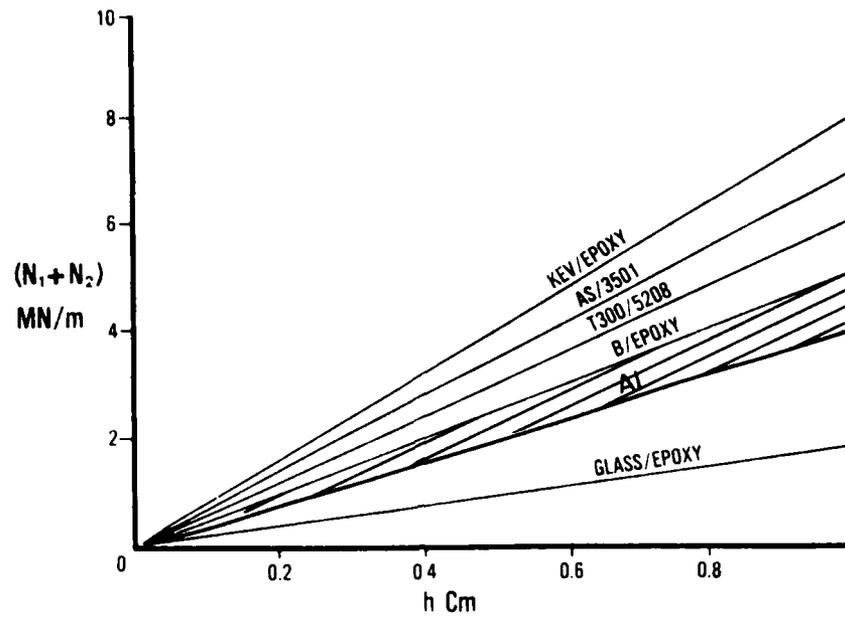


Figure 8. Laminate Sizing: The Thickness of the Optimum Laminate to Support a Given Stress-Resultant in the First Quadrant of Stress-Resultant Space

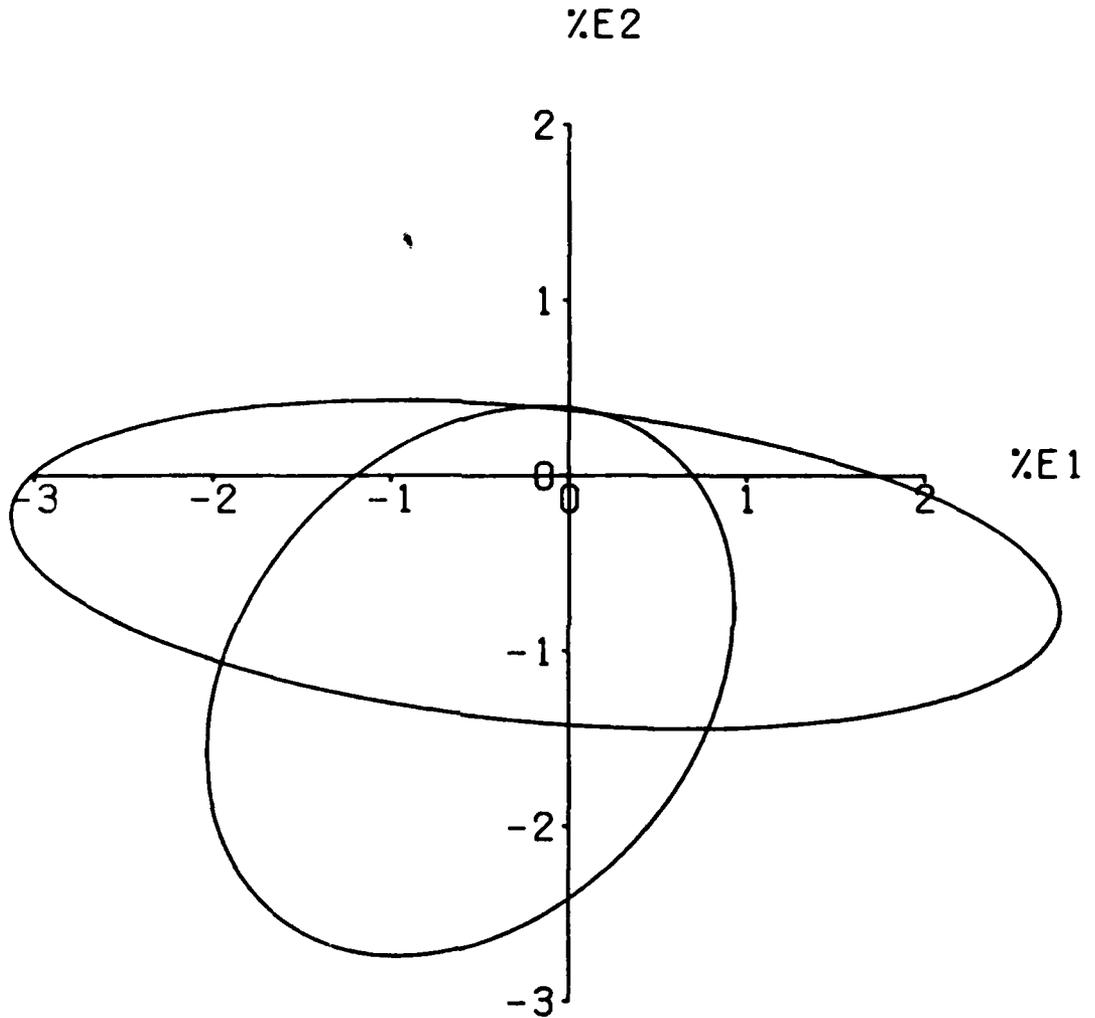


Figure 9. Failure Surfaces of Graphite-Glass-Epoxy Hybrid Composites

AFWAL-TR-82-4007

A TECHNIQUE FOR PREVENTION OF DELAMINATION

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OBJECTIVES:

- 0 TO DEVELOP A TECHNIQUE TO PREVENT DELAMINATION OF A TENSILE COUPON IN THE PRESENCE OF IN-PLANE TENSILE LOAD
- 0 TO STUDY THE EFFECT OF DELAMINATION ON THE LAMINATE STRENGTH

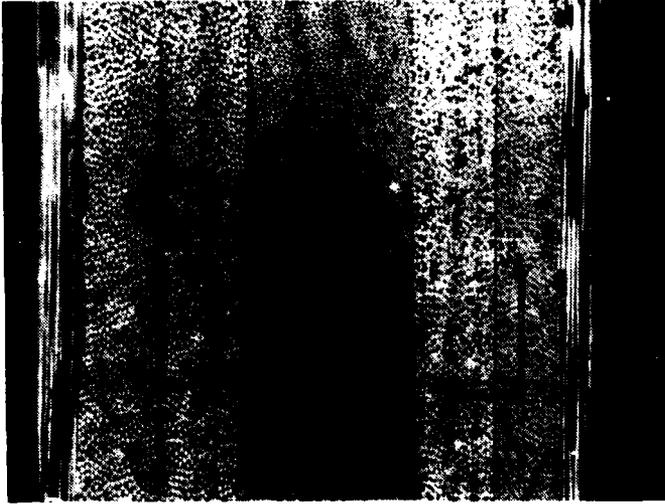
APPROACH:

- 0 REINFORCING THE FREE EDGES OF THE TENSILE COUPON WITH FIBERGLASS CLOTH

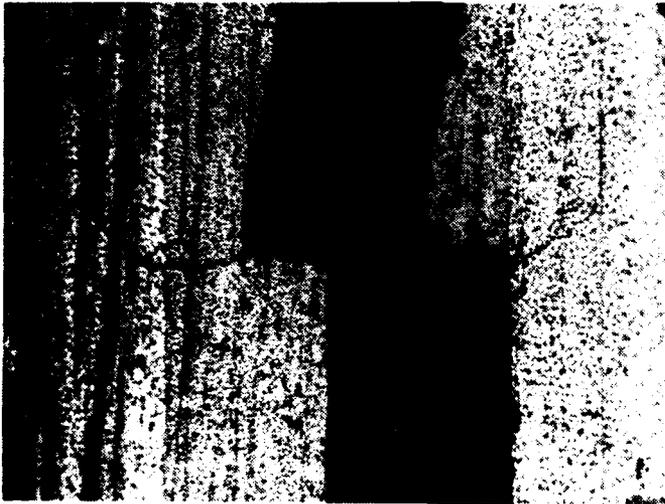


MATERIAL: FIBER GLASS CLOTH
ADHESIVE: EPON 828

Figure 1. Sketch of Reinforced Specimen



80 KSI
REINFORCED



60 KSI
UNREINFORCED

Figure 2. Microphotographs Showing Free Edge Delamination of the $[0\pm 45/90]_s$ Laminate Under Static Tension

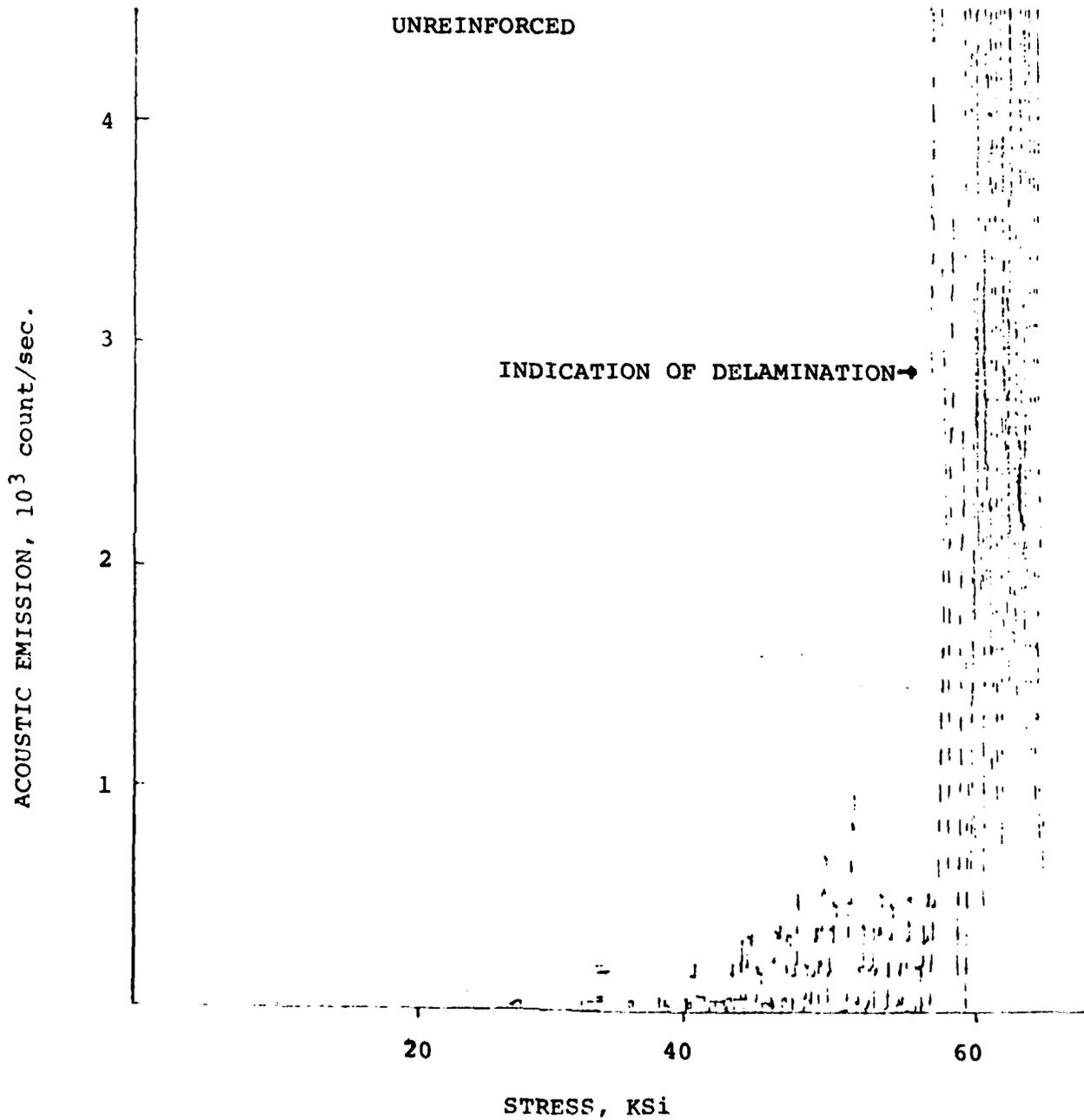


Figure 3. Applied Stress vs. Acoustic Emission for a $[0/\pm 45/90]_s$ Laminate

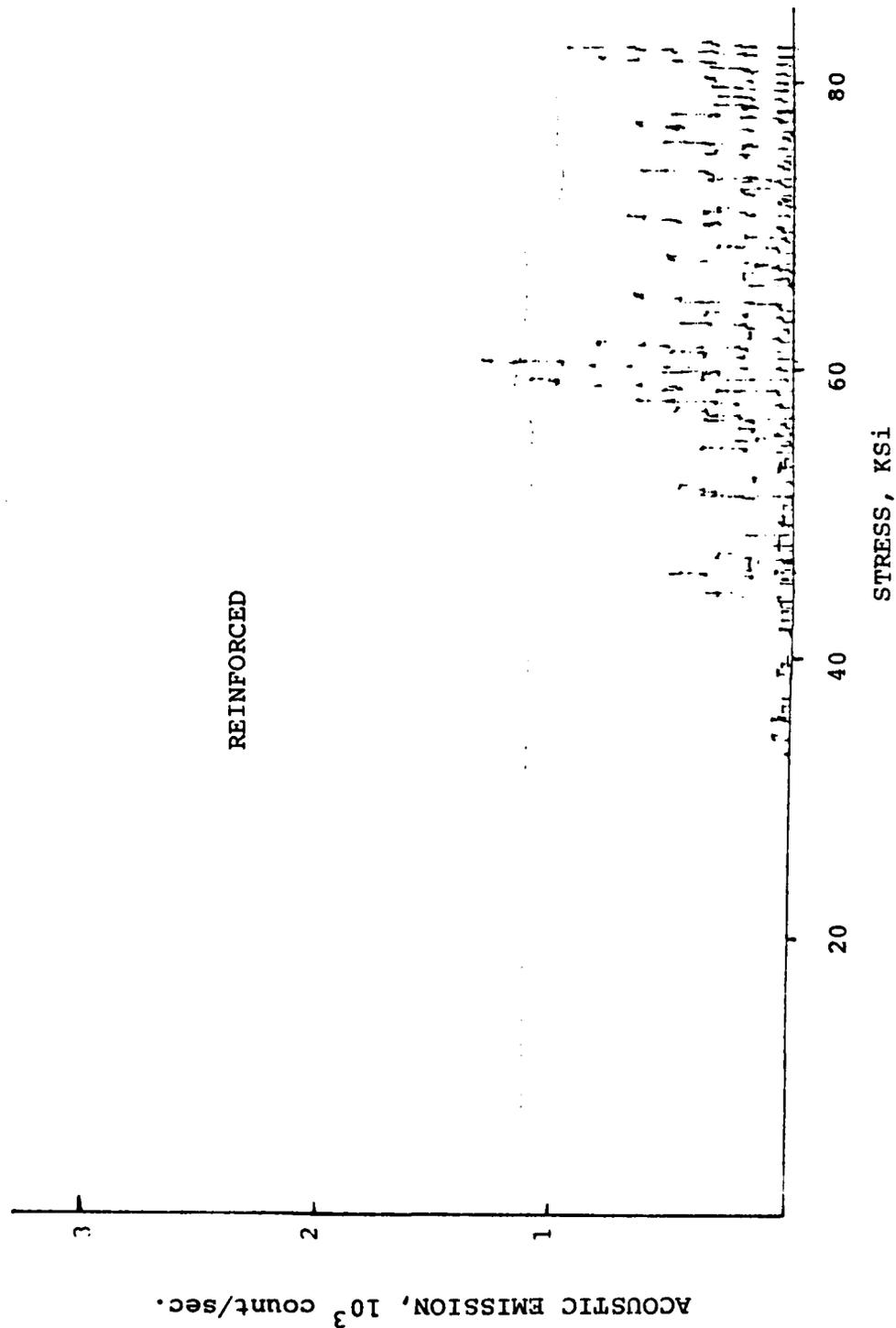
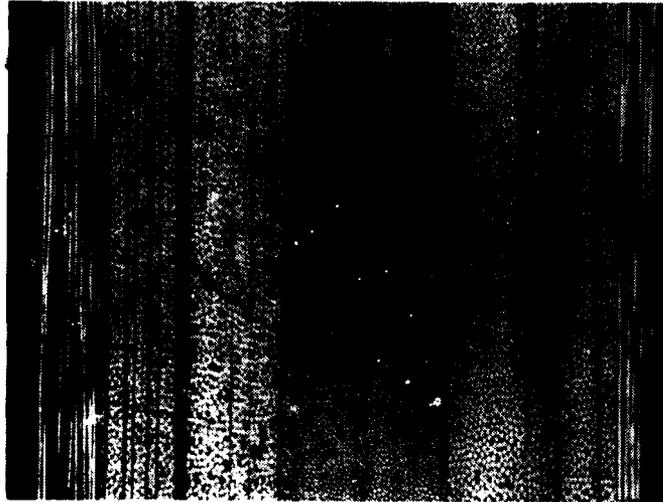


Figure 4. Applied Stress vs. Acoustic Emission for a Reinforced $[0/\pm 45/90]_5$ Laminate

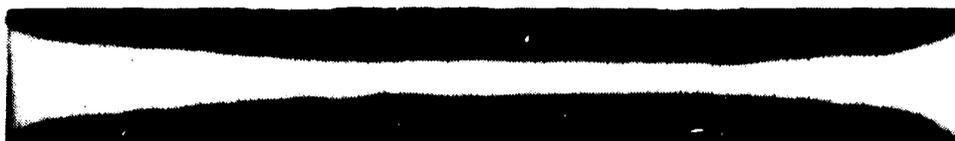


$N = 1.5 \times 10^6$ CYCLE
 $S_{\max} = 50$ KSI
REINFORCED



$N = 10^4$ CYCLE
 $S_{\max} = 50$ KSI
UNREINFORCED

Figure 5. Microphotographs Showing Free Edge Delamination of the $[0/\pm 45/90]_5$ Laminate Under Tension-Fatigue



$N = 10^4$ CYCLE, $S_{\max} = 50$ KSI

UNREINFORCED



$N = 1.5 \times 10^6$ CYCLE, $S_{\max} = 50$ KSI

REINFORCED

Figure 6. X-ray Picture Showing Extension of Delamination into the Middle of Specimen Width Under Tension-Tension Fatigue. $(0/\pm 45/90)_s$

PRIOR TO FATIGUE
 AFTER 10^4 CYCLE
 AT $S_{max} = 50$ KSI

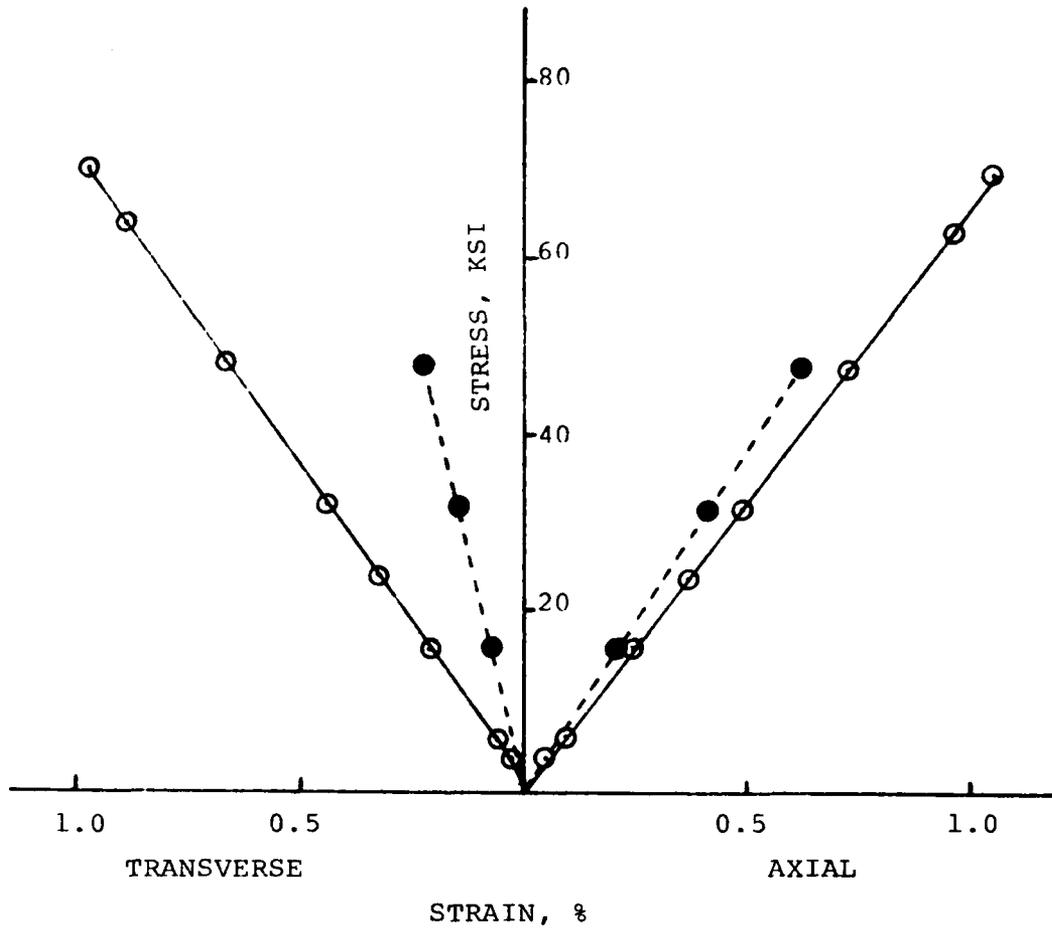


Figure 7. Stress vs. Strain Prior to and After Fatigue for a $(0/\pm 45/90)_s$ Laminate

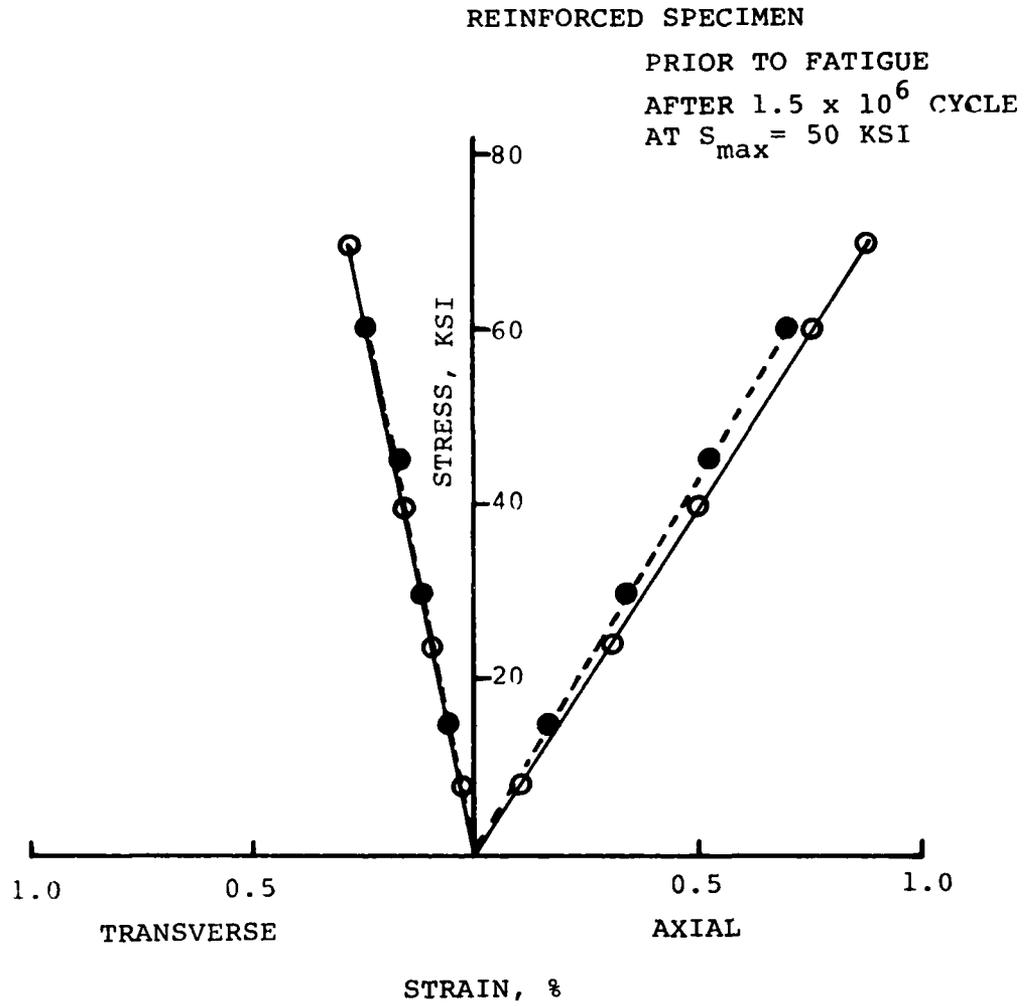


Figure 8. Stress vs. Strain Prior to and After Fatigue for a Reinforced $(0/\pm 45/90)_s$ Laminate

TABLE 1
 DELAMINATION THRESHOLD STRAIN LEVEL DETERMINED BY EXPERIMENT

Laminate	Delamination threshold strain, %	
	Unreinforced	Reinforced
$[\pm 45/0/90]_S$	0.52	No delamination
$[0/\pm 45/90]_S$	0.66	No delamination
$[0_2/\pm 45_2/90_2]_S$	0.54	No delamination
$[\pm 30/90]_S$	0.39	No delamination
$[\pm 30_4/90]_S$	0.26	.50
$[\pm 30_6/90]_S$	0.22	.48

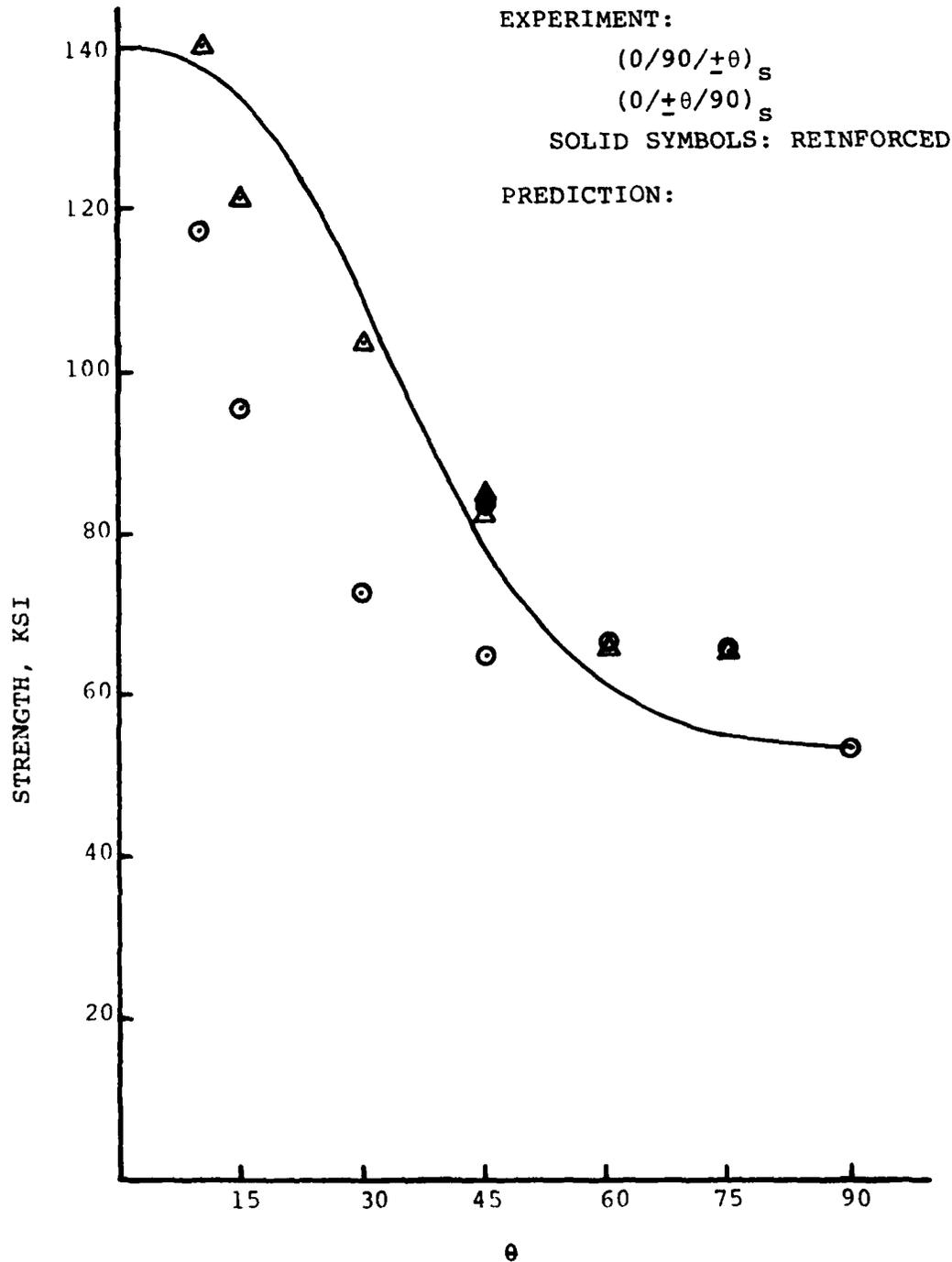


Figure 9. Tensile Strength of $(0/90/\pm\theta)_S$ and $(0/\pm\theta/90)_S$ Laminates. Delamination occurred in the $(0/\pm\theta/90)_S$ Laminates for $\theta \leq 45$ degree

CONCLUSIONS:

- o PRELIMINARY TESTING INDICATES THAT REINFORCEMENT OF THE FREE EDGES OF THE SPECIMEN IS VERY EFFECTIVE TO PREVENT AND/OR DELAY INITIATION OF DELAMINATION
- o BONDING PROCESS, INCLUDING SELECTION OF REINFORCING MATERIAL AND ADHESIVE, MUST BE FURTHER DEVELOPED
- o DETRIMENTAL EFFECT OF DELAMINATION TO THE LAMINATE STRENGTH WAS GREATLY REDUCED WITH THE REINFORCED EDGES

AFWAL-TR-82-4007

THE DETERMINATION OF INTERLAMINAR MODULI OF
GRAPHITE/EPOXY COMPOSITES

30 OCTOBER 1981

OBJECTIVE

- TO INVESTIGATE EXPERIMENTAL TECHNIQUES FOR THE DETERMINATION OF INTERLAMINAR MODULI OF GRAPHITE/EPOXY COMPOSITES
- TO OBTAIN DATA ON THE INTERLAMINAR MODULI OF GRAPHITE/EPOXY COMPOSITES

APPROACH

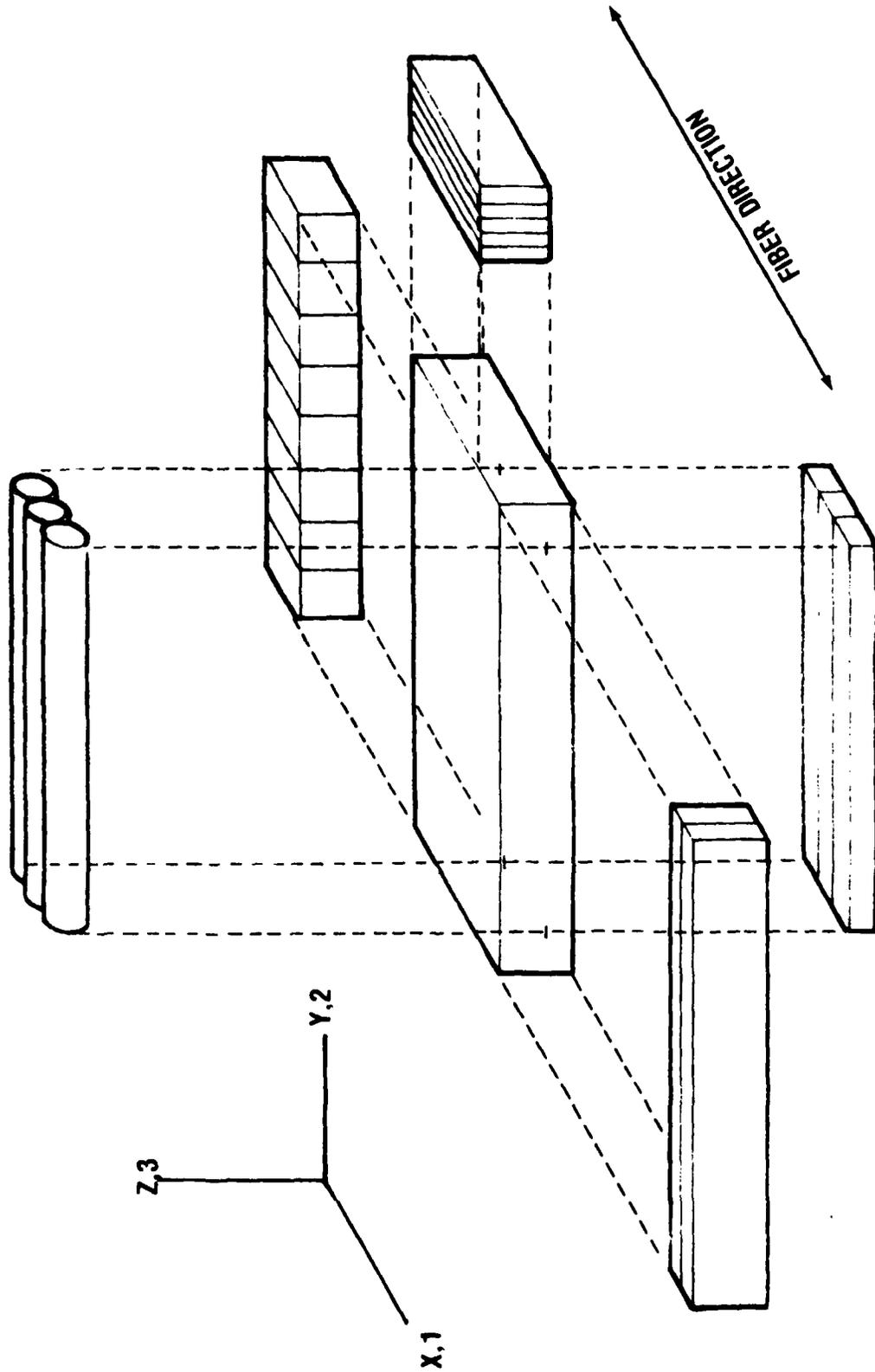
- FABRICATE AND TEST THICK GRAPHITE/EPOXY LAMINATES
- COMPARE THE DATA TO REDUNDANT TEST RESULTS AND TO MICROMECHANICS MODELS

CONCLUSIONS

- EXPERIMENTAL TECHNIQUES EXIST THAT PRODUCE ACCEPTABLE DATA ON THE INTERLAMINAR MODULI OF GRAPHITE/EPOXY.
- GOOD AGREEMENT EXISTS BETWEEN THE DATA AND MICROMECHANICS MODELS AND REDUNDANT TESTS.

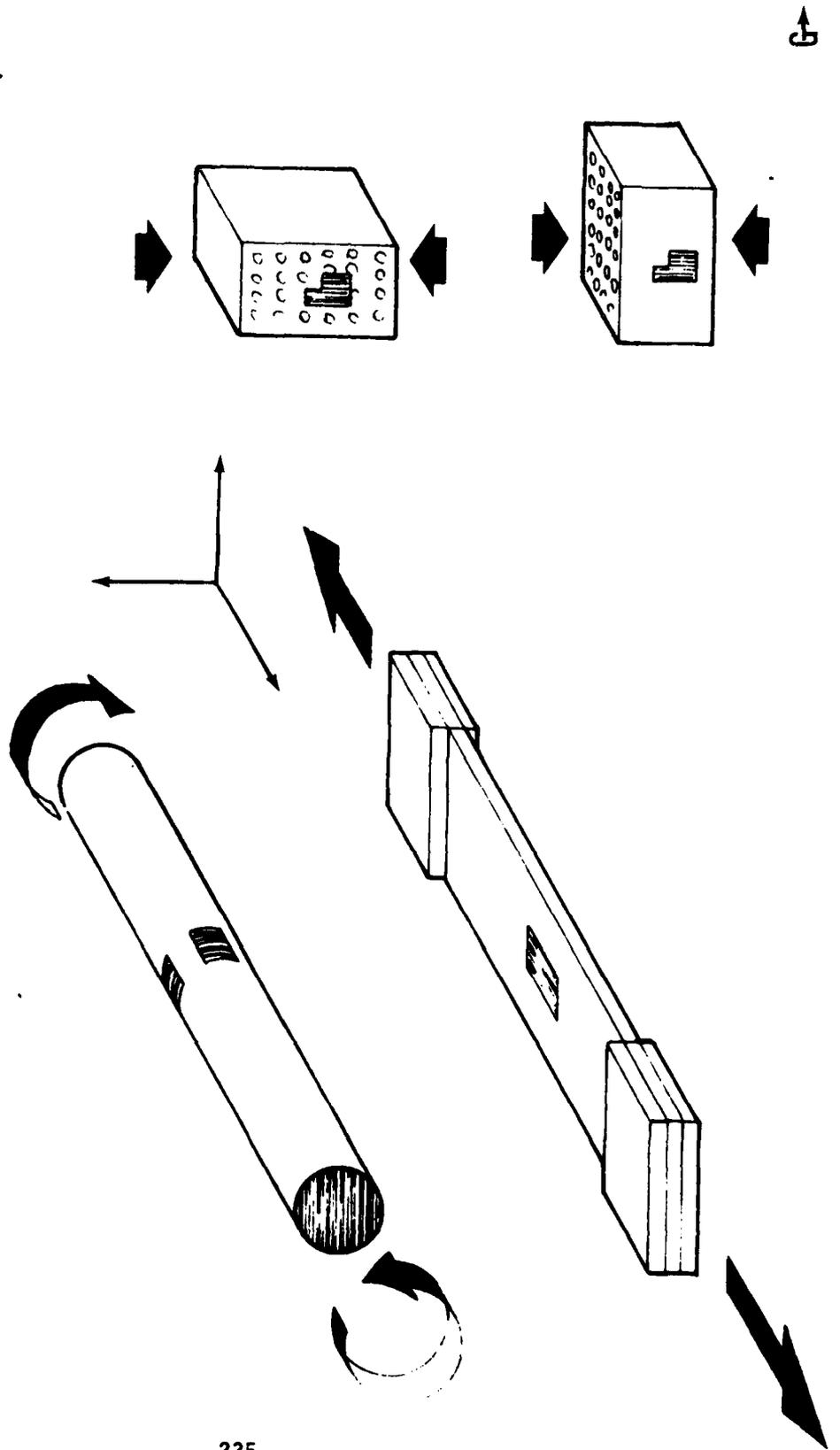


SPECIMEN PLAN



ML MLB 9 1-6-6

SPECIMEN SHAPE AND GAGES



YOUNG'S MODULI FROM COMPRESSION TEST
ON BLOCK SPECIMENS

T300/5208*			AS/3502**		
E_1, E_x	E_2, E_y	E_3, E_z	E_1, E_x	E_2, E_y	E_3, E_z
10^6 psi					
-	1.643	1.54	21.58	1.619	1.626
-	1.636	1.49	21.81	1.668	1.715
-	1.588	1.470	18.15	1.618	1.532
-	1.462	1.407	19.17	-	1.684
-	1.483	1.500	20.5	-	1.745
-	1.429	1.470	-	-	1.697
-	1.609	1.513	-	-	1.630
-	1.448	1.513	-	-	1.578
-	-	-	-	-	1.558
-	-	-	-	-	1.509
-	-	-	-	-	1.611
-	-	-	-	-	1.611
ave. = -	1.530	(1.488)	(20.24)	(1.635)	(1.626)

* fiber volume fraction, $V_f = .63$

** fiber volume fraction, $V_f = .73$

POISSON'S RATIOS FROM COMPRESSION TEST

T300/5208 *		AS/3502 **		
ν_{23}, ν_y	ν_{32}, ν_y	ν_{23}, ν_y	ν_{32}, ν_y	ν_{13}, ν
.532	.61	.519	.533	.0232
.527	.61	.529	.503	.0235
.540	.49	.581	.516	.0258
.510	.54	.580	.512	.0277
.556	.522	.567	.516	.0284
.535	.547	.556	.503	.0276
.495	.521			
.500	.539			
.528	.527			
.555	.534			
.568	.506			
<u>.566</u>	<u>.542</u>	_____	_____	_____
ave. = .534	.541	.555	.514	.0260

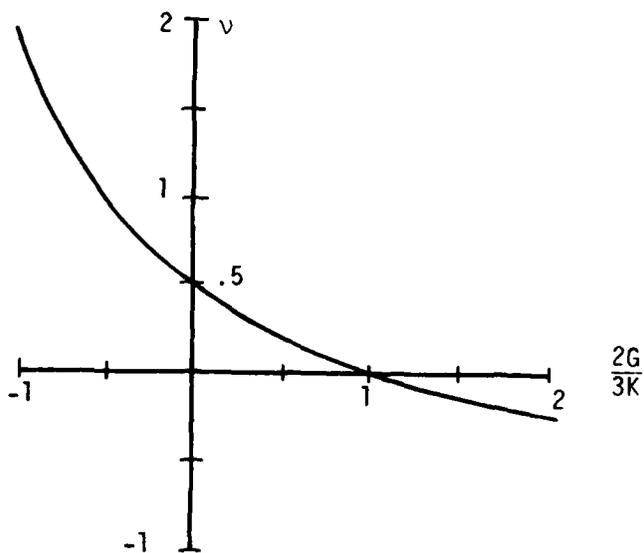
* fiber volume fraction, $V_f = .63$

** fiber volume fraction, $V_f = .73$

BOUNDS ON POISSON'S RATIO

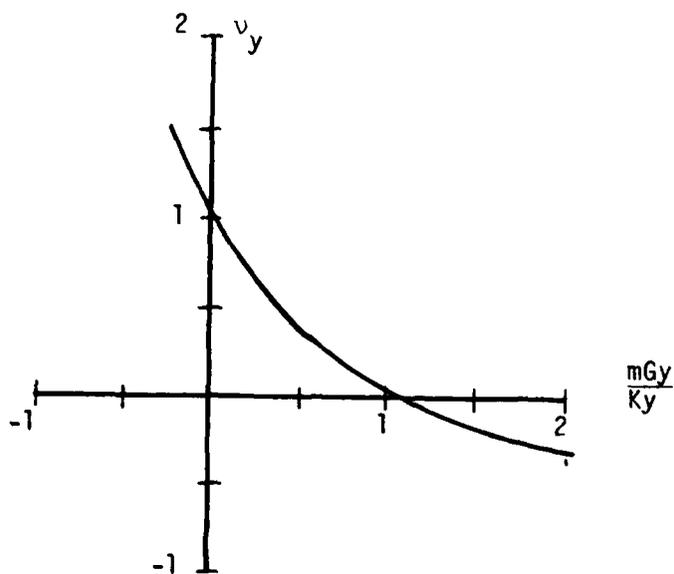
ISOTROPIC MATERIALS

$$\nu = \frac{1 - \frac{2G}{3K}}{2 + \frac{2G}{3K}}$$



TRANSVERSELY ISOTROPIC MATERIALS

$$\nu_y = \frac{1 - \frac{mG_y}{K_y}}{1 + \frac{mG_y}{K_y}}$$



ELASTIC PROPERTIES OF GRAPHITE/EPOXY

Property	T300/5208*		AS/3502**	
	Theory	Experiment	Theory	Experiment
$E_x, E_1, 10^6 \text{ psi}$	21.6	20.0	25.0	20.1
$E_y, E_2, 10^6 \text{ psi}$	1.49 1.60	1.54	1.68 1.79	1.60
$E_x, E_3, 10^6 \text{ psi}$	1.49 1.60	1.49	1.68 1.79	1.63
$E_s, G_{12}, 10^6 \text{ psi}$.630 .920	.866	1.22	.878
$G_y, G_{23}, 10^6 \text{ psi}$.515 .580	.506	.587 .632	.548
ν_x, ν_{21}	.315 .315	.30	.312 .310	.313
ν_x, ν_{31}				.324
ν_y, ν_{12}				.024
ν_y, ν_{23}	.416 .466		.404 .449	.542
ν, ν_{13}				.026
ν_y, ν_{32}	.416 .466	.541	.404 .466	.514

* fiber volume fraction, $V_f = .63$

** fiber volume fraction, $V_f = .73$

SHEAR MODULI FROM TORSIONAL SHEAR TEST

T300/5208 *		AS/3502**	
G_{12}, E_s	G_{23}, G_y	G_{12}, E_s	G_{23}, G_y
10^6 psi	10^6 psi	10^6 psi	10^6 psi
.849		.892	.551
.835			.550
.887	.519	.876	.542
.856	.503		.546
.893	.523	.867	.554
.866	.491		.545
<u>.859</u>	<u>.486</u>	_____	_____
ave. = .869	.504	.878	.548
.815	.489		
.895	.525		
.906	.526		
.874	.503		
<u>.859</u>	<u>.491</u>		
ave. = .877	.507		

* fiber volume fraction, $V_f = .63$

** fiber volume fraction, $V_f = .73$

AFWAL-TR-82-4007

DIGITAL PROGRAMS FOR LAMINATED COMPOSITES ANALYSIS

AFWAL/MLBM

28-30 OCTOBER 1981

OBJECTIVE

TO PROVIDE EASY TO USE DIGITAL PROGRAMS
TO CALCULATE STIFFNESS AND STRENGTH OF
LAMINATED COMPOSITE MATERIALS. THE LEVEL
OF SOPHISTICATION IS GEARED TO THE
CAPABILITY OF EACH COMPUTER.

CONCLUSIONS

• TECHNICAL REPORTS READY FOR DISTRIBUTION:

S. W. TSAI AND R. AOKI, "TI-59 MAGNETIC CARD CALCULATOR SOLUTIONS TO COMPOSITE MATERIALS FORMULAS", AFML-TR-79-4040

S. W. TSAI AND S. D. GATES, "INSTRUCTIONS FOR TI-59 COMBINED CARD/MODULE CALCULATIONS FOR IN-PLANE AND FLEXURAL PROPERTIES OF SYMMETRIC LAMINATES", AFWAL-TR-81-4116

W. J. PARK, "RADIO SHACK TRS-80 POCKET COMPUTER SOLUTIONS TO COMPOSITE MATERIALS FORMULAS", AFWAL-TR-81-4074

S. SONI, "A DIGITAL ALGORITHM FOR COMPOSITE LAMINATE ANALYSIS - FORTRAN", AFWAL-TR-81-4073

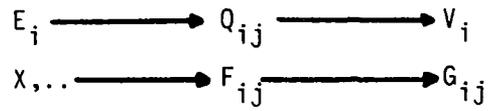
- BOTH ABSOLUTE AND NORMALIZED STIFFNESS AND STRENGTH ARE GIVEN. DIRECT COMPARISON OF LAMINATE PROPERTIES IS NOW POSSIBLE.
- PRIOR EXPERIENCE IN COMPOSITE MATERIALS IS NOT REQUIRED. SELF TEACHING IS EASY TO ACHIEVE.

COMPUTING CAPABILITIES

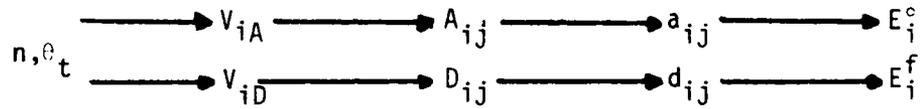
	SYMMETRIC LAMINATES	HYGRO-THERMAL	GENERAL LAMINATES	HYBRIDS
TI-59 CARDS ONLY	YES	YES	YES	NO
TI-59 COMBO	YES	NO	NO	YES (in-plane only)
TRS-80	YES	YES (in-plane only)	NO	NO
FORTRAN	YES	YES	YES	YES

ALGORITHM

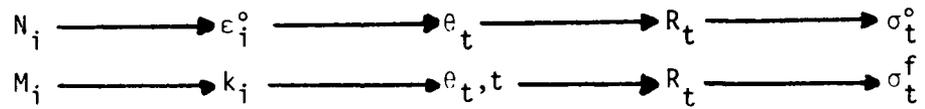
• PLY DATA



• STIFFNESS



• STRENGTH



STRESS-STRAIN RELATIONS OF LAMINATED PLATES

$$\begin{Bmatrix} N \\ M \end{Bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \begin{Bmatrix} \epsilon^0 \\ \kappa \end{Bmatrix} = \begin{bmatrix} A^* & B^* \\ 3B^* & D^* \end{bmatrix} \begin{Bmatrix} \sigma^0 \\ \sigma^f \end{Bmatrix}$$

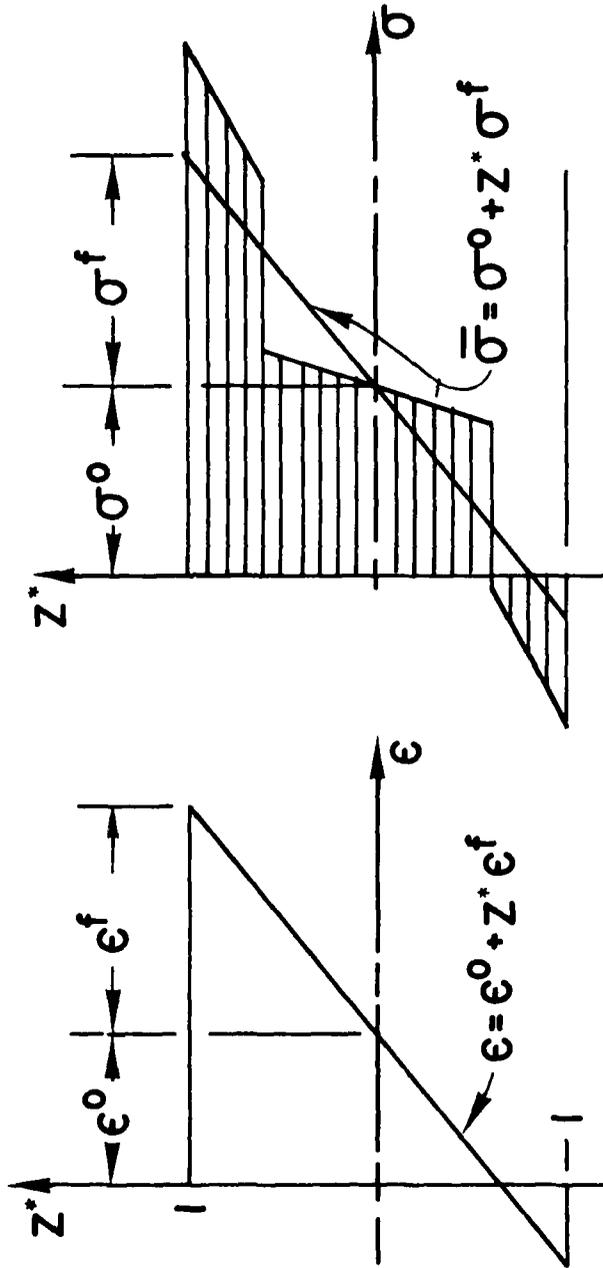
$$\begin{Bmatrix} \epsilon^0 \\ \kappa \end{Bmatrix} = \begin{bmatrix} \alpha & \beta \\ \tilde{\beta} & \delta \end{bmatrix} \begin{Bmatrix} N \\ M \end{Bmatrix} = \begin{bmatrix} \alpha^* & \frac{1}{3}\beta^* \\ \tilde{\beta}^* & \delta^* \end{bmatrix} \begin{Bmatrix} \sigma^0 \\ \sigma^f \end{Bmatrix}$$

$$\sigma^0 = N^* = N/h \quad A^* = A/h \quad \alpha^* = h\alpha$$

$$\sigma^f = M^* = 6M/h^2 \quad B^* = 2B/h^2 \quad \beta^* = h^2\beta/2$$

$$\epsilon^f = \kappa^* = h\kappa/2 \quad D^* = 12D/h^3 \quad \delta^* = h^3\delta/12$$

IN-PLANE AND FLEXURAL STRAINS AND STRESSES



AFWAL-TR-82-4007

APPENDIX A

ABSTRACTS

TITLE: EFFECT OF DEFECTS IN COMPOSITE STRUCTURES
G. P. Sendeckyj, AFWAL/Flight Dynamics Laboratory

With the acceptance of composites as airframe structural materials, development of an understanding of the effect of defects in composites is beginning to receive renewed emphasis. The results of a review of the literature on the effects of defects will be presented in the light of current and potential design strain levels. Research areas requiring additional work will be identified.

TITLE: RESIN SELECTION CRITERIA FOR ENGINE COMPOSITE STRUCTURES
C. C. Chamis and G. T. Smith, NASA Lewis Research Center

An integrated mechanistic approach is described to assess, evaluate, and identify desirable resin characteristics for improved composite properties such as toughness and impact resistance. The approach consists of composite micromechanics, composite macromechanics, laminate theory and structural/stress analyses. All these are used formally to identify the resin characteristics which have significant effect on composite mechanical behavior. The composite mechanical behavior is assessed with respect to static strength, fatigue resistance, stress concentration, defect initiation, and growth, and impact resistance as well as buckling, vibration and damping. The resin effects on composite mechanical behavior are assessed with respect to (1) load transfer (at the interface, at the end of broken fibers, at free surfaces and through the interply layer); (2) fracture modes and associate fracture surface characteristics; (3) residual stresses; and (4) hygrothermal environmental effects. The results are summarized into convenient criteria which can be used to select resins a priority with desirable characteristics for improved and/or specific composite "toughness".

TITLE: DAMAGE PROGRESSION IN GRAPHITE-EPOXY COMPOSITES BY A DEPLYING
TECHNIQUE
S. M. Freeman, Lockheed-Georgia Company

Open holes and mechanically fastened joint specimens employing three different symmetric, stacking sequences were used for this project. Replicates for each specimen type and stacking sequence were loaded to ultimate and four load levels below ultimate to produce specimens containing progressive amounts of damage. During the loading of each specimen acoustic emissions were monitored as a function of load. The lowest load level was based on acoustic emissions indicating the first occurrence of significant damage in the ultimate tests. The highest load level was 90% of the minimum ultimate specimen. The other load levels were equally spaced between the low and high level. Specimens from each of the four load levels were inspected using penetrant enhanced x-ray radiography to determine the extent of matrix cracking, delaminations and fiber bundle fractures. The deply technique, a unique but destructive inspection method, was used to separate the cured

graphite-epoxy composite into its individual lamina while maintaining the integrity of each lamina. With the application of a gold chloride penetrant before deplying, the matrix damage as well as fiber bundle fracture could be readily observed on the individual laminae. The acoustic emission data and the penetrant enhanced x-ray radiograph indications are interpreted in terms of damage observed using the deplying technique. Photographs of typical lamina locations showing fiber fracture and matrix damage are presented.

TITLE: FRACTURE THEORY AND DAMAGE TOLERANCE OF COMPOSITE LAMINATES
C. C. Poe, Jr., NASA Langley Research Center

A method is being developed to predict the strength of composite laminates with crack-like damage using only fiber and matrix properties. To this end, a fracture toughness parameter, which is independent of layup and material, was derived from a strain criterion for failure of fibers in the principal load-carrying plies. Numerous data are being analyzed to verify that the parameter is independent of layup and material, and that strengths can be predicted from only lamina tensile properties.

Panels with crack-like damage are being tested to measure the effectiveness of buffer strips and bonded stringers to increase strength. Buffer strip material and configuration and stringer configuration are being systematically varied. Analyses are being developed to predict strengths in terms of material, configuration, and damage size.

TITLE: CAPTIVE BALL IMPACT STUDIES: METHODS, ANALYSIS, AND RESULTS FOR GRAPHITE/EPOXY PLATES
W. Elber, NASA Langley Research Center

A captive ball impactor, consisting of a steel ball mounted on a fiber-glass cantilever, was built to test the low-velocity impact resistance of graphite/epoxy. An electrical circuit between ball and plate was switched on during contact and measured the duration of impact. The results agreed very well with first-mode deformation analysis. Load and stress, calculated at the maximum load, showed that matrix shear strength and fiber tensile strength were the governing material performance criteria. Specimen size was found to be the dominant test parameter. Small diameter plates suffered matrix shear failures, whereas large diameter plates suffered fiber tensile failures.

TITLE: TEST SYSTEM FOR CONDUCTING BIAXIAL TESTS OF COMPOSITE LAMINATES
I. M. Daniel, S. W. Schramm, and G. M. Koller, IIT Research Institute

A system was designed for testing composite laminates under any general in-plane biaxial state of stress. A thin-wall tubular specimen with end tabs

was selected as the basic specimen to be loaded by means of internal or external pressure, axial tension or compression and torque. Anisotropic elastic finite element analyses were conducted to study the load transfer mechanism at the end of the specimen and to minimize stress discontinuities in the transition between the test section and tabbed section by varying the tab materials and geometry and the tab compensating pressures. The most critical loading from the point of view of stress discontinuity is pressure loading. The most critical stresses are the axial bending stresses in the transition region. Tapered tabs with tapered extensions of a lower stiffness material resulted in the lowest peak discontinuity stresses. Torsional loading does not introduce stress peaks. Under axial loading, significant but not excessive axial bending stresses are generated in the tabs near the end grips. The results of buckling analyses for various composite tubes showed that the most effective means of increasing the buckling load is to increase the specimen wall thickness. Decreasing the specimen length or introducing internal stabilizing pressure is much less effective. A complete system design is presented consisting of the load introduction and control, test section, load measurement, data acquisition, and support structure subsystems.

TITLE: STIFFNESS, STRENGTH, AND FATIGUE LIFE RELATIONSHIPS FOR COMPOSITE LAMINATES

T. K. O'Brien, NASA Langley Research Center; J. T. Ryder, Lockheed-California Company; and F. W. Crossman, Lockheed Palo Alto Research Laboratory

The objective of this work was to determine the effect of matrix cracking and delamination on the stiffness, strength, and fatigue life of unnotched, quasi-isotropic, graphite/epoxy laminates. Dye-penetrant-enhanced X-radiography and edge replication were used to monitor the formation and growth of delaminations and matrix cracks. During tensile tests, strains were measured over a long (4 in) gage length. Quasi-three-dimensional finite-element analysis and laminated plate theory were used to model damage and predict laminate behavior.

Stiffness loss due to matrix cracking was estimated using master curves, developed from finite-element analysis, that correlate crack density to reductions in lamina properties. Stiffness loss due to delamination was estimated using the rule of mixtures and laminated plate theory. Comparison of data with analysis indicated that laminate stiffness loss results primarily from delamination, with only a small contribution from matrix cracks in off-axis plies.

Stress concentrations in 0-deg plies due to matrix cracks in adjacent off-axis plies were small. In addition, strain-energy-release rates calculated at the failure load were much less than the fracture toughness required to propagate a matrix crack into a 0-deg ply. Hence, matrix cracks alone should not cause premature laminate failures. Furthermore, the mean nominal tensile strain at fracture was constant for quasi-isotropic laminates with different laminate thicknesses and stacking sequences. Therefore, tensile strength could be estimated from the laminate stiffness loss calculated at the fracture strain.

Work is continuing to determine (1) the effect of matrix cracks on the formation and growth of delaminations and (2) the effect of delamination and matrix cracks on fatigue life.

TITLE: FRACTURE GROWTH IN COMPOSITE LAMINATES

A. S. D. Wang, Drexel University and F. W. Crossman, Lockheed Palo Alto Research Laboratory

An investigation is conducted to delineate the mechanics of two important matrix-dominant cracking processes in fibrous composite laminates; these are identified as multiple transverse cracking and free-edge induced ply-delamination. The investigation consists of a comprehensive experimental examination of these two different cracking processes under statically applied loads, and a descriptive modeling method based on classical linear fracture mechanics. Main results obtained in this study include the establishment of an analytical technique which describes quantitatively the two types of cracking as they occur independently, and to understand their interaction qualitatively when they occur simultaneously.

The presentation will include both the analytical approach, the experimental results and their correlations. It is to be added by photographs obtained through non-destructive as well as destructive inspection procedures.

TITLE: RESEARCH ON COMPOSITE MATERIALS FOR STRUCTURAL DESIGN

R. A. Schapery, Texas A&M University

Research on composites at Texas A&M University sponsored by the Air Force Office of Scientific Research is reviewed. Much of the effort during the current year concerned seven M.S. and one Ph.D. student/faculty projects: "The Effect of Matrix Degradation on Fatigue Strength of a Graphite/Epoxy Laminate", (Arenburg/Schapery); "The Effect of Geometry on the Design of Filament-Wound Fiberglass Tension Lugs", (Braswell/Alexander); "Shear Deformation Effects in Composite Laminates", (Coulter/Weitsman); "Mode I Delamination of Unidirectional Graphite/Epoxy Composite Under Complex Load Histories", (Cullen/Jerina); "Compression Induced Delamination in a Unidirectional Graphite/Epoxy Composite", (Early/Jerina); "Mode I - Mode II Delamination Fracture Toughness of a Unidirectional Graphite/Epoxy Composites", (Vanderkley/Bradley); Ph.D: "On the Effects of Post Cure Cool Down and Environmental Conditioning on Residual Stresses in Composite Laminates", (Harper/Weitsman). Related faculty research has been concerned with development of new theoretical models for viscoelastic mechanical response, including damage growth and fracture phenomena.

TITLE: MODELING THE CURING PROCESS OF GRAPHITE EPOXY COMPOSITES
G. S. Springer, University of Michigan

A model will be described which simulates the curing process of epoxy matrix composites. The model relates the resin properties, the cure cycle (cure temperature, cure pressure), and the curing stresses and strains. The model provides (a) the temperature inside the material as a function of position and time, (b) the degree of resin conversion as a function of position and time, (c) the resin viscosity as a function of position and time, (d) the resin flow into the bleeder plies as a function of time, and (e) the stress-strain distributions inside the material after curing. A method will be presented which - together with the model - can be used to establish the optimum cure cycle in a given application.

TITLE: IMPACT DAMAGE CONTAINMENT IN STRENGTH CRITICAL GRAPHITE/EPOXY
COMPRESSION STRUCTURES
M. D. Rhodes, NASA Langley Research Center

Analytical and experimental research investigations have been conducted at the Langley Research Center to evaluate damage containment in strength critical graphite/epoxy compression structures. These investigations have focused on identifying those resin properties which would improve the local damage tolerance of graphite epoxy materials and evaluating the broader structural aspects of local and global damage containment. The results suggest that additives to the base epoxy can significantly improve the response of a laminate to impact with little or no loss in room temperature mechanical properties. However, there appears to be a limit beyond which additional improvements may be difficult to achieve. Configuration concepts have been evaluated to arrest propagating damage and several have been successfully demonstrated in static tests. Global damage tolerance has been evaluated from the standpoint of failure prediction techniques and the structural mass penalty associated with incorporating damage tolerance in the initial structural design.

TITLE: AEROELASTIC TAILORING OF COMPOSITES
W. A. Rogers, General Dynamics/Fort Worth Division and M. H. Shirk, AFWAL/
Flight Dynamics Laboratory

Aeroelastic tailoring provides a measure of control over the interaction of aerodynamic loading and structural response during the design of composite lifting surfaces. A recent investigation involving the design, fabrication, and test of an aeroelastically tailored fighter wing was conducted to provide data for validating the design methodology. Three sets of composite wings with different design objectives were tested in addition to a set of rigid steel wings. The static aeroelastic tests featured the measurement of model forces, pressure distributions, and deflected shapes in the transonic regime. Test results are compared with analytical predictions and show significant aeroelastic benefits.

TITLE: DAMAGE TOLERANCE OF CONTINUOUS FILAMENT ISOGRID STRUCTURES
L. W. Rehfield and A. D. Reddy, Georgia Institute of Technology

Damage tolerant nature of continuous filament isogrid structure is demonstrated through static buckling and dynamic tests. The observed bending failure mode is simulated on the panel by cutting the rib at nodal sites. The panels are tested non-destructively as clamped wide columns with buckling loads determined from a stiffness plotting technique. The vertical ribs are progressively damaged in a most naturally occurring parallel damage pattern - failure of vertical ribs across panel - and the panels retested. Dynamic test data and strain data to ascertain the redistribution of stresses near rib failure sites are generated at each damage level. Finite element analyses are carried out for theoretical correlation of frequency and strain data.

TITLE: SPACE ENVIRONMENTAL EFFECTS ON POLYMER MATRIX COMPOSITES
R. C. Tennyson, University of Toronto

Results are presented on the behaviour of selected Polymer matrix composites (such as graphite/epoxy, Kevlar/epoxy and boron/epoxy) subjected to prolonged exposure to a simulated space environment. The conditions investigated include thermal cycling in a hard vacuum with U.V. radiation. Test data were then obtained on coefficient of thermal expansion, stiffness and creep response, material damping and ultimate strength. In addition, analytical models were developed to predict laminate response based on principal material properties.

TITLE: STUDY OF BUCKLING, POSTBUCKLING BEHAVIOR AND VIBRATION OF LAMINATED COMPOSITE PLATES
A. Leissa, Ohio State University

Advances in the understanding of vibration and buckling behavior of laminated plates made of filamentary composite material are summarized in this survey paper. Depending upon the number of lamina and their orientation, vibration and buckling analyses of composite plates may be treated with: (1) orthotropic theory, (2) anisotropic theory, or (3) more complicated, general theory involving coupling between bending and stretching of the plate. The emphasis of the present overview is upon the last. Special consideration is given to the complicating effects of: inplane initial stresses, large amplitude (nonlinear) transverse displacements, shear deformation, rotary inertia, effects of surrounding media, inplane nonhomogeneity and variable thickness. Nonclassical buckling considerations such as initial imperfections are included, as well as postbuckling behavior.

TITLE: DEPENDENCE OF FIBER-MATRIX FAILURE MODES ON INTERPHASE PROPERTIES
L. T. Drzal, AFWAL/Materials Laboratory

The interrelationships between graphite fiber surface chemistry and morphology, interfacial shear strength in epoxy and mode of failure have been determined through the use of a single fiber testing technique. The technique not only provides a measure of interfacial shear strength between graphite fiber and epoxy matrix but also allows direct observation of the fiber-matrix interface under stress. Transitions in failure mode from frictional sliding of the fiber in the matrix to interfacial crack growth to matrix crack growth have been observed and correlated with changes in the graphite fiber surface chemistry and morphology and properties of the matrix interphase. The mechanisms will be explained and discussed.

TITLE: A METHOD FOR OPTIMIZATION OF COMPOSITE MATERIALS
N. Balasubramanian, AFWAL/Materials Laboratory

The influence of the properties of the fiber and the matrix on the failure envelopes of laminates is shown. Failure envelopes are obtained for a number of composite materials, both in strain space and the stress-resultant space. In strain space, the ply failure surfaces are superposed to obtain failure envelopes for the laminate. The inner envelope corresponds to the first-ply failure (FPF) and can be approximated by an ellipse in invariant strain space. The aim of optimization is to select the laminate with the highest FPF strength for a given loading condition. It is shown that the failure envelopes provide a simple graphical method for optimization. The failure envelopes for hybrid composites are obtained and it is shown that deviations from the rule of mixtures can be expected.

TITLE: A TECHNIQUE FOR PREVENTION OF DELAMINATION
R. Y. Kim, University of Dayton Research Institute

Delamination of laminated composites in the presence of inplane loading can be prevented by reinforcing the free-edge regions of the specimen. A simple technique for reinforcing the free-edges was given. The experimental evidence of effectiveness of the technique under static and fatigue loading was presented in the forms of microphotograph, x-ray, acoustic emission, and strain behavior. With the reinforced edges, the detrimental effect of delamination to the laminate strength can be eliminated.

TITLE: THE DETERMINATION OF INTERLAMINAR MODULI OF GRAPHITE/EPOXY COMPOSITES
M. Knight and N. J. Pagano, AFWAL/Materials Laboratory

The analysis of bodies built from thick laminates requires data on interlaminar properties. Calculation of interlaminar stresses also depends on these properties. However, this type of data are usually not determined

experimentally. A program has been completed in which data were obtained on in-plane and interlaminar elastic properties of thick graphite/epoxy laminates. Two thick (a 125-ply, T300/5208 and a 150-ply AS/3502) laminates were fabricated. These laminates were nondestructively inspected, and cut into specimens for characterization. Tests were conducted in tension, compression and shear to provide data on the elastic properties in the three principal directions. Young's moduli, E_{ij} , Poisson's ratios, ν_{ij} , and shear moduli, G_{ij} , were defined. These values were compared to data from eight-ply laminates and to theoretical values. Comparison by use of redundant test procedures was also accomplished. Good agreement was obtained. It is concluded that an acceptable approach is available for the experimental determination of the elastic moduli in both the in-plane and thickness directions.

TITLE: DEMONSTRATION OF COMPUTER PROGRAMS FOR COMPOSITE LAMINATE ANALYSIS
S. W. Tsai, AFWAL/Materials Laboratory

Three programs for laminate analysis will be explained and demonstrated. The first is a combined card/module operation for TI-59 which performs stiffness and strength analyses of symmetric laminates under in-plane or flexural loading. Inclusion of sandwich core and in-plane hybrids can also be solved. The second program is written for Radio Shack TRS-80 pocket computer which performs essentially the same as that for TI-59, except hygrothermal stresses are included. The third program is written in Fortran and has all the features of a point-stress analysis including unsymmetric plates. All program instructions and module can be made available for interested parties.

AFWAL-TR-82-4007

APPENDIX B
PROGRAM LISTINGS

AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
MATERIALS LABORATORY

INHOUSE

ADVANCED COMPOSITES
WORK UNIT DIRECTIVE (WUD) NUMBER 45
77 April - 84 April

WUD Leader: James M. Whitney
Materials Laboratory
Air Force Wright Aeronautical Laboratories
AFWAL/MLBM
Wright-Patterson AFB, OH 45433
(513) 255-6685 Autovon: 785-6685

Objective: The objective of the current thrust under this work is to develop and demonstrate concepts of damage resistance as applied to fiber reinforced composite laminates. Short term objectives (1-3 yrs) include the following:

- (a) Development of failure mode models with emphasis on delamination and matrix cracking.
- (b) Assess the role of matrix toughness in composite failure processes.
- (c) To develop concepts of interface/interphase strengthening.

CONTRACTS

NOVEL DESIGN OF COMPOSITE MATERIALS
F33615-77-C-5155
77 June - 82 June

Project Engineer: Stephen W. Tsai
Materials Laboratory
Air Force Wright Aeronautical Laboratories
AFWAL/MLBM
Wright-Patterson AFB, OH 45433
(513) 255-3068 Autovon: 785-3068

Principal Investigator: James W. Mar
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology
Cambridge, MA 02139
(617) 253-2426

Objective: To train undergraduate and graduate students to design, fabricate and test composite laminates and simple structural components. Properties to be evaluated include stiffness, strength, damping, fracture and fatigue. Innovative design and processing of laminates and components are to be explored.

AFWAL-TR-82-4007

CUMULATIVE DAMAGE MODEL FOR COMPOSITE MATERIALS

F33615-80-C-5039

81 Feb 23 - 82 Aug 24

Project Engineer: Marvin Knight
Materials Laboratory
Air Force Wright Aeronautical Laboratories
AFWAL/MLBM
Wright-Patterson AFB, OH 45433
(513) 255-7131 Autovon: 785-7131

Principal Investigator: P. C. Chou
Dyna East Corporation
227 Hemlock Road
Wynnewood, PA 19096
(215) 895-2288

Objective: This program will develop a methodology, including analytical modeling, for predicting and experimentally characterizing advanced composite materials' mechanical responses to defined load histories. A cumulative damage model is the ultimate goal.

CUMULATIVE DAMAGE MODEL FOR COMPOSITE MATERIALS

F33615-81-C-5049

81 Feb 23 - 82 Aug 24

Project Engineer: Marvin Knight
Materials Laboratory
Air Force Wright Aeronautical Laboratories
AFWAL/MLBM
Wright-Patterson AFB, OH 45433
(513) 255-7131 Autovon: 785-7131

Principal Investigator: J. Masters
General Dynamics Corporation
Fort Worth Division
P.O. Box 748
Fort Worth, TX 76101
(817) 732-4811 Ext 5375

Objective: This program will develop a methodology, including analytical modeling, for predicting and experimentally characterizing advanced composite materials' mechanical responses to defined load histories. A cumulative damage model is the ultimate goal.

FLIGHT DYNAMICS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES

IN-HOUSE

STRUCTURAL INTEGRITY RESEARCH FOR ENGINES AND AIRFRAMES
JON: 2307N101*
77 January 1 - 82 March 30

Project Engineer: Dr. George P. Sendeckyj
Air Force Wright Aeronautical Laboratories
AFWAL/FIBEC
Wright-Patterson AFB, Ohio 45433
(513) 255-6104 Autovon 785-6104

Objective: To resolve theoretical questions and develop damage tolerance and life analysis methods which can be used to satisfy the requirements of MIL-STD-1530A for advanced composite and metallic airframe structures. The specific objectives in the composites area are:

- (a) develop procedures for analyzing composite materials static strength and fatigue life data;
- (b) assess the effect of fabrication variability and percentage of zero degree plies in a composite on the shape of the S-N curve and data scatter statistics;
- (c) demonstrate experimentally that a state of damage approach is viable for predicting the life of composites under block and random spectrum loading; and
- (d) explore various nondestructive inspection methods for accurately documenting damage in resin matrix composites.

SONIC FATIGUE DESIGN OF ADVANCED STRUCTURES
JON: 24010146
79 November 11 - 82 November 12

Project Engineer: Howard F. Wolfe
Air Force Wright Aeronautical Laboratories
AFWAL/FIBED
Wright-Patterson AFB, Ohio 45433
(513) 255-5753 Autovon 785-5753

Objective: Develop test techniques and sonic fatigue design data for graphite/epoxy skin stringer composite structures.

* JON is an internal Laboratory number assigned to the work unit.

AFWAL-TR-82-4007

AEROELASTIC STUDY OF SWEEP WINGS WITH ANISOTROPIC BEHAVIOR

JON: 24010239

79 September 3 - 83 March 30

Project Engineer: Michael H. Shirk
Air Force Wright Aeronautical Laboratories
AFWAL/FIBRC
Wright-Patterson AFB, Ohio 45433
(513) 255-6832 Autovon 785-6832

Objective: To provide analytical and experimental data on the aeroelastic behavior of wings constructed with advanced composite materials. The studies will include parameter variations, such as aspect ratio, sweep, and ply orientation. Experiments will include load deflection, influence coefficient measurement, ground vibration and wind tunnel testing.

ANALYSIS AND OPTIMIZATION OF AEROSPACE STRUCTURES

JON: 24010244

80 March 10 - 83 March 30

Project Engineer: Dr. V. B. Venkayya
Air Force Wright Aeronautical Laboratories
AFWAL/FIBR
Wright-Patterson AFB, Ohio 45433
(513) 255-4893 Autovon 785-4893

Objective: The key to the successful design of lighter and more reliable airframe structures is the ability to accurately predict structural response and to make rapid sensitivity analysis with parametric changes. The sensitivity analysis in turn is the important element in the evolution of dependable and cost effective structures. The objective of the effort is to develop computational tools for rapid analysis and optimization of metallic and composite aerospace structures.

STRUCTURAL TESTING OF COMPOSITE PANELS

JON: 24010246

80 April 28 - 83 June 30

Project Engineer: Dr. N. S. Khot
Air Force Wright Aeronautical Laboratories
AFWAL/FIBR
Wright-Patterson AFB, Ohio 45433
(513) 255-4893 Autovon 785-4893

Objective: To develop experimental methods and to conduct tests to determine the buckling and postbuckling strength of stiffened and unstiffened composite panels.

AFWAL-TR-82-4007

COMPOSITE TEST METHODS (Compressive Test Fixture Evaluation)

JON: 24010344

79 January 1 - 82 June 1

Project Engineer: Rick Rolfes
Air Force Wright Aeronautical Laboratories
AFWAL/FIBCC
Wright-Patterson AFB, Ohio 45433
(513) 255-6658 Autovon 785-6658

Objective: To evaluate various compressive test fixtures currently in use by industry, together with an in-house prototype design. Efforts will focus on (a) elimination of the predominate brooming and buckling failure modes associated with present test fixtures, (b) 0 degree compressive strengths analogous to 0 degree tensile strengths, and (c) a reduction in costs of test specimen fabrication.

HYDRODYNAMIC RAM ASSESSMENT OF INTEGRAL SKIN/SPAR DESIGNS

JON: 24010349

80 March 24 - 82 March 30

Project Engineer: B. White
Air Force Wright Aeronautical Laboratories
AFWAL/FIBCA
Wright-Patterson AFB, Ohio 45433
(513) 255-5864 Autovon 785-5864

Objective: To study the effect of hydrodynamic ram caused by ballistic penetration on advanced composite structures and to evaluate the relative susceptibility of several integral composite skin/spar concepts. This will provide designers with information necessary to allow transition of composites technology to operational aircraft.

ASSESSMENT OF CORROSION CONTROL PROTECTIVE COATINGS

JON: 24010350

80 April 28 - 85 May 1

Project Engineer: S. D. Thompson
Air Force Wright Aeronautical Laboratories
AFWAL/FIBCA
Wright-Patterson AFB, Ohio 45433
(513) 255-5864 Autovon 785-5864

Objective: To determine the susceptibility of graphite/epoxy-aluminum joints to corrosion when protective coatings, that have undergone fatigue loading, are used. The knowledge gained will be used to determine if present corrosion control systems actually prevent corrosion and if not, how they could be modified to prevent corrosion from occurring.

AFWAL-TR-82-4007

COMPOSITE IMPACT STUDY

JON: 22510115

80 September 1 - 84 September 30

Project Engineer: James M. Remar
Air Force Wright Aeronautical Laboratories
AFWAL/FIES
Wright-Patterson AFB, Ohio 45433
(513) 255-6302 Autovon 785-6302

Objective: To investigate characteristics of advanced filamentary composites impacted by single fragment projectiles. This program will develop basic core of data to predict penetration characteristics useful in preliminary design analysis.

GRANTS

CONDUCTION HEAT TRANSFER ANALYSIS IN COMPOSITE MATERIALS

Grant AFOSR 78-3640

JON: 2307N112

78 July 1 - 81 December 31

Project Engineer: N. D. Wolf
Air Force Wright Aeronautical Laboratories
AFWAL/FIBR
Wright-Patterson AFB, Ohio 45433
(513) 255-4893 Autovon 785-4893

Principal Investigator: Dr L. S. Han
Ohio State University Research Foundation
1314 Kinnear Road
Columbus, Ohio 43212
(614) 422-6349

Objective: To investigate a class of heat conduction problems in fiber-matrix composite materials for which the proximity effects of embedded fibers are significant and to strengthen the modelling approach by establishing bounds of accuracy through comparisons with exact data of analysis.

DURABILITY OF REPEATEDLY BUCKLED PANELS

Grant AFOSR 81-0016

JON: 2307N114

80 May 12 - 83 September 30

Project Engineer: Dr. V. B. Vankayya
Air Force Wright Aeronautical Laboratories
AFWAL/FIBRA
Wright-Patterson AFB, Ohio 45433
(513) 255-5651 Autovon 785-5651

Principal Investigator: Dr. Josef Singer
Department of Aeronautical Engineering
Technion - Israel Institute of Technology
Haifa, 32000
Israel

Objective: Metallic and composite shear panels in aircraft structures are generally designed to operate in the post-buckled range to reduce structural weight. The objective of this effort is to study the durability of repeatedly buckled panels and to provide guidelines for the design of flat and curved shear panels with various types of stiffener configurations.

CONTRACTS

TEST SYSTEM FOR CONDUCTING BIAXIAL TESTS OF COMPOSITE LAMINATES
Contract F33615-77-C-3014 JON: 2307N103
77 September 19 - 82 September 20

Project Engineer: T. N. Bernstein
Air Force Aeronautical Laboratories
AFWAL/FIBR
Wright-Patterson AFB, Ohio 45433
(513) 255-4893 Autovon 785-4893

Principal Investigator: Dr. Isaac M. Daniel
IIT Research Institute
10 West 35th Street
Chicago, Illinois 60616
(312) 567-4000

Objective: To develop, design and fabricate a biaxial test machine capable of applying, without constraints, in-plane loads, singly and in any combination, to laminated tubular composite specimens.

A STUDY OF THE BUCKLING, POST-BUCKLING BEHAVIOR AND VIBRATION OF LAMINATED COMPOSITE PLATES
Contract F33615-81-K-3203 JON: 2307N115
80 November 20 - 83 November 20

Project Engineer: Dr. N. S. Khot
Air Force Wright Aeronautical Laboratories
AFWAL/FIBRA
Wright-Patterson AFB, Ohio 45433
(513) 255-5651 Autovon 785-5651

AFWAL-TR-82-4007

Principal Investigator: Professor Arthur Leissa
Department of Engineering Mechanics
Boyd Laboratory
Ohio State University
155 West Woodruff Avenue
Columbus, Ohio 43210

Objective: To prepare a monograph summarizing the state of the art in buckling, post-buckling and vibration behavior of laminated composite plates

FATIGUE DAMAGE-STRENGTH RELATIONSHIPS IN COMPOSITE MATERIALS
Contract F33615-81-K-3225 JON: 2307N117
80 December 12 - 83 September 30

Project Engineer: Dr. George P. Sendeckyj
Air Force Wright Aeronautical Laboratories
AFWAL/FIBEC
Wright-Patterson AFB, Ohio 45433
(513) 255-6104 Autovon 785-6104

Principal Investigator: Professor K. L. Reifsnider
Engineering Science & Mechanics Department
Virginia Polytechnic Institute & State University
Blacksburg, Virginia 24061
(703) 961-5316

Objective: Develop an understanding of the initiation of fiber fractures from matrix cracks and delaminations in resin-matrix composites.

EFFECTS OF VARIANCES AND MANUFACTURING TOLERANCES ON THE DESIGN STRENGTH AND LIFE OF MECHANICALLY FASTENED COMPOSITE JOINTS
Contract F33615-77-C-3140 JON: 24010110
78 February 15 - 81 December 15

Project Engineer: Capt. M. Becker
Air Force Wright Aeronautical Laboratories
AFWAL/FIBEC
Wright-Patterson AFB, Ohio 45433
(513) 255-6104 Autovon 785-6104

Principal Investigator: Samuel P. Garbo
McDonnell Company
P. O. Box 516
St. Louis, Missouri 63166
(314) 232-3356

Objective: To develop improved analytical methods and failure criteria which account for design variances and manufacturing anomalies in the prediction of failure load, mode, location, and fatigue life of bolted composite joints.

AFWAL-TR-82-4007

ADVANCED RESIDUAL STRENGTH DEGRADATION RATE MODELING FOR ADVANCED COMPOSITE STRUCTURES

Contract F33615-77-C-3084

JON: 24010117

76 December 27 - 82 January 30

Project Engineer: Dr. George P. Sendeckyj
Air Force Wright Aeronautical Laboratories
AFWAL/FIBEC
Wright-Patterson AFB, Ohio 45433
(513) 255-6104 Autovon 785-6104

Principal Investigator: K. N. Lauraitis
Lockheed-California Company
Rye Canyon Research Laboratory
Dept. 74-71, Bldg. 204, P/2
P. O. Box 551
Burbank, California 91520
(213) 847-6121 ext. 131 291

Objective: To develop procedures and the required supporting data needed to predict (a) the growth of damage zones as a function of fatigue loading, (b) the residual strength as a function of the size and shape of the fatigue induced damage zones, (c) the mechanisms of fatigue induced damage formation, and (d) the threshold levels of damage.

ENVIRONMENTAL TRACKING OF F-15 HORIZONTAL STABILATOR

Contract F33615-79-C-3210

JON: 24010132

79 June 15 - 83 October 1

Project Engineer: Carl L. Rupert
Air Force Wright Aeronautical Laboratories
AFWAL/FIBED
Wright-Patterson AFB, Ohio 45433
(513) 255-5753 Autovon 785-5753

Principal Investigator: Thomas V. Hinkle
McDonnell Douglas Corporation
P. O. Box 516
St. Louis, Missouri 63166
(314) 232-3356

Objective: To evaluate the effects of additional exposure to a service environment on the the F-15 boron-epoxy stabilator.

SPECIAL FASTENER DEVELOPMENT FOR COMPOSITE STRUCTURES

Contract F33615-80-C-3223

JON: 24010144

79 November 19 - 82 June 15

Project Engineer: J. M. Potter

AFWAL-TR-82-4007

Air Force Wright Aeronautical Laboratories
AFWAL/FIBEC
Wright-Patterson AFB, Ohio 45433
(513) 255-6104 Autovon 785-6104

Principal Investigator: Robert T. Cole
Lockheed-Georgia Company
86 S. Cobb Drive
Marietta, Georgia 30063
(404) 424-3085

Objective: To develop fasteners that will improve the durability of bolted joints in composite structures.

DAMAGE PROGRESSION IN GRAPHITE-EPOXY BY A DEPLYING TECHNIQUE
Contract F33615-80-C-3224 JON: 24010148
79 November 17 - 81 December 30

Project Engineer: Dr. George P. Sendeckyj
Air Force Wright Aeronautical Laboratories
AFWAL/FIBEC
Wright-Patterson AFB, Ohio 45433
(513) 255-6104 Autovon 785-6104

Principal Investigator: Samuel Freeman
Lockheed-Georgia Company
86 S. Cobb Drive
Marietta, Georgia 30063
(404) 424-4730

Objective: To document the state of damage as a function of applied load in simple bolted joints in composites. Damage will be documented by using acoustic emission monitoring, penetrant enhanced x-ray radiography, and deplying.

FATIGUE/IMPACT STUDIES IN LAMINATED COMPOSITES
Contract F33615-80-K-3243 JON: 24010152
80 May 12 - 83 December 30

Project Engineer: Dr. George P. Sendeckyj
Air Force Wright Aeronautical Laboratories
AFWAL/FIBEC
Wright-Patterson AFB, Ohio 45433
(513) 255-6104 Autovon 785-6104

Principal Investigator: Dr. Avva V. Sharma
Mechanical Engineering Department
North Carolina Agricultural & Technical State Univ.
Greensboro, North Carolina 27411
(919) 379-7620

AFWAL-TR-82-4007

Objective: To systematically document the fatigue induced damage accumulation process in impact damaged structural composite laminates.

DESIGN METHODOLOGY AND LIFE ANALYSIS OF POSTBUCKLED METAL AND COMPOSITE PANELS

Contract F33615-81-C-3208
80 June 23 - 84 August 30

JON: 24010154

Project Engineer: Capt. M. L. Becker
Air Force Wright Aeronautical Laboratories
AFWAL/FIBEC
Wright-Patterson AFB, Ohio 45433
(513) 255-6104 Autovon 785-6104

Principal Investigator: Dr. Ben Agarwal
Northrop Corporation
Structural Mechanics Research
3901 West Broadway
Hawthorne, California 90250
(213) 970-5075

Objective: Develop analytical techniques and design procedures for metal and composite aircraft structures operating in the post-buckled range.

DAMAGE ACCUMULATION IN COMPOSITES

Contract F33615-81-C-3226
80 August 18 - 84 December 30

JON: 240101057

Project Engineer: Dr. George P. Sendeckyj
Air Force Wright Aeronautical Laboratories
AFWAL/FIBEC
Wright-Patterson AFB, Ohio 45433
(513) 255-6104 Autovon 785-6104

Principal Investigator: David A. Utman
Structures & Design Department
General Dynamics Corporation/Fort Worth Division
P. O. Box 748
Fort Worth, Texas 76101
(817) 732-4811 ext 4179

Objective: Develop a state-of-damage based procedure for predicting the life of composite structures subjected to spectrum fatigue loading.

AFWAL-TR-82-4007

VALIDATION OF AEROELASTIC TAILORING BY STATIC AEROELASTIC AND FLUTTER TESTS
Contract F33615-77-C-3105 JON: 24010214
77 December 5 - 81 November 4

Project Engineer: Michael H. Shirk
Air Force Wright Aeronautical Laboratories
AFWAL/FIBRC
Wright-Patterson AFB, Ohio 45433
(513) 255-6832 Autovon 785-6832

Principal Investigator: William Rogers
General Dynamics/Fort Worth Division
P. O. Box 748
Fort Worth, Texas 76101
(817) 732-4811 ext 2320

Objective: To generate wind tunnel test data using static aeroelastic and flutter models to: (1) evaluate current analytical procedures used to predict aeroelastic tailoring benefits, (2) develop aeroelastic and flutter model scaling and fabrication techniques, and (3) demonstrate performance benefits attainable through aeroelastic tailoring, e. g. reduced drag at maneuver conditions. A rigid model, three aeroelastic models, and two flutter models will be designed and tested. All models will be of the wing-body type, will utilize the same body of revolution and will also employ the AFTI-16 wing planform. The aeroelastic wings will have large design variations to provide the data needed to properly evaluate the aeroelastic tailoring design methods. The wings to be designed are: (1) a rigid undeformed wing designed to the jig shape, (2) an aeroelastically tailored wing, (3) an aeroelastically tailored wing designed to twist in the opposite direction of (2) and (4) a non-tailored wing. The two flutter wing designs will be representative of the two tailored aeroelastic models.

DESIGN VERIFICATION FOR OPTIMIZED PANELS
Contract F33615-81-C-3222 JON: 24010248
81 September 15 - 84 July 15

Project Engineer: Dr. N. S. Khot
Air Force Wright Aeronautical Laboratories
AFWAL/FIBRA
Wright-Patterson AFB, Ohio 45433
(513) 255-5651 Autovon 785-5651

Principal Investigator: Mr. Bo Almroth
Lockheed Palo Alto Research Laboratory
Bldg 255
3251 Hanover
Palo Alto, California 94304
(415) 858-4027

AFWAL-TR-82-4007

Objective: To experimentally investigate the behavior of optimized composite stiffened panels.

DOD/NASA ADVANCED COMPOSITES DESIGN GUIDE
Contract F33615-78-C-3203 JON: 24010324
78 March 1 - 82 April 1

Project Engineer: B. White
Air Force Wright Aeronautical Laboratories
AFWAL/FIBCA
Wright-Patterson AFB, Ohio 45433
(513) 255-5864 Autovon 785-5864

Principal Investigator: G. Howard Arvin
Rockwell International Corporation
LA Aircraft Division
5701 W. Imperial Highway
Los Angeles, California 90009
(213) 670-9151 ext 1666

Objective: To develop a new, updated version of the "Advanced Composites Design Guide." The new version will incorporate new data and analysis techniques. The guide will be reorganized and condensed to make it a more useful document to designers.

INTEGRAL COMPOSITE SKIN/SPAR DESIGN STUDIES
Contract F33615-78-C-3209 JON: 24010328
78 September 1 - 81 December 1

Project Engineer: Dale E. Nelson
Air Force Wright Aeronautical Laboratories
AFWAL/FIBCA
Wright-Patterson AFB, Ohio 45433
(513) 255-5864 Autovon 785-5864

Principal Investigator: Carlos Cacho-Negrete
Grumman Aerospace Corporation
Bethpage, L. I., New York 11714
(516) 575-2648

Objective: To obtain extensive design information on three advanced concepts for integral skin/spar construction. This information can then be used to incorporate these designs into future aircraft.

COMPOSITE WING/FUSELAGE PROGRAM
Contract F33615-79-C-3203 JON: 69CW0152
79 July 1 - 84 July 30

AFWAL-TR-82-4007

Project Engineer: Neal V. Loving
Air Force Wright Aeronautical Laboratories
AFWAL/FIBAC
Wright-Patterson AFB, Ohio 45433
(513) 255-6639 Autovon 785-6639

Principal Investigator: J. Eves, Program Manager
Northrop Corporation/Aircraft Division
39010 West Broadway
Hawthorne, California 90250

Objective: To develop composites structural design technology and durability qualification methodology for advanced composite aircraft.

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

IN HOUSE

NONE

CONTRACTS

DYNAMIC RESPONSE AND NONLINEAR ANALYSIS OF COMPOSITES
82 January 01 - 82 December 31

Project Engineer: Dr Anthony K Amos
AFOSR/NA
Bolling AFB, DC 20332
(202) 767-4937 Autovon 297-4937

Principal Investigator: Dr Satyr N Atluri
Georgia Institute of Technology
Atlanta, GA 30332
(404) 894-2758

Objective: To extend the hybrid finite element methodology developed for laminated composite structures under static loading, to analysis involving dynamic response, buckling and general nonlinear behavior.

FRACTURE BEHAVIOR OF BORON ALUMINUM COMPOSITES
79 April 01 - 82 May 31

Project Engineer: Dr Anthony K Amos
AFOSR/NA
Bolling AFB, DC 20332
(202) 767-4937 Autovon 297-4937

Principal Investigator: Dr Jonathan Awerbach
Drexel University
Philadelphia, PA 19104
(215) 895-2291

Objective: To provide insight into the fracture mechanisms in boron aluminum composites at room and elevated temperatures through a comprehensive experimental program and correlation of test data with analytical predictions.

ASSUMED STRESS FINITE ELEMENT ANALYSIS OF EDGE EFFECTS IN COMPOSITE LAMINATES
81 June 30 - 82 June 29

Project Engineer: Dr Anthony K Amos
AFOSR/NA
Bolling AFB, DC 20332
(202) 767-4937 Autovon 297-4937

AFWAL-TR-82-4007

Principal Investigator: Dr Sung W Lee
University of Maryland
College Park, MD 20742
(301) 454-2426

Objective: To develop a computationally efficient assumed stress hybrid finite element technique for accurate determination of interlaminar stresses near stress-free edges in composite laminates.

NONLINEAR TRANSIENT ANALYSIS OF LAYERED COMPOSITE PLATES AND SHELLS
81 April 01 - 82 March 31

Project Engineer: Dr Anthony K Amos
AFOSR/NA
Bolling AFB, DC 20332
(202) 676-4937 Autovon 297-4937

Principal Investigator: Dr J N Reddy
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061
(703) 961-6651

Objective: To evaluate the stability and convergence characteristics of penalty-finite elements applied to the dynamic analysis (e.g. low velocity impact) of composite plates and shells, and to evolve a transient analysis capability with greatly improved accuracy, numerical stability and computational efficiency.

STUDIES OF ADVANCED AND COMPOSITE STRUCTURES
80 November 15 - 82 December 31

Project Engineer: Dr Anthony K Amos
AFOSR/NA
Bolling AFB, DC 20332
(202) 767-4937 Autovon 297-4937

Principal Investigator: Dr Lawrence W Rehfield
Georgia Institute of Technology
Atlanta, GA 30332
(404) 894-3067

Objective: To establish accurate theoretical and experimental methods for the analysis and evaluation of dynamic behavior, failure processes and design validation of advanced composites and structures.

AFWAL-TR-82-4007

ELEVATED TEMPERATURE BEHAVIOR OF METAL MATRIX COMPOSITES
79 April 01 - 81 September 30

Project Engineer: Dr Anthony K Amos
AFOSR/NA
Bolling AFB, DC 20332
(202) 767-4937 Autovon 297-4937

Principal Investigator: Walter B Rosen
Material Sciences Corporation
Blue Bell, PA 19422
(215) 542-8400

Objective: To develop greater understanding of the response of metal matrix composite materials to loads and temperature changes, and to develop models for this behavior which can be incorporated into engineering analysis/design procedures.

COMPOSITES FOR STRUCTURAL DESIGN
78 January 15 - 81 December 31

Project Engineer: Dr Anthony K Amos
AFOSR/NA
Bolling AFB, DC 20332
(202) 767-4937 Autovon 297-4937

Principal Investigator: Dr Richard A Schapery
Texas A&M University
College Station, Texas 77843
(713) 845-7512

Objective: To investigate parameters which govern advanced composite structural performance from processing variables (pressure, temperature, hold times, etc.) to environmental factors of moisture and temperature; to characterize degradation processes due to elevated temperature and high humidity; and to develop nondestructive techniques for quality assessment, failure detection, and quantification of diffusion processes.

NONLINEAR LARGE DEFORMATION BEHAVIOR OF COMPOSITE CYLINDRICAL SHELLS
81 June 30 - 82 June 29

Project Engineer: Dr Anthony K Amos
AFOSR/NA
Bolling AFB, DC 20332
(202) 767-4937 Autovon 297-4937

Principal Investigator: Dr George J Simites
Georgia Institute of Technology
Atlanta, GA 30332
(404) 894-2770

AFWAL-TR-82-4007

Objective: To develop nonlinear solution methodology for the response characteristics of stiffened laminated cylindrical shells, including pre-limit point and post-limit point behavior, and to use the methodology to study nonlinear phenomena in such shell structures.

SPACE ENVIRONMENTAL EFFECTS ON POLYMER MATRIX COMPOSITES
78 September 01 - 82 August 31

Project Engineer: Dr Anthony K Amos
AFOSR/NA
Bolling AFB, DC 204332
(202)767-4937 Autovon 297-4937

Principal Investigator: Dr Rodney C Tennyson
Univeristy of Toronto
Downsview, Ontario, Canada M3H 5T6
(416) 667-7710

Objective: To identify the influence of simulated and in-situ space environmental conditions on the mechanical characteristics of advanced composite materials in real time, and to evaluate accelerated environmental exposure techniques.

INTERLAMINAR AND INTRALAMINAR FRACTURE GROWTH IN COMPOSITE MATERIALS
79 September 01 - 83 September 30

Project Engineer: Dr Anthony K Amos
AFOSR/NA
Bolling AFB, DC 20332
(202) 767-4937

Principal Investigator: Dr Albert S D Wang
Drexel University
Philadelphia, PA 19104
(215) 895-2297

Objective: To develop qualitative understanding of and analytical/computational prediction capability for fracture initiation and propagation processes in composite laminates.

NASA LANGLEY RESEARCH CENTER

INHOUSE

EFFECT OF MATRIX ON IMPACT RESISTANCE OF LAMINATES
81 May 1 - 82 September 30

Project Engineer: Walter Illg
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2338 FTS 928-2338

Objective: To determine the impact behavior of graphite composites in which the matrices' shear properties are systematically altered.

EFFECT OF FOIL TOUGHENING ON IMPACT RESISTANCE OF LAMINATES
81 May 1 - 82 June 30

Project Engineer: Walter Illg
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2338 FTS 928-2338

Objective: To determine the effect on impact resistance of partial interlaminar separations between layers of a laminate. Perforated mylar foil produces the partial separations.

MECHANICS OF LOW-VELOCITY IMPACT
81 June 1 - 82 May 31

Project Engineer: Dr. Wolf Elber
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-3192 FTS 928-3192

Objective: From quasi-static deformation analysis, determine the criteria for low-velocity impact damage; establish threshold levels for impact damage.

AFWAL-TR-82-4007

ASSESSING THE ROLE OF SHOCK WAVES IN IMPACT DAMAGE
81 April 1 - 83 March 31

Project Engineer: Dr. Joseph S. Heyman
Mail Stop 499
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-3418 FTS 928-3418

Objective: To examine impact damage reduction to composites through acoustic impedance matching techniques and to assess the role shock waves play in low-velocity impact-induced material degradation.

SHOCK WAVE SPECTRAL ENERGY ANALYSIS
81 July 1 - 83 June 30

Project Engineer: Dr. William P. Winfree
Mail Stop 499
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-3418 FTS 928-3418

Objective: To develop systems for the study of the energy frequency spectra of impact-induced shock waves in graphite/epoxy composites and related materials to determine damage mechanisms.

TOUGHNESS TEST METHODOLOGY
80 October 1 - 82 September 30

Project Engineer: Dr. Norman J. Johnston
Mail Stop 226
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-3041 FTS 928-3041

Objective: To investigate, develop (if necessary), and select appropriate test methods for screening the impact resistance and fracture toughness properties of neat polymers and composites. Methodology will help guide programs to synthesize new toughened matrix resins.

FRACTURE OF LAMINATED COUPONS
78 October 1 - 82 September 30

Project Engineer: C. C. Poe, Jr.
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2338 FTS 928-2338

Objective: To develop a methodology to predict residual strengths of damaged composite laminates using, as starting points, lamina properties or possibly the properties of the fibers and matrix. To determine the parameters that lead to tough composites.

AFWAL-TR-82-4007

DAMAGE TOLERANT COMPOSITE STRUCTURES
74 June 1 - 83 May 31

Project Engineer: C. C. Poe, Jr.
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2338 FTS 928-2338

Objective: To measure the ability of buffer strips and bonded stringers to increase the residual tension strength of damaged panels, and to develop an analysis to predict residual strength in terms of panel configuration and damage size.

EFFECT OF ELEVATED TEMPERATURE ON GRAPHITE/POLYIMIDE BUFFER STRIP PANELS
80 November 1 - 81 December 31

Project Engineer: C. A. Bigelow
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-3191 FTS 928-3191

Objective: To experimentally determine the effect of elevated temperature on the fracture behavior of graphite/polyimide buffer strip panels under static loading.

EFFECT OF MOISTURE AND ELEVATED TEMPERATURE ON GRAPHITE/EPOXY BUFFER STRIP PANELS
80 November 1 - 82 September 30

Project Engineer: C. A. Bigelow
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-3191 FTS 928-3191

Objective: To experimentally determine the effect of moisture and elevated temperature on the fatigue life of graphite/epoxy buffer strip panels.

WOVEN COMPOSITE BUFFER STRIP PANELS
81 January 1 - 82 June 1

Project Engineer: J. M. Kennedy
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-3191 FTS 928-3191

Objective: To demonstrate that buffer strip panels built with woven cloth have the crack-arresting capability of panels built with conventional prepreg tape. Damaged panels will be tested in shear and tension.

AFWAL-TR-82-4007

ANALYSIS OF BOLT CLAMPUP RELAXATION
80 January 5 - 82 January 5

Project Engineers: Dr. John H. Crews, Jr.
Dr. K. N. Shivakumar
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2318 FTS 928-2318

Objective: To develop a procedure to calculate the viscoelastic relaxation of bolt clampup force. This analysis will provide a basis for calculating joint strength degradation due to clampup relaxation.

ANALYSIS OF MULTI-FASTENER JOINTS
79 July 1 - 84 September 30

Project Engineer: Dr. John H. Crews, Jr.
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2318 FTS 928-2318

Objective: To develop the basic understanding needed to predict the failure-onset strength, the failure sequence, and the ultimate strength of multi-fastener joints.

FAILURE ANALYSIS OF LOADED HOLES
81 April 1 - 83 April 1

Project Engineer: Dr. John H. Crews, Jr.
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2318 FTS 928-2318

Objective: To develop the basic understanding needed for an analytical procedure to predict bolt hole failure under combined bearing and bypass loads.

ADHESIVELY BONDED LAMINATE EVALUATION
79 October 1 - 83 September 30

Project Engineer: Dr. W. S. Johnson
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2715 FTS 928-2715

Objective: To improve fracture toughness and damage tolerance of titanium by adhesive bond lamination. To develop analytical capability for the durability of laminated joint/structures.

AFWAL-TR-82-4007

ADHESIVE DEBOND CHARACTERIZATION
76 October 1 - 86 September 30

Project Engineers: Dr. W. S. Johnson
R. A. Everett, Jr.
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2715 FTS 928-2715

Objective: To verify that identical specimens manufactured at different facilities using the same adhesive/adherent (7075 Al/FM 73) bonding techniques behave in a similar manner when subjected to cyclic loading. To develop an approach to calculate cyclic debond threshold and rate such that the cyclic behavior of the bondline can be predicted for any geometry (using finite elements) for a given adhesive/adherent system. To expand from metal-to-metal to composite-to-composite bonds and to examine temperature, moisture, and spectrum loading effects.

STRESS ANALYSIS OF ADHESIVE BONDS
80 October 1 - 84 September 30

Project Engineer: Dr. B. Dattaguru
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-3178 FTS 928-3178

Objective: To review currently available finite-element routines and their applicability to the adhesive bondline stress analysis. To modify available model or develop a new model to assess G_I and G_{II} at debond front, and to incorporate into model material and geometric nonlinear behavior.

FAILURE MODES OF ADHESIVELY BONDED COMPOSITE JOINTS
81 June 1 - 82 May 31

Project Engineer: Dr. S. Mall
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2715 FTS 928-2715

Objective: To conduct experimental tests to determine the failure modes and mechanisms of adhesively bonded composite joints. To assess secondary bonding versus concurring in graphite/epoxy and Kevlar/epoxy joints.

AFWAL-TR-82-4007

REALISTIC ADHESIVELY BONDED JOINT ELEMENT
81 October 1 - 83 September 30

Project Engineer: R. A. Everett, Jr.
Mail Stop 188E
Structures Laboratory, USARTL (AVRADCOM)
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2715 FTS 928-2715

Objective: To manufacture several variations of a simple adhesively bonded wing splice joint under contract (metal-to-composite specimens). To determine fatigue and fracture failure modes for a "realistic" aircraft adhesively bonded structure.

FRACTURE OF COMPOSITES CONTAINING CIRCULAR CUTOUTS
80 January 1 - 82 March 31

Project Engineer: Dr. W. S. Johnson
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2715 FTS 928-2715

Objective: To conduct tests to document the failure mechanisms in boron/aluminum composites; X-ray, acoustic emission, and strain measurements are utilized.

ELASTIC-PLASTIC ANALYSIS OF FIBROUS METAL MATRIX COMPOSITES
80 October 1 - 82 September 30

Project Engineer: C. A. Bigelow
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-3191 FTS 928-3191

Objective: To develop a three-dimensional finite-element program for the elastic-plastic analysis of fibrous composite materials that will predict fiber breakage, crack growth, and the failure load of the specimen. With this program, fracture behavior of composite laminates can be predicted using the individual properties of the fiber and matrix phases. Additionally, the program can efficiently model the nonlinear behavior of metal matrix composites, previously a difficult, cumbersome problem.

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PROCEEDINGS OF THE SEVENTH ANNUAL MECHANICS OF COMPOSITES REVIE--ETC(U)
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AFWAL-TR-82-4007

FATIGUE AND FRACTURE BEHAVIOR OF THICK LAMINATES
81 October 1 - 83 September 30

Project Engineers: Edward P. Phillips
C. C. Poe, Jr.
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-3192 FTS 928-3192

Objective: To identify potential fatigue and fracture problems associated with scale-up of graphite/epoxy laminates to thicknesses of about 100 plies. This study will consist mostly of tests of thick laminates containing through-thickness holes and slits.

PREDICTION OF FATIGUE LIFE OF NOTCHED COMPOSITE LAMINATES
73 June 1 - 85 September 30

Project Engineers: Dr. T. Kevin O'Brien
John D. Whitcomb
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-3011 FTS 928-3011

Objective: To develop a method to design fatigue resistant composite laminates. The method addresses three areas: failure mechanisms are identified; analyses to predict inplane and interlaminar damage growth are developed; and inplane and interlaminar data bases are developed to evaluate the methodology.

THE EFFECTS OF REALISTIC FLIGHT ENVIRONMENTS ON FATIGUE OF COMPOSITE MATERIALS
72 June 1 - 83 May 31

Project Engineer: John D. Whitcomb
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-3011 FTS 928-3011

Objective: To determine the effects of realistic environments on the fatigue behavior of composite materials. Flight environments of conventional and supersonic aircraft transports and the Space Shuttle are being investigated. Tests are either accelerated or conducted in real time. Temperatures and load spectra are simulated for transport or Space Shuttle environments.

PREDICTION OF STIFFNESS LOSS, RESIDUAL STRENGTH, AND FATIGUE LIFE OF UNNOTCHED LAMINATES

80 June 1 - 83 October 31

Project Engineer: Dr. T. Kevin O'Brien
Mail Stop 188E
Structures Laboratory, USARTL (AVRADCOM)
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-3011 FTS 928-3011

Objective: To predict the stiffness loss, residual strength, and fatigue life of realistic unnotched laminates using baseline data from simple laminates.

PREDICTION OF INSTABILITY-RELATED DELAMINATION GROWTH

79 January 2 - 83 December 31

Project Engineer: John D. Whitcomb
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-3011 FTS 928-3011

Objective: To predict rate of instability-related delamination growth. Approximate stress analyses will be developed based on understanding gained from rigorous analyses. Experiments will be performed to obtain a data base for use by the analysis in making predictions and for verifying and improving the analysis.

FLIGHT SERVICE EVALUATION OF COMPOSITE COMPONENTS ON COMMERCIAL AND MILITARY AIRCRAFT

72 March 1 - 90 December 31

Project Engineer: H. Benson Dexter
Mail Stop 188A
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2869 FTS 928-2869

Objective: To evaluate the long-term durability of composite components installed on commercial and military transport and helicopter aircraft. Over 200 components constructed of boron, graphite, and Kevlar composites will be evaluated after extended service. Components include graphite/epoxy rudders, spoilers, tail rotors, vertical stabilizers, Kevlar/epoxy fairings, doors and ramp skins, boron-reinforced aluminum center wing boxes and tail cone, and boron/aluminum aft pylon skins. Note: Over 2 million total component flight hours have been accumulated since initiation of flight service in 1972. Composite components on L-1011, B-737, and DC-10 aircraft have accumulated over 20,000 flight hours each. Excellent in-service performance and maintenance experience have been achieved with the composite components.

AFWAL-TR-82-4007

POSTBUCKLING RESPONSE OF COMPOSITE MATERIAL SUBJECTED TO SHEAR LOADING
79 July 1 - 82 June 30

Project Engineer: Gary L. Farley
Mail Stop 188A
Structures Laboratory, USARTL (AVRADCOM)
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2850 FTS 928-2850

Objective: To determine the postbuckling strength of Kevlar and Kevlar-graphite/epoxy composites under static shear and spectrum fatigue loading. This study will establish a basis for demonstrating the use of thin composite laminates beyond the point of initial shear instability. A shear fixture has been developed that virtually eliminates the adverse stresses in the corners of the shear panel.

THE ENERGY ABSORPTION OF COMPOSITE CRASHWORTHY STRUCTURE
80 August 1 - 85 December 31

Project Engineer: Gary L. Farley
Mail Stop 188A
Structures Laboratory, USARTL (AVRADCOM)
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2850 FTS 928-2850

Objective: To determine the energy absorption of glass, Kevlar, and graphite/epoxy composite material and crashworthy composite floor structure subject to static and impact crushing test conditions. Tube specimens have been statically crushed to determine the specific energy absorption and postcrushing structural integrity of 33 different composite laminates.

THE EVALUATION OF GRAPHITE/POLYIMIDE HONEYCOMB SANDWICH PANELS
79 June 15 - 82 March 31

Project Engineer: Jane A. Hagaman
Mail Stop 188A
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2850 FTS 928-2850

Objective: To evaluate the shear behavior of an optimized sandwich panel at room and elevated temperatures using a diagonal tension test method, and to correlate the behavior with analytical predictions.

ENVIRONMENTAL EFFECTS ON METAL MATRIX COMPOSITES
78 January 1 - 82 December 31

Project Engineer: W. D. Brewer
Mail Stop 226B
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-3043 FTS 928-3043

Objective: To determine the effects of exposure to fabrication and various service environments on titanium and aluminum matrix composites, to identify the controlling mechanisms for material property changes, and to develop techniques and materials to control these changes to yield optimum composite properties for selected high-temperature aerospace applications.

POSTBUCKLING AND CRIPPLING OF COMPRESSION-LOADED COMPOSITE STRUCTURAL COMPONENTS
79 March 1 - 82 September 30

Project Engineer: Dr. James H. Starnes, Jr.
Mail Stop 190
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2552 FTS 928-2552

Objective: To study the postbuckling and crippling of compression-loaded composite components and to determine the limitations of postbuckling design concepts to structural applications.

DESIGN TECHNOLOGY FOR STIFFENED CURVED COMPOSITE PANELS
79 October 1 - 82 September 30

Project Engineer: Dr. James H. Starnes, Jr.
Mail Stop 190
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2552 FTS 928-2552

Objective: To develop verified design technology for generic advanced-composite stiffened curved panels.

COMPRESSION STRENGTH OF COMPOSITE LAMINATES WITH CUTOUTS
77 October 1 - 82 September 30

Project Engineer: Mark Shuart
Mail Stop 190
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2813 FTS 928-2813

Objective: To study the effects of cutouts on the compression strength of composite structural components and to identify the failure modes that govern the behavior of compression-loaded components with cutouts.

PRELIMINARY BOLTED JOINT DATA
78 July 1 - 81 October 31

Project Engineer: Gregory R. Wichorek
Mail Stop 188A
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2848 FTS 928-2848

Objective: To determine bolted joint strength and failure modes for advanced graphite/polyimide laminates from 116K and 589K, as well as the effect of joint geometry and temperature on joint strength and failure mode.

DEVELOPMENT OF PRECISION ALIGNMENT FIXTURE FOR TENSILE TESTING
78 September 1 - 82 March 31

Project Engineer: Dr. Donald R. Rummier
Mail Stop 188B
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2143 FTS 928-2143

Objective: To determine the effect of precision alignment on the mean and variance of the tensile strength of composite materials.

EFFECTS OF THERMAL CYCLING ON DIMENSIONAL STABILITY OF GRAPHITE/EPOXY COMPOSITES
81 October 1 - 84 September 30

Project Engineer: Dr. S. S. Tompkins
Mail Stop 188B
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2143 FTS 928-2143

Objective: To determine the effects of thermal cycling from 117K to 400K on dimensional stability of graphite/epoxy composites.

RADIATION EFFECTS ON MATERIALS FOR STRUCTURAL COMPOSITES
79 July 1 - 84 June 30

Project Engineer: Dr. Edward R. Long, Jr.
Mail Stop 396
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-3892 FTS 928-3892

Objective: To determine and correlate the effects of particulate radiation exposure on the properties and chemical structure of materials for structural composites and to develop procedures for accelerated laboratory simulation of long-term missions in a space radiation environment.

AFWAL-TR-82-4007

POSTBUCKLING OF FLAT STIFFENED GRAPHITE/EPOXY SHEAR WEBS

81 July 1 - 82 September 30

Project Engineer: Marshall Rouse
Mail Stop 190
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-4585 FTS 928-4585

Objective: To study the postbuckling response and failure characteristics of flat stiffened graphite/epoxy shear webs.

STRENGTH OF PREFORMED AND STITCHED GRAPHITE/EPOXY LAP JOINTS

81 June 1 - 82 September 30

Project Engineer: Dr. J. Wayne Sawyer
Mail Stop 190
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-3714 FTS 928-3714

Objective: To study the effects of stitching and preformed adherends on graphite/epoxy lap-joint strength.

CURVED GRAPHITE/EPOXY PANELS SUBJECTED TO INTERNAL PRESSURE

80 October 1 - 82 September 30

Project Engineer: Richard L. Boitnott
Mail Stop 190
Structures Laboratory, USARTL (AVRADCOM)
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-3714 FTS 928-3714

Objective: To study the effects of internal pressure on the nonlinear response and failure characteristics of curved graphite/epoxy panels.

POSTBUCKLING ANALYSIS OF GRAPHITE/EPOXY LAMINATES

80 October 1 - 82 September 30

Project Engineer: Dr. Manuel Stein
Mail Stop 190
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2813 FTS 928-2813

Objective: To develop accurate analyses for the postbuckling response of graphite/epoxy laminates and to determine the parameters that govern postbuckling behavior.

AFWAL-TR-82-4007

STRUCTURAL PANEL ANALYSIS AND SIZING CODE FOR STIFFENED COMPOSITE PANELS
79 October 1 - 82 September 30

Project Engineers: Dr. Melvin S. Anderson
Dr. W. Jefferson Stroud
Mail Stop 190
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-3054 FTS 928-3054

Objective: To develop an accurate analysis and structural optimization capability for stiffened composite panels subjected to inplane tension, compression, shear, normal pressure, and thermal loads.

COMPRESSION STRENGTH OF COMPOSITE LAMINATES WITH LOW-VELOCITY IMPACT DAMAGE
76 October 1 - 82 September 30

Project Engineer: Marvin D. Rhodes
Mail Stop 190
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-3596 FTS 928-3596

Objective: To study the effects of low-velocity impact damage on the compression strength of composite structural components and to identify the failure modes that govern the behavior of compression-loaded components subjected to low-velocity impact damage.

DAMAGE TOLERANT DESIGN TECHNOLOGY FOR COMPRESSION-LOADED COMPOSITE STRUCTURAL COMPONENTS
78 October 1 - 82 September 30

Project Engineer: Dr. Jerry G. Williams
Mail Stop 190
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-3524 FTS 928-3524

Objective: To develop structural design concepts for containing and resisting damage in compression-loaded composite structural components.

CONTRACTS

INCREMENTAL ANALYSIS OF IMPACT DAMAGE

NASI-15888

79 August 3 - 82 November 30

Project Engineer: Walter Illg
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2338 FTS 928-2338

Principal Investigator: Edward A. Humphreys
Materials Sciences Corporation
Blue Bell Office Campus
Merion Towle House
Blue Bell, Pennsylvania 19422
(215) 542-8400

Objective: To develop an incremental damage analysis that predicts the extent of fiber breaks and matrix delaminations as a projectile transfers energy to a laminate in discrete steps. At each step, failure criteria determine the advance of damage and thus establish the configuration for the next increment of deformation.

TRANSIENT STRAINS DUE TO IMPACT

NASI-16763

81 August 20 - 82 November 5

Project Engineer: Walter Illg
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2338 FTS 928-2338

Principal Investigator: Dr. I. M. Daniel
IIT Research Institute
10 West 35th Street
Chicago, Illinois 60616
(312) 542-4402

Objective: To characterize impact damage in graphite/epoxy composite laminates and correlate it with transient strain and deformation history during impact. Plate and beam specimens containing embedded strain gages will be impacted with projectiles of various radii at two velocities.

AFWAL-TR-82-4007

IMPACT CONTACT STRESS ANALYSIS
(Contract Number Pending)
81 October 1 - 83 September 30

Project Engineer: Walter Illg
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2338 FTS 928-2338

Principal Investigator: Dr. C. T. Sun
School of Aeronautics and Astronautics
Purdue University
West Lafayette, Indiana 47907
(317) 749-2527

Objective: To integrate the contact behavior and dynamic structural response to solve impact problems involving laminates under initial stress. With the aid of the previously-developed contact law, the dynamic response of the laminate will be modeled by finite elements. Impact damage will be investigated experimentally and correlated with the results of the analysis.

QUANTITATIVE RECONSTRUCTIVE ULTRASONIC IMAGING
NCCI-50
81 April 1 - 84 March 31

Project Engineer: Dr. Joseph S. Heyman
Mail Stop 499
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-3418 FTS 928-3418

Principal Investigator: Dr. Gary Brandenburger
Virginia Associated Research Campus
College of William and Mary
12070 Jefferson Avenue
Newport News, Virginia 23606
(804) 877-9231

Objective: To develop a state of the art ultrasonic reconstructive imaging system for quantitative materials characterization.

AFWAL-TR-82-4007

QUANTITATIVE PHYSICAL ANALYSIS OF IMPACT DAMAGE

NSG-1601

80 March 1 - 84 February 28

Project Engineer: Dr. Joseph S. Heyman
Mail Stop 499
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-3418 FTS 928-3418

Principal Investigator: Professor James G. Miller
Laboratory for Ultrasonics
Physics Department
Washington University
St. Louis, Missouri 63130
(314) 889-6229

Objective: To improve nondestructive acoustic/ultrasonic techniques for quantitative characterization of defects in composite materials and to investigate new quantitative measurement phenomena applicable to graphite/epoxy.

NONEQUILIBRIUM MATERIAL EFFECTS ON THE BEHAVIOR OF POLYMERIC COMPOSITE MATRICES AND THEIR RELATED COMPOSITES

NAG-1-78

80 July 1 - 81 September 30

Project Engineer: Dr. Norman J. Johnston
Mail Stop 226
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-3041 FTS 928-3041

Principal Investigator: Dr. Garth L. Wilkes
Department of Chemical Engineering
Virginia Polytechnic Institute & State University
Blacksburg, Virginia 24061
(703) 961-5498

Objective: Following their processing as composite matrices, polymeric resins such as epoxies and polyimides initially are in a nonequilibrium state. The contractor will measure mechanical and sorption property changes of the resins as, over several thousand hours, they approach an equilibrium state. A determination will be made whether, and to what extent, resin property changes are reflected in carbon fiber composite property changes.

AFWAL-TR-82-4007

APPLICATION OF NONLINEAR IRREVERSIBLE THERMODYNAMICS TO COMPOSITE MATERIALS
NAS1-16301

80 August 18 - 82 January 03

Project Engineer: Dr. Norman J. Johnston
Mail Stop 226
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-3041 FTS 928-3041

Principal Investigator: Dr. Paul H. Lindenmeyer
Boeing Aerospace Company
P. O. Box 3999
Seattle, Washington 98124
(206) 237-5650

Objective: To apply nonlinear irreversible thermodynamics to the fracture mechanics of composite materials; namely, to determine how a composite will respond to a changing environment when the flow of energy (i.e., the power) becomes sufficiently great so that the system responds by the formation of dissipative rather than equilibrium structures or defects.

GRAPHITE FIBER SURFACE TREATMENT
NAS1-15869

80 September 26 - 81 September 30

Project Engineer: Dr. Terry L. St. Clair
Mail Stop 226
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-3041 FTS 928-3041

Principal Investigator: Dr. James T. Paul, Jr.
Hercules Incorporated
Research Center
Wilmington, Delaware 19899
(302) 995-3000

Objective: To determine how various sizings and coatings on graphite fibers affect the impact tolerance of composite panels made with the modified fibers. To determine the effect of such modifications on the mechanical and thermo-oxidative properties of laminates.

AFWAL-TR-82-4007

FIBER/MATRIX LOAD INTERACTIONS

NAS1-15749

80 September 19 - 81 December 1

Project Engineer: Dr. Stephen S. Tompkins
Mail Stop 188B
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2143 FTS 928-2143

Principal Investigator: Dr. Paul McMahon
Celanese Research Company
86 Morris Avenue
Summit, New Jersey 07901
(201) 522-7500, ext. 425

Objective: To characterize and model the interactions between fibers and resin within graphite/epoxy composite materials. To determine the effects of the interface properties on composite laminate properties and correlate the properties of the interface with lamina and laminate properties.

FRACTURE AND CRACK GROWTH IN ORTHOTROPIC LAMINATES

NSG-1606

79 July 1 - 82 April 30

Project Engineer: C. C. Poe, Jr.
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2338 FTS 928-2338

Principal Investigator: Dr. Jonathan Awerbuch
Department of Mechanical Engineering
Drexel University
Philadelphia, Pennsylvania 19104
(215) 895-2291

Objective: To explore the fracture characteristics of graphite/polyimide composites at elevated temperatures using laminates with slits.

FRACTURE AND CRACK GROWTH IN ORTHOTROPIC LAMINATES

NSG-1297

74 October 16 - 82 October 15

Project Engineer: C. C. Poe, Jr.
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2338 FTS 928-2338

Principal Investigator: Dr. James G. Goree
Department of Mechanical Engineering
Clemson University
Clemson, South Carolina 29631
(803) 656-3291

Objective: To develop analyses that predict strength of buffer strip panels using models that treat the fiber and matrix as discrete elements.

THREE-DIMENSIONAL STRESS ANALYSIS OF FASTENER HOLES

NCCI-15

80 October 1 - 83 September 30

Project Engineer: Dr. John H. Crews, Jr.
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2318 FTS 928-2318

Principal Investigator: Dr. I. S. Raju
Mail Stop 188E
Joint Institute for Advancement of Flight Sciences
George Washington University at NASA Langley Research
Center
Hampton, Virginia 23665
(804) 827-3178 FTS 928-3178

Objective: To compute 3-D stresses near unloaded and loaded fastener holes in laminated composites. These stresses are needed to predict the delamination onset in bolted joints.

THE VISCOELASTIC CHARACTERIZATION AND LIFETIME PREDICTION OF STRUCTURAL ADHESIVES

(Contract Number Pending)

81 October 1 - 82 September 30

Project Engineer: Dr. W. S. Johnson
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2715 FTS 928-2715

Principal Investigator: Dr. H. F. Brinson
Department of Engineering Science and Mechanics
Virginia Polytechnic Institute & State University
Blacksburg, Virginia 24061
(703) 961-6627

Objective: To develop a procedure to predict the failures of adhesive joints where service life must span 10 to 20 years using, as a basis, analytical projections or extrapolations from short-time test data.

FRACTURE TESTING OF GRAPHITE/POLYIMIDE

NAS1-15080, Task 4; and NSG-1571

78 March 27 - 81 November 30

Project Engineer: R. A. Everett, Jr.
Mail Stop 188E
Structures Laboratory, USARTL (AVRADCOM)
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2715 FTS 928-2715

Principal Investigator: Dr. Don H. Morris
Department of Engineering Science and Mechanics
Virginia Polytechnic Institute & State University
Blacksburg, Virginia 24061
(703) 961-5726

Objective: To establish the fracture characteristics of graphite/polyimide laminates containing round holes at cryogenic, room, and elevated temperatures.

AFWAL-TR-82-4007

EVALUATION OF THE DURABILITY AND DAMAGE TOLERANCE OF CTOL COMPOSITE STRUCTURES
NAS1-15107
77 October 12 - 82 July 1

Project Engineer: Edward P. Phillips
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-3192 FTS 928-3192

Principal Investigator: Ray Horton
Boeing Commercial Airplane Company
P. O. Box 3707
Seattle, Washington 98124
(206) 241-3443

Objective: To perform selected analysis, fabrication, and testing tasks in the general area of durability and damage tolerance of graphite/epoxy composites, laminates, and structures. Current tasks involve design and fabrication of damage tolerance test specimens--unstiffened panels containing glass or Kevlar buffer strips and stiffened panels without buffer strips.

A STUDY OF STIFFNESS, RESIDUAL STRENGTH, AND FATIGUE LIFE RELATIONSHIPS FOR COMPOSITE LAMINATES
NAS1-16406
80 October 1 - 81 November 30

Project Engineer: Dr. T. Kevin O'Brien
Mail Stop 188E
Structures Laboratory, USARTL (AVRADCOM)
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-3011 FTS 928-3011

Principal Investigators: Dr. James T. Ryder
Lockheed-California Company
Burbank, California 91520
(213) 847-6121, ext. 291

Dr. Frank W. Crossman
Lockheed Research Laboratory
Palo Alto, California 94304
(415) 858-4034

Objective: To develop quantitative relationships between laminate stiffness, residual strength, and fatigue life for unnotched laminates.

AFWAL-TR-82-4007

DETERMINATION OF STIFFNESS REDUCTIONS DURING FATIGUE OF UNNOTCHED ANGLE-PLY,
GRAPHITE/EPOXY LAMINATES

NAS1-16557

81 March 1 - 82 February 28

Project Engineer: Dr. T. Kevin O'Brien
Mail Stop 188E
Structures Laboratory, USARTL (AVRADCOM)
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-3011 FTS 928-3011

Principal Investigators: Professor Donald Adams
David Walrath
Department of Mechanical Engineering
University of Wyoming
Laramie, Wyoming 82071
(307) 766-2371

Objective: Determine axial stiffness reductions during fatigue of $[\pm 45]_{2s}$ and $[\pm 67.5]_{2s}$ graphite/epoxy laminates.

QUANTITATIVE STUDY OF INSTABILITY-RELATED DELAMINATION GROWTH

NAS1-16727

81 July 13 - 83 January 13

Project Engineer: John D. Whitcomb
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-3011 FTS 928-3011

Principal Investigator: Dr. R. L. Ramkumar
Dept. 3852/82
Northrop Corporation
Aircraft Division
3901 West Broadway
Hawthorne, California 90250
(213) 970-5075

Objective: To predict the rate of instability-related delamination growth. Simple tests will be performed to quantify the relationship between delamination growth rate and Mode I and Mode II strain-energy-release rates. An approximate analysis will be developed.

THERMOMECHANICAL RESPONSE OF GRAPHITE/POLYIMIDE COMPOSITES

NAS1-15841

79 October 1 - 81 October 31

Project Engineer: Dr. John G. Davis, Jr.
Mail Stop 188A
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2036 FTS 928-2036

Principal Investigator: E. A. Derby
Materials Sciences Corporation
Blue Bell Office Campus
Blue Bell, Pennsylvania 19422
(215) 542-8400

Objective: To develop the capability to predict the response of graphite/polyimide composites under thermal and mechanical loading. Non-linear and viscoelastic matrix behavior will be incorporated in laminate stress analysis. Report scheduled to be issued in October 1981.

DESIGN ALLOWABLES CHARACTERIZATION OF C6000/LARC-160 GRAPHITE/POLYIMIDE

NAS1-15183

80 October 1 - 82 January 1

Project Engineer: Gregory R. Wichorek
Mail Stop 188A
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2848 FTS 928-2848

Principal Investigator: H. Q. Norris
Rockwell International Corporation
Space Division
Seal Beach, California 90740
(231) 594-3289

Objective: To experimentally determine mechanical properties of graphite/polyimide laminates for use in designing aerospace structures for service at temperatures from 117K (-250°F) to 589K (600°F).

AFWAL-TR-82-4007

DESIGN ALLOWABLES CHARACTERIZATION OF C6000/PMR-15 GRAPHITE/POLYIMIDE
NAS1-15644
80 October 1 - 81 October 1

Project Engineer: Gregory R. Wichorek
Mail Stop 188A
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2848 FTS 928-2848

Principal Investigator: D. E. Skoumal
Boeing Aerospace Company
P. O. Box 3999
Seattle, Washington 99124
(206) 773-8016

Objective: To experimentally determine mechanical properties of graphite/
polyimide laminates for use in designing aerospace structures for
service at temperatures from 117K (-250°F) to 589K (600°F).

LSST HOOP/COLUMN ANTENNA: MATERIALS TASK
NAS1-15763
79 April 1 - 83 March 31

Project Engineer: Dr. Darrel R. Tenney
Mail Stop 188B
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2143 FTS 928-2143

Principal Investigator: Marvin Sullivan
Harris Corporation
P. O. Box 37
Melbourne, Florida 32901
(305) 727-5813

Objective: To develop tension stabilizing cables with a high degree of
dimensional stability for use on a 100-meter diameter space
deployable antenna; to develop lightweight, thermally stable
composite materials for structural members and joints.

AFWAL-TR-82-4007

COMPOSITE MATERIALS RESEARCH AND EDUCATION
NCCI-15
81 September 1 - 82 August 31

Project Engineer: Dr. Darrel R. Tenney
Mail Stop 188B
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2143 FTS 928-2143

Principal Investigators: Dr. Carl T. Herakovich
Dr. M. W. Hyer
Department of Engineering Science and Mechanics
Virginia Polytechnic Institute & State University
Blacksburg, Virginia 20461
(703) 961-5372

Objective: To develop accurate analytical and experimental techniques to determine the dimensional stability of composites.

EFFECTS OF HIGH-ENERGY RADIATION ON THE MECHANICAL PROPERTIES OF GRAPHITE FIBER REINFORCED EPOXY RESINS
NSG-1562
79 October 1 - 82 December 31

Project Engineer: Dr. Edward R. Long, Jr.
Mail Stop 396
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-3892 FTS 928-3892

Principal Investigators: Dr. Jasper D. Memory
Dr. Raymond E. Fornes
Departments of Physics and Textiles
North Carolina State University
Raleigh, North Carolina 27650
(919) 737-2503/737-3231

Objective: To investigate the effects of high-energy radiation on graphite fiber composites by study of composite curing effects, radiation exposure rates, mechanical fracture surfaces, and electron spin resonance properties.

AFWAL-TR-82-4007

ENVIRONMENTAL EXPOSURE EFFECTS ON COMPOSITE MATERIALS FOR COMMERCIAL AIRCRAFT
NAS1-15148
77 November 1 - 88 November 30

Project Engineer: Dr. Ronald K. Clark
Mail Stop 188B
NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2143 FTS 928-2143

Principal Investigator: Daniel J. Hoffman
Boeing Commercial Airplane Company
P. O. Box 3707
Seattle, Washington 98124
(206) 241-3443

Objective: To provide technology in the areas of characterization methods and environmental effects on graphite/epoxy composite materials, including development of accelerated test and analysis methods to predict long-term performance of advanced resin-matrix composite materials within 20 percent of real-time aircraft service exposure results.

TIME-TEMPERATURE-STRESS CAPABILITIES OF COMPOSITE MATERIALS FOR ADVANCED
SUPERSONIC TECHNOLOGY APPLICATIONS
NAS1-12308
73 June 1 - 84 September 30

Project Engineer: Bland A. Stein
Mail Stop 226
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Hampton, Virginia 23665
(804) 827-3041 FTS 928-3041

Principal Investigator: J. F. Haskins
Mail Zone 43-6320
General Dynamics
P. O. Box 80847
San Diego, California 92138
(714) 891-8900, ext. 2088

Objective: To establish the time-temperature-stress characteristics and capabilities of five classes of high-temperature composite materials (graphite/epoxy, boron/epoxy, graphite/polyimide, boron/polyimide, and boron/aluminum) subjected to a simulated supersonic cruise flight environment for up to 50,000 hours. Note: Phase I of this contract has been documented in NASA CR-165711.

COMBINED RADIATION EXPOSURE
(Contract Number Pending)
81 September 28 - 84 October 1

Project Engineer: Wayne S. Slemp
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NASA Langley Research Center
Hampton, Virginia 23665
(804) 827-2507 FTS 928-2507

Principal Investigator: Lawrence B. Fogdall
Boeing Aerospace Company
P. O. Box 3999
Seattle, Washington 98124
(206) 773-6711

Objective: To determine the effects of simulated space radiation on the mechanical and chemical properties of composite materials. This study will provide data for establishing the long-term space durability of current composites. Particular attention will be directed toward combined proton and electron effects to determine whether synergistic interactions occur.

FIBER-REINFORCED TITANIUM MATERIALS AND PROCESS INTERACTIONS
NAS1-16403
80 September 15 - 81 December 31

Project Engineer: W. D. Brewer
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(804) 827-3043 FTS 928-3043

Principal Investigator: Gordon S. Doble
T/M 2127
TRW, Inc.
Materials Technology
2355 Euclid Avenue
Cleveland, Ohio 44117
(216) 383-2127

Objective: To develop, through innovative materials systems and processing techniques, fiber-reinforced titanium composites that are stable after high-temperature processing and that have sufficiently good properties for long-term service in high-performance aircraft structures applications.

LOW-SPEED IMPACT DAMAGE ON COMPOSITE MATERIALS
NSG-1483
78 January 15 - 82 January 15

Project Engineer: Dr. James H. Starnes, Jr.
Mail Stop 190
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(804) 827-2552 FTS 928-2552

Principal Investigators: Dr. Wolfgang G. Knauss
Dr. Charles D. Babcock
California Institute of Technology
Pasadena, California 91125
(213) 795-6811, ext. 1524/1528

Objective: To study the effects of low-speed impact damage in composite structural components using high-speed motion pictures and to develop an analytical procedure for the propagation of the resulting impact damage.

ADVANCED COMPOSITE STRUCTURAL DESIGN TECHNOLOGY FOR COMMERCIAL TRANSPORT AIRCRAFT
NAS1-15949
79 September 24 - 84 September 24

Project Engineer: Dr. James H. Starnes, Jr.
Mail Stop 190
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(804) 827-2552 FTS 928-2552

Principal Investigator: John N. Dickson
Lockheed-Georgia Company
86 South Cobb Drive
Marietta, Georgia 30063
(404) 424-3085

Objective: To design, analyze, fabricate, and test generic advanced-composite structural components for transport aircraft applications in order to develop verified design technology.

AFWAL-TR-82-4007

STRUCTURAL OPTIMIZATION FOR IMPROVED DAMAGE TOLERANCE

NAG-1-168

81 September 1 - 82 October 15

Project Engineer: Dr. James H. Starnes, Jr.
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Hampton, Virginia 23665
(804) 827-2552 FTS 928-2552

Principal Investigator: Dr. Raphael T. Huftka
Virginia Polytechnic Institute & State University
Blacksburg, Virginia 24061
(703) 961-6611

Objective: To develop a structural optimization procedure for composite wing boxes that includes the influence of damage-tolerance considerations in the design process.

MEASUREMENT OF DISPLACEMENT AROUND HOLES IN COMPOSITE PLATES SUBJECTED TO QUASI-STATIC COMPRESSION

NAG-1-193

81 June 1 - 82 May 31

Project Engineer: Dr. James H. Starnes, Jr.
Mail Stop 190
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(804) 827-2552 FTS 928-2552

Principal Investigators: Dr. John C. Duke
Dr. Daniel Post
Virginia Polytechnic Institute & State University
Blacksburg, Virginia 24061
(703) 961-6063/961-6349

Objective: To measure the through-the-thickness deformations near open holes in compression-loaded graphite/epoxy laminates.

AFWAL-TR-82-4007

COMPRESSION STRENGTH FRACTURE MECHANISMS IN UNIDIRECTIONAL COMPOSITE LAMINATES
CONTAINING A HOLE

NAG-1-201

81 June 15 - 82 August 31

Project Engineer: Dr. James H. Starnes, Jr.
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Hampton, Virginia 23665
(804) 827-2552 FTS 928-2552

Principal Investigator: Dr. Eric R. Johnson
Virginia Polytechnic Institute & State University
Blacksburg, Virginia 24061
(703) 961-5905

Objective: To develop analytical models of the three-dimensional deformations
near a hole in a unidirectional composite laminate.

STRUCTURAL TEST SPECIMENS USING FIBER-REINFORCED COMPOSITE MATERIALS

NAS1-12675

73 September 6 - 82 March 6

Project Engineer: Dr. Jerry G. Williams
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Hampton, Virginia 23665
(804) 827-3524 FTS 928-3524

Principal Investigator: Cliff Kam
Douglas Aircraft Company
3855 Lakewood Blvd.
Long Beach, California 90846
(213) 593-5332

Objective: To design, fabricate, and test composite compression components for
structural applications; to develop fabrication procedures for
stiffened panels; and to evaluate damage tolerant materials.

AFWAL-TR-82-4007

EVALUATION OF THE DURABILITY AND DAMAGE TOLERANCE OF COMPOSITE STRUCTURES SUIT-
ABLE FOR COMMERCIAL TRANSPORT AIRCRAFT
NAS1-15107

77 October 1 - 82 September 30

Project Engineer: Marvin D. Rhodes
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(804) 827-3596 FTS 928-3596

Principal Investigator: John E. McCarty
Boeing Commercial Airplane Company
P. O. Box 3707
Seattle, Washington 98124
(206) 433-1430

Objective: To design, fabricate, and test generic composite structural com-
ponents for commercial aircraft applications that are durable and
damage tolerant.

NASA LEWIS RESEARCH CENTER

IN HOUSE

STRUCTURAL INTEGRITY OF FLAWED COMPOSITES
74 June 11 - 82 September 30

Project Engineer: C. C. Chamis
NASA Lewis Research Center, 49-6
21000 Brookpark Road
Cleveland, Ohio 44135
(216) 433-4000 - Ext. 6831 FTS

Objective: Develop and correlate experimental and analytical description of failure processes occurring in multidirectional composite structural materials containing natural and artificial defects.

COMPOSITE IMPACT STUDIES
73 June 11 - 82 September 30

Project Engineer: R. F. Lark
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Cleveland, Ohio 44135
(216) 433-4000 - Ext. 5103 FTS

Objective: Develop computational methods, design procedures and design data for composite engine components subject to high-velocity impact loading.

STRUCTURAL MECHANICS OF COMPOSITES
70 June 11 - 82 September 30

Project Engineer: C. C. Chamis
NASA Lewis Research Center, 49-6
21000 Brookpark Road
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(216) 433-4000 - Ext. 6831

Objective: Develop, verify and incorporate advanced analysis methods in a computer-aided design/analysis capability for advanced fiber engine structures.

CONTRACTS

COMPRESSION AND COMPRESSION FATIGUE TESTING OF COMPOSITE LAMINATES
NAS3-22812
81 June 5 - 82 March 30

AFWAL-TR-82-4007

Project Engineer: G. T. Smith
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Principal Investigator: T. R. Porter
Boeing Military Airplane Company
Advanced Airplane Branch
Seattle, Washington 98124

HIGH STRAIN RATE PROPERTIES
NAS3-21016
77 July 11 - 81 December 1

Project Engineer: C. C. Chamis
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Cleveland, Ohio 44135

Principal Investigator: I. M. Daniels
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Chicago, Illinois 60616

ENVIRONMENTAL EFFECTS ON DEFECT GROWTH IN COMPOSITE MATERIALS
NAS3-20405
77 July 5 - 81 November 1

Project Engineer: G. T. Smith
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Principal Investigator: T. R. Porter
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ENVIRONMENTAL EFFECTS ON FOD RESISTANCE OF COMPOSITE FAN BLADES
NAS3-21017
77 January 21 - 81 December 1

Project Engineer: G. T. Smith
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Principal Investigator: G. C. Murphy
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GRANTS

DYNAMIC FRACTURE OF COMPOSITES

NSG-3179

28 February 1 - 81 December 1

Project Engineer: C. C. Chamis
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Principal Investigator: G. C. Sih
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Bethlehem, Pennsylvania 18015

IMPACT ENERGY MODELS

NSG-3185

78 February 1 - 81 December 1

Project Engineer: C. C. Chamis
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Principal Investigator: C. T. Sun
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SPECIAL FINITE ELEMENT ANALYSIS OF FLAWED COMPOSITES

NSG-3044

75 February 1 - 81 December 1

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NASA LEWIS RESEARCH CENTER

IN HOUSE

SYNTHESIS OF HIGH TEMPERATURE POLYMERS
81 October 1 - 82 September 30

Project Engineer: P. Delvigs
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(216)433-4000 ext. 6967

Objective: Develop matrix resins with improved thermo-oxidative stability at temperatures and pressures up to 371°C and 1.0 MPa (absolute), respectively, compared to state of the art high temperature resins.

MORE PROCESSABLE PMR
81 October 1 - 82 September 30

Project Engineer: W. B. Alston
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Cleveland, Ohio 44135
(216)433-4000 ext. 6179

Objective: Develop PMR Polyimides with lower curing temperatures than state of the art PMR-15 and to improve the handling characteristics of prepreg materials based on PMR-15.

IMPROVED TOUGHNESS POLYMERS
80 October 1 - 82 September 30

Project Engineer: R. W. Lauver
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Cleveland, Ohio 44135
(216)433-4000 ext. 369

Objective: Develop polymer matrix composites with improved toughness characteristics and to achieve a fundamental understanding of the factors which control the toughness characteristics of matrix resins and composites and to evolve criteria for predicting composite performance.

CONTRACTS

IMIDE MODIFIED EPOXY MATRIX RESINS
NAS 3-22521
80 September 12 - 81 November 12

Project Engineer: P. Delvigs
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Principal Investigator: D. A. Scola
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CHARACTERIZATION OF PMR POLYIMIDE AND PREPREG
NAS 3-22523
80 October 16 - 81 December 15

Project Engineer: R. W. Lauver
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21000 Brookpark Road
Cleveland, Ohio 44135

Principal Investigator: C. H. Sheppard
Boeing Aerospace Division
Seattle, WA 98124

PMR ENGINE DUCT DEVELOPMENT
NAS 3-21854
79 June 27 - 82 September 30

Project Engineer: R. D. Vannucci
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NAVAIR
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GRANTS

INJECTION MOLDING OF PMR-15
NAG3-129
81 January 1 - 83 January 1

Project Engineer: T. T. Serafini
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Principal Investigator: S. C. Malguarnera
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AFWAL-TR-82-4007

POLYIMIDE DEGRADATION

NAG3-126

81 January 15 - 83 January 14

Project Engineer: R. W. Lauver
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21000 Brookpark Road
Cleveland, Ohio 44135

Principal Investigator: H. Ishida
Case Western Reserve University
Cleveland, Ohio 44106

CORRELATION OF NMR PARAMETERS WITH POLYMER MECHANICAL PROPERTIES

NAG3-158

81 February 25 - 83 February 24

Project Engineer: R. W. Lauver
NASA Lewis Research Center, 49-1
21000 Brookpark Road
Cleveland, Ohio 44135

Principal Investigator: W. M. Ritchey
Case Western Reserve University
Cleveland, Ohio 44106

LOWER CURING TEMPERATURE POLYMERS

NAG3-163

81 March 3 - 83 March 2

Project Engineer: T. T. Serafini
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21000 Brookpark Road
Cleveland, Ohio 44135

Principal Investigator: W. M. Ritchey
Case Western Reserve University
Cleveland, Ohio 44106

IN-HOUSE

MODEL OF BORON FIBER GROWTH AND ANNEALING
79 June 1 - present

Project Engineer: Dr. Donald R. Behrendt
NASA Lewis Research Center
21000 Brookpark Road, MS 106-1
Cleveland, OH 44135
(216) 433-4000 (X6603)

Objective: To model chemical vapor deposition of boron to determine the factors which lead to the residual stresses in this fiber.

CONTRACTS

ENERGY ABSORPTION MECHANISMS DURING CRACK PROPAGATION IN METAL MATRIX COMPOSITES
NSG-3217
78 August 1 - 82 July 30

Project Engineer: Dr. James A. DiCarlo
NASA Lewis Research Center
21000 Brookpark Road, MS 106-1
Cleveland, OH 44135
(216) 433-4000 (X6602)

Principal Investigator: Dr. Donald F. Adams
Mechanical Engineering Department
University of Wyoming
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(307) 766-2371

Objective: To model, using finite element micromechanics, crack initiation and propagation in a generalized fiber composite with an elasto-plastic matrix in order to optimize composite design and materials selection for best strength and impact resistance.

AFWAL-TR-82-4007

NASA LEWIS RESEARCH CENTER

IN HOUSE (NDE Section)

NONDESTRUCTIVE EVALUATION OF COMPOSITES

81 October - 82 September

Project Engineer: A. Vary
NASA Lewis Research Center, 106-1
21000 Brookpark Road
Cleveland, Ohio 44135
(216)433-4000, ext. 357 (FTS 6357)

Objective: Advance state of the art in nondestructive evaluation (NDE) for better defect characterization and direct determination of material properties in structural composite components. Establish NDE correlations with deformation and fracture in composite laminates.

GRANTS (NDE Section)

ACOUSTO-ULTRASONIC NONDESTRUCTIVE EVALUATION

81 October - 82 September

Project Engineer: A. Vary
NASA Lewis Research Center, 106-1
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(216)433-4000, ext. 357 (FTS 6357)

Principal Investigator: J. H. Williams, Jr.
Department of Mechanical Engineering, 3-360
Massachusetts Institute of Technology
77 Massachusetts Avenue
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Objective: Establish acousto-ultrasonic wave propagation theory and stress wave factor parameters relative to nondestructive evaluation of strength and strength degradation in fiber reinforced composite laminates.

APPENDIX C
ATTENDANCE LIST

MECHANICS OF COMPOSITES REVIEW
SHERATON HOTEL
DAYTON, OHIO

28-30 October 1981

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