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Reliability Evaluation of Composite Hardware: a probabilistic micromechanics approach

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**Reliability evaluation of composite hardware: A probabilistic
micromechanics approach**

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San Jose State University, 1991

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Reliability Evaluation of Composite Hardware:

A Probabilistic Micromechanics Approach

A Dissertation Submitted to

The Faculty of the Mechanical Engineering Department

In Candidacy for the Degree of

Masters of Science

Department of Mechanical Engineering

By:

Ms. Susan E. Blackson

December, 1990

APPROVED FOR THE DEPARTMENT OF MECHANICAL ENGINEERING

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ABSTRACT

The recent marked growth in the composite materials marketplace reflects the need by designers for materials of special capability which provide simplicity and cost effectiveness during manufacturing process. Although composite systems provide the flexibility in the design cycle where the material employed may be optimized to support stringent and directional property requirements, they are also highly sensitive to the consistency of the constituent materials, the method of processing, and the methods of post fabrication finishing and assembly. To fully understand the impact of the variation of these material and process parameters on the quality of the finished part, the technical state of the art must first be reviewed and assessed.

To understand the technical merits which drive the development of composite materials, the current methods of design must first be reviewed. Further, when the knowledge of the the generally accepted methods has been established, then impacts of material and process sensitivities on the composite system characteristics may be addressed. In this manner, once the state of the technology is known and the material and process sensitivities are identified, then the impacts of the current design methods may be evaluated and assessed. It will be shown in this study that analytical methods currently exist which assist in the determination of the impact of material and process variability on the resulting quality of the composite hardware.

Predictive techniques which relate the variability of constituent materials to the thermal/mechanical properties of the final composite material system require further investigation and development. Background on current methods of the phenomenism and analytical aspects of statistical characterization of strength and stress of advanced composites will be reviewed. Analytical predictive techniques of including both micromechanics and macromechanics approaches of composite strength will be discussed. Further, a probabilistic micromechanical approach which relates the lot-to-lot variability of the composite system to the reliability of the laminate property will be demonstrated.

PREFACE

Composites have been established during the past twenty years for use in components of military, aerospace, and commercial application. The reasons for the acceptance of the continuous fiber resinous composite in the aerospace community is the successful optimization in design and utilization in manufacturing of the outstanding non-isotropic specific strength and specific modulus of these materials. During the past ten years of my personal study and research into the chemistry, analysis, fabrication, and test of composite materials, the tremendous and diverse supply of reference texts have greatly assisted in my pursuit of the engineering understanding of these systems. There is no proper way to thank the efforts of such great authors as Chamis, Broutman, Rosen, Bathe, Petit, Halpin, Tsai, Springer, Jones, and Haughen, although it should be noted that the awesome knowledge assembled and published by these individuals permits the student a unique perspective of the natural laws followed by these composite systems. These reference volumes provided the technical foundation of understanding of the many aspects of applications development required for the successful utilization of the potential of these complex material systems.

In these ten years of investigation into composite materials, two mentors have provided the technical breadth and guidance I required to direct my education of the composites industry. First, I would like to thank Dr. Roger Fountain for his patient tutelage on polymeric processing and concurrent engineering concepts. The direction Dr. Fountain provided truly piqued my interest concerning the optimization and cost effective application of composites in modern commercial and military applications.

Secondly, I would like to thank an equally significant mentor, Dr. Kim Bailie who assisted in my education of structural analysis as well as provided an excellent background on the current manufacturing procedures and limitations. My sincere thanks and appreciation to all those individuals who freely gave of their time and expertise in response to my constant list of queries, who provided insight into the workings of the complicated world of composite materials.

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LIST OF ABBREVIATIONS

α_{11}	Thermal Expansion Coefficient, direction 11
α_{22}	Thermal Expansion Coefficient, direction 22
α_{33}	Thermal Expansion Coefficient, direction 33
δ_c	Composite elongation
δ_f	Fiber elongation
δ_m	Matrix elongation
ϵ_{11}	Strain to failure, direction 11
ϵ_{22}	Strain to failure, direction 22
ϵ_{33}	Strain to failure, direction 33
ϵ_t	Transverse strain
ϵ_{tu}	Transverse ultimate strain
E_f	Fiber Elastic Modulus
E_m	Elastic Modulus of Matrix
E_{11}	Engineering Elastic Modulus, direction 11
E_{22}	Engineering Elastic Modulus, direction 22
E_{33}	Engineering Elastic Modulus, direction 33

σ_t	Composite Tensile Strength
σ_{lu}	Composite Longitudinal Compression, Ultimate Strength
V_f	Fiber Volume
V_m	Matrix Volume
ν_f	Poisson's Ratio, fiber
ν_m	Poisson's Ratio, matrix

DEDICATION

To my parents, James and Elizabeth Blackson, who showed me the vision;
and to my husband, Joel, who chose to accompany me in search of the vision.

EPIGRAPH

As identified by Haughen in 1968, " ... statistical methods of design lead to greater realism in engineering science in any application."

CHAPTER 1

INTRODUCTION

Composite material systems have been used since the dawn of time in applications such as Egyptian mud bricks reinforced with straw to Japanese swords laminated with iron-steel plies. Throughout history, composite materials were developed to provide the mechanical properties required for the component to meet the demands of its service life. Mr. Theodore Reinhart from the Wright Patterson Air Force Laboratory, principal author of the American Metals Society Composites Handbook provides this definition;

A composite material can be defined as a macroscopic combination of two or more distinct materials having recognizable interface between them. However, because composites are usually used for their structural properties, the definition can be restricted to include only those materials that contain a reinforcement (such as fibers or particles) supported by a binder (matrix) material.¹

In general, composite materials have been developed to meet the desired attributes of a specific application for which no homogenous material may be used. Furthermore, these materials may be specially tailored to optimize a performance parameter such as specific strength or specific modulus for a given design and application. Fiber reinforced and metal matrix composites are examples of recently developed material systems by the aerospace community to provide the high specific strength and stiffness required to improve the performance of aircraft structures.

Goals of the Study

Recent marked growth in the composite materials marketplace reflects the need by designers for materials of special capability which not only provide ease of manufacture but also cost effectiveness. Although composite systems provide the flexibility in design where the material employed may be optimized to support stringent and directional property requirements, they are also highly sensitive to the consistency of the constituent materials, the method of processing, and the methods of post fabrication finishing and assembly. To fully understand the impact of the variation of these material and process parameters on the quality of the finished part, the technical state of the art which is shown in figure 1, must first be reviewed and assessed. In Part I: Overview and Assessment of the State of the Technology, the primary technical merits which drive the development of composite materials will be reviewed. Those accepted methods which incorporate the design, analysis, test, and production efforts will be revisited for assumptions and limitations. Further, when the knowledge of the generally accepted methods have been established, then impacts of material and process sensitivities on the composite system characteristics may be addressed. In this manner, as the state of the technology is known, the material and process sensitivities are identified, and the impact on the current methods of design and fabrication of production quality hardware may be evaluated and assessed.

The subsequent section, Part II: Thesis Project, Reliability Evaluation of Composite Hardware: A Probabilistic Micromechanics Approach, will show through research and

development completed by this author, that analytical methods currently exist which will assist in the determination of the impact of material and process variability on the resulting quality of the composite hardware. Predictive techniques which relate the variability of constituent materials to the thermal/mechanical properties of the final composite material system will be developed through a lamination micromechanics model which is supplied probabilistic material property data. This experimental data is employed during the calculation of ply failure in the micromechanics analysis. The failure criterion, calculated through a random selection of material properties of this composite system, is compared to the strength level requirements of the hardware. Impacts on assumptions during the implementation of the project concerning current methods of the phenomenism and analytical aspects of statistical characterization of strength and stress of T300/976 graphite epoxy composite system will be reviewed. In table 1, the typical material properties of several unidirectional fiber reinforced epoxy resin systems has been included for comparison to the T300/976 experimental data. Further, the typical constituent material properties for these resin systems have also been included in figure 2 to provide a generic assessment of the mechanical property attributes of these materials. Details of the implementation will be discussed and the major results of the study will be noted. In this manner, the author has implemented a probabilistic micromechanics approach which relates the lot-to-lot variability of the composite system to the reliability of the laminate property, verifying the quality of the production hardware in service.

TABLE 1

Typical properties of unidirectional fiber reinforced epoxy resin

[source: ASM, 1]

Property	Fiber type		
	E-Glass	Kevlar-49	Graphite (Thornel 300)
Fiber volume fraction	46	60-65	63
Specific gravity	1.80	1.38	1.61
Tensile strength, 0° (MPa)	1104	1310	1725
Tensile modulus, 0° (GPa)	39	83	159
Tensile strength, 90° (MPa)	36	39	42
Tensile modulus, 90° (GPa)	10	5.6	10.9
Compression strength, 0° (MPa)	600	286	1366
Compression modulus, 0° (GPa)	32	73	138
Compression strength, 90° (MPa)	138	138	230
Compression modulus, 90° (GPa)	8	5.6	11
In-plane shear strength (MPa)	—	60	95
In-plane shear modulus (GPa)	—	2.1	6.4
Longitudinal Poisson's ratio (ν_{LT})	0.25	0.34	0.38
Interlaminar shear strength (MPa)	31	69	113
Longitudinal coefficient of thermal expansion ($10^{-6}/^{\circ}\text{C}$)	5.4	-2.3 to -4.0 ^a	0.045
Transverse coefficient of thermal expansion ($10^{-6}/^{\circ}\text{C}$)	36	35 ^b	20.2

^a-79°C to +100°C^b-195°C to +120°C

FIGURE 1

Design and Development Procedures

[source: Blackson, 37]

FIGURE 2

Typical constituent material properties

[source: ASM, 1]

Fig. 2(a) Specific tensile strength (strength-to-density ratio) versus specific tensile modulus (modulus-to-density ratio) for various commercially available 65 vol% unidirectional epoxy-matrix composites and for steel and aluminum. Strength and modulus are based on fiber values. Note that T1000 carbon fiber is currently available only in limited quantities.

Fig. 2(b) Specific tensile strength (strength-to-density ratio) versus specific tensile modulus (modulus-to-density ratio) for various commercially available 65 vol% quasi-isotropic epoxy matrix composites and for steel and aluminum. Strength and modulus are based on fiber values. Note that T1000 carbon fiber is currently available only in limited quantities.

PART I: OVERVIEW AND ASSESSMENT OF THE STATE OF THE TECHNOLOGY

The driving pace of composite materials development has accentuated the need for a predictive analytical method which incorporates a probabilistic approach to ascertain a realistic expectation of the properties of these materials. Many authors describe the need for statistical process control of homogenous materials to control the variability of the end item product.² Composite materials, which are by definition a combination of one or more constituents that are processed into a single material system, require further investigation to understand the complex relationship between the variability of material and process on the quality of the end item composite hardware. Variability in the manufacturing process of a fiber reinforced composite system can be found not only in the initial processing of the constituent fibers and matrix but also in the composite material cure window. Furthermore, the test method and test technique employed to determine the material properties has also been shown to impact the variability of the composite system.³ Often, the manufacturer of a composite material system must determine and control the acceptable range of over four thousand processing parameters to obtain an consistent product.⁴ One method which has been implemented by several end item manufacturers to control the processing variability of the composite during cure is provided by Applied Polymer Technology, as may be seen in figure 3. Since composite material systems frequently have different failure mechanisms in each principal direction, the test method and technique employed to determine the thermal/mechanical capability of each material system requires careful consideration of both the service life and environment.⁵ As noted by Haughen in 1968, " ... statistical methods of design lead to greater realism in engineering science in any application."⁶

FIGURE 3

Computer Process Control of the Cure Window of the T300/976 Composite Hardware

[source: Rose, 3]

FIGURE 4

Classical Design Allowables and Factor of Safety

[source: Jones,14]

One-sided tolerance limits and sample size for the normal distribution at 95% confidence level. $\bar{x}$ = sample mean; s_x = sample standard deviation.

Design allowables based on population and sample coefficients of variation.

CHAPTER 2

GENERAL DESIGN CONCEPTS

Composite material systems provide diverse, new challenges for designers. Due to the anisotropic nature of these materials, special procedures have been developed to assist designers in the utilization of the directional properties of composites. Commonly, the design limit load stresses are chosen such that the laminated structure does not exceed limits ascertained from the lamina properties. A properly characterized composite material system, in which the lot-to-lot variability of the constituent materials and the subsequent composite hardware processing window are related to the end item properties, not only defines a known, repeatable composite material system but also ensures a safe life design.⁷ The standard practice in the aerospace community includes the determination of acceptable range and control of highly sensitive processing parameters in the manufacturer's process control document. The subsequent "A" or "B" basis mechanical property allowables are then generated to assist the designer in the implementation of a fail safe design.

BASIC DEFINITIONS

limit load - maximum load likely encountered during service

ultimate load - limit load times the factor of safety

proof load - limit load times the proof factor of safety, evaluation of quality of the component or assembly prior to acceptance.

allowable stress - maximum stress permitted for the material system in a given design to prevent rupture, collapse, or detrimental deformation.

material strength - stress level of the material is capable of withstanding in local structural configuration in the service environment.

"A" allowable - value above which 99% of the population is expected to fall within 95 % confidence.

"B" allowable - value above which 90% of the population is expected to fall within the 95% confidence.

reliability - probability that structural load bearing capability exceeds the applied load.

matrix - essentially homogenous resin or polymer material in which the fiber system is imbedded; may include thermoplastics, thermosets, ceramics, and carbon.

reinforcement - a strong material bonded into a matrix to improve its mechanical properties, may include long or short filaments, whiskers, and particulate.

tow - an untwisted bundle of continuous filament, commonly in reference to man made fiber, particularly carbon, graphite, and glass.

denier - a yarn or filament numbering system in which the yarn number is numerically equal to the weight in grams of 9000 meters of filaments.

ply - thin sheet of material consisting of an oriented array of fibers embedded in a continuous matrix material. These plies are stacking in a predefined sequence and orientation, and bonded together to produce a laminate.

laminate material properties - Defined by the eight material constants which are:

Engineering Elastic Moduli, E_1 , E_2 , G_{12}

Engineering Strains to failure, ϵ_{11} , ϵ_{22} , ϵ_{66}

Thermal Expansion Coefficients, α_{11} , α_{22}

TABLE 2

Lamina Design Properties as a Function of the Material

[source: Halpin, 9]

MATERIAL	E11	E12	G12	V12	α_1	α_2
	[msi]	[msi]	[msi]	[-]	(10 ⁻⁶) in/in/F	(10 ⁻⁶) in/in/F
GLASS / EPOXY	5.6	1.2	0.6	0.26	3.5	11.4
PDR 49-1 EPOXY	15	0.83	0.6	0.21	-0.6	*
HIGH STRENGTH GRAPHITE EPOXY	21	1.7	0.65	0.28	-0.4	17
HIGH MODULUS EPOXY	27.6	1.1	0.8	0.21	-0.55	*
BORON / EPOXY	30	2.7	0.65	0.21	2.5	13
BORON / ALUMINUM	33	21	7	0.23	3.2	10.6
HM - HS GRAPHITE / EPOXY	46	1	0.6	0.25	0.65	20

CLASSICAL DESIGN ALLOWABLES

The intent of materials design allowables is to address the impacts of variability of the material properties on the design margins of composite hardware. The classical definition of design allowables accounts for the probability of weaker material existing in the population. Reduction in nominal material properties are justified to account for:

- A. Finite sample size, the γ - % statistical percentage.
- B. Reliability level - the probability of survival; the segment of the population which has the desired strength level.
- C. Fleet size, complexity level.
- D. Effects of proof test.

The most global definition of design allowables includes the impacts on the fleet size and complexity level as well as the impacts of proof test on the reliability of the accepted population. Fracture strength which is governed by a two parameter Weibull distribution, expressed in the form of

$$F(x) = 1 - \exp\{ - (x/b)^a \}$$

where: a , b are the Weibull distribution shape and scale parameters, respectively.

Therefore, the allowable stress is determined by the expression:

$$F_{\text{allowable}} = K \underline{b}$$

where: $\underline{b}$ is the estimated Weibull scale parameter.

$K_{\text{allowable}}$ is reduction factor which accounts for impacts of (A-D) above.

The reduction factor which accounts the contributions of each type variation in the material properties, may be expressed in the following manner:⁸

$$K_{\text{allowable}} = K_R K_n(\gamma) K_N K_P$$

where: K_R is the reduction factor assessing the impacts of the reliability level.

K_N is the reduction factor assessing impacts of the fleet size .

$K_n(\gamma)$ is the reduction factor for the γ confidence level estimate of a scale parameter, b , based on the test sample size, n .

K_P is the reduction factor assessing the impacts of proof test data.

Proof testing of a statistical sampling of components is common to account for the statistical segment of the population of manufactured hardware of quasi-isotropic glass reinforced epoxy systems which does not meet the proof load requirement as referenced in figure 5. Proof testing show the greatest advantage when the material property population shape parameter is small. As the data is explained for the percentage of the proof test load is compiled against the Weibull shape parameter, the proof load determination is very sensitive to the distribution shape parameter.⁹ For a large shape parameter, the proof test must be a large percentage of the allowable to achieve appreciable merit or improvement of the allowable level.

Analytical tools both statistical and probabilistic in nature which have been developed specifically to address variability assessment. These methods should be employed to evaluate material property design allowables as well as to assess the reliability of material wear out and its impact on component service life. The assumptions of a reliability analysis, however, should be noted:

- E. Reliability analysis is totally dependant on the experimental test data, which by definition equates the test environment with the service environment.
- F. Weibull and log normal statistical distributions are representative of the fatigue behavior in composites.

Lemon, James, and Norton had completed a significant research effort in the late 1970's to define a reliability analysis method for characterizing composite materials.¹⁰ As their work postulates, the cumulative structural damage of a composite may be characterized through an basic understanding of the probabilistic residual strength as a function of time. Further, a strength failure criteria which reflects a probabilistic wear out model was developed to assess fatigue, ramp and creep loading of composites and to assist in the evaluation of this behavior on design concepts.

FIGURE 5

Proof Testing Impact on Design Allowables of Quasi-isotropic Glass/Epoxy System

[source: Halpin,18]

FIGURE 6

Composite Fatigue Structural Evaluation Data of Quasi - isotropic Glass/Epoxy System

[source: Halpin,18]

CONCLUSIONS

Composite material systems which are anisotropic in nature provide new challenges to designers who wish to utilize these directional properties. The standard practise in aerospace where the manufacturer's process control document defines the accepted variability of the material properties of the composite system has been employed for many years. Further, the generation of "A" or "B" basis design allowables that reflect a statistical k-factor knock down of a material property to reflect the finite sample size, the reliability level of the hardware, the fleet size and complexity level, and the effects of proof testing has been shown to be conservative in its approach. The major drawback in this methodology has been identified with the intrinsic variability of the constituent materials and the resulting processing window used in the cure of these composite systems. It is not uncommon that the composite system shows a high degree of sensitivity to consistency of the constituents or the parameters of cure such as heat rate. Therefore, several studies which incorporate the impacts of these parameters into a probabilistic wear out model assist in the evaluation of fatigue, ramp, and creep wear out behavior on composite design concepts.

CHAPTER 3

FAILURE OF COMPOSITES

Failure of composite structural component has occurred when it ceases to perform within its designed capacity. To this end, in order to correctly utilize the directional properties of a composite material in component design, accurate knowledge of the failure modes as well as assimilation of predictive techniques required to determine composite strength and stiffness are essential. Due to the anisotropic nature of composite materials, the failure mechanisms are frequently different in each principal direction. Therefore, a brief review of the failure modes and predictive methods of strength and stiffness for a unidirectional composite are included. Once a general understanding of the failure mode and expected strength of a composite material is attained, then the layup configuration which will promote specific properties of the material may be developed.

FAILURE MODES AND PREDICTIVE ANALYTICAL TECHNIQUES

FOR COMPOSITE MATERIAL PROPERTIES OF LONGITUDINAL STRENGTH AND STIFFNESS

Composite material properties in the longitudinal direction are dominated by the type of constituent fiber and its interfacial bond to the matrix. Initially, a review of the possible failure modes for a composite material under a longitudinal tensile or compressive load will be discussed. Then, a summary of the predictive analytical techniques for longitudinal strength and stiffness will be reviewed.

FAILURE MODES OF COMPOSITE UNDER A LONGITUDINAL TENSILE LOAD

Failure modes of unidirectional composites under a longitudinal tensile load may be generally classified as one of the following:

- A. brittle
- B. brittle with fiber pullout
- C. brittle with fiber pullout, interface - matrix shear failure, constituent debond

Glass reinforced composites which have less than forty percent fiber volume commonly failure in the class of brittle failure as referenced in figure 8. The intermediate glass and graphite reinforced composites which contain forty to sixty five percent fiber volume usually exhibit a brittle failure with fiber pullout. Finally, the higher fiber volume composite materials, greater than sixty five percent reinforcement by volume, commonly exhibit a brittle failure with fiber pullout and may contain interface - matrix shear failure as well as constituent debond.

FAILURE MODES OF COMPOSITE UNDER LONGITUDINAL COMPRESSION LOAD

Failure modes of a unidirectional composite under a longitudinal compression load may be defined as one of the following:

1. transverse tensile failure
2. fiber microbuckling failure in extensional mode
3. fiber microbuckling failure in shear mode

The transverse tensile failure in a composite is observed as a pure matrix dominated behavior. In the later two methods of failure, the continuous fibers act as columns, in which distortion and deflection under compressive load provide instability followed by microbuckling of the reinforcement. . This mode is commonly proceeded by matrix yield, constituent debond and matrix microcracking.

FIGURE 7

Scanning Electron Microscope Photograph of T300/976 Laminate Failure

[source: Barto, 4]

FIGURE 8

Failure Modes of Unidirectional Composites under Longitudinal Tensile Load

[source: Broutman,16]

Failure under Longitudinal Compression Load

FIGURE 9

Process Control Assessment Test Part, Fabrication and Test

[source: Blackson, 38]

PREDICTIVE ANALYSIS OF LONGITUDINAL STRENGTH AND STIFFNESS

The longitudinal tensile strength of composites is dominated by fiber strength. Early research into the causes of fiber failure have lead to two basic theories, the cumulative weakening failure theory and the weakest link failure theory.

The cumulative weakening model, first introduced by Rosen in 1964, theorized that a failure in a composite was due to a weakened cross section resulting from accumulation of individual fiber fractures. Failure occurs by the progressive, random fracture of filaments in the material under gradually increasing stress levels. Further, the strength of an individual filament has been shown to be related to the overall fiber length.¹¹ A fiber is analogous to a chain of links, the longer the chain, the higher the probability of a weak link. A reinforcement tow, or package of filaments of unequal strength, has statistically been shown to follow a Weibull distribution.¹² In general, the strength of the fiber tow is less than the summation of the individual fiber strengths due to the cumulative weakening of the tow due to a statistical number of imperfect filaments.¹³

Rosen demonstrated the statistical mode of composite tensile strength, σ_t , which is based on fiber area as:

$$\sigma_t = [a b \frac{\sigma}{\sigma_0} \epsilon]^{b-1}$$

where: a, b are Weibull shape and scale parameters

σ_0 is an ineffective length parameter

Later, Zweben in 1968 postulates that composites undergo a catastrophic failure, induced by filament failure causing a redistribution of internal stresses in the composite, initiating failure. This redistribution creates a rapid instability in the composite component which manifests as a stress wave and there by causes instantaneous failure.¹⁴ The formulation by Zweben also relates the statistical tensile failure in composites as:

$$\sigma_t = (b - 1) \{ [N L a b]^{**(-1)} \}$$

where: a,b are Weibull shape and scale parameters

N is the number of fibers

L is the fiber length

Research into the failure of composites in longitudinal compression has been considered by many authors. The basic approach assumes the matrix material provides stability to the individual fibers in compression. Hashin in 1967 addressed this instability by modeling the composite as a continuous body of matrix material which supports an array of non-straight filaments. Rosen further developed this concept into a model for longitudinal compression failure theory which is initiated through fiber buckling mode.¹⁵ This method of buckling in an extensional mode is expressed by:

$$\sigma_{lu} = G_m \{ [1 - V_f]^{**(-1)} \}$$

where: G_m is the matrix shear modulus

V_f is the fiber volume

This very conservative model frequently predicts values which are lower than the measured data. Observation indicates that transverse splitting or debond actually initiates the failure, where the failure criterion is:

$$\epsilon_t > \epsilon_{tu}$$

Greszezuk in 1974 postulated through his research that the ultimate stress of the composite under compression may be expressed in the following terms:

$$\sigma'_{lu} = \frac{[E_f V_f + E_m V_m] [1 - V_f^{1/3}] \epsilon_{mu}}{[v_f V_f + v_m V_m]}$$

where: E_f = fiber elastic modulus

V_f = fiber volume

E_m = elastic modulus of the matrix

V_m = volume of matrix material

ϵ_m = ultimate strain of the matrix

v_f = Poisson of fiber

v_m = Poisson of matrix

Halpin furthered this analytical approach and extended into research into redefining the accepted methods of characterization of composite materials in the aerospace industry. As may be seen in the referenced figure 11, this model has good agreement with measured, experimental data from epoxy matrix based resinous composites. It should be noted, this model is acutely sensitive to the ultimate matrix strain at time of failure.

VARIABILITY OF COMPOSITE LONGITUDINAL PROPERTIES

The longitudinal strength and stiffness which may be expected from a composite material is affected by several factors which include:

- A. fibers of nonuniform strength
- B. interfacial conditions
- C. misorientation of fibers
- D. residual stresses

The primary influence on the variability of constituent fiber reinforcement is directly attributable to tolerance control during manufacture. Early drawn glass or silica fiber, for example, exhibits a highly variability mechanical properties due to the production tolerances of the glass fiber diameter. This variation in the fiber diameter, and ultimately the fiber denier leads to inconsistency in the low properties of the reinforcement.

Another primary influence on composite strength and stiffness includes the formulation, consistency, and method of application of the interfacial sizing. The interfacial filament sizing which is specific to the composite system, promotes effective load transfer from the matrix into the fiber. A strong bond between the matrix and fiber is imperative to eliminate the propagation of cracks parallel to the fiber, which in turn would reduce the effectiveness of the reinforcement. Therefore, to fully utilize the

properties of the reinforcement, the formulation and consistency of the sizing is an essential part of the composite material system.

Finally, two important factors which influence the strength and stiffness of a composite are determined during actual fabrication of the composite laminate. Misorientation of the fibers both in the as manufactured ply or in the preparation of the laminate prior to cure ultimately affect the final properties of the composite.¹⁶ Commonly, the manufacturer installs appropriate tolerances in the factory to control the variability of fiber alignment in the product. Secondly, residual stresses caused by difference in the coefficient of thermal expansion of the constituent materials during cure affect the composite material properties. The formulation of the interfacial sizing, which interacts between the highly oriented fiber reinforcement and the more isotropic matrix material, is unique to the composite system and essential to minimize the cured laminate residual stresses.

In conclusion, efforts have been made by current manufacturers to control the tolerance of processing parameters which determine the end item variability of their product.¹⁷ In fact, many aerospace companies have recently identified and incorporated statistical process control on all manufactured hardware in an effort to restrain cost impacts resulting from variation in the quality of the components produced.

FIGURE 10

Statistical Process Control Data for T300/976 Composite System

[source: Blackson, 4]

FIGURE 11

Comparison of Theory with Experimental Data

[source: Halpin, 18]

*FAILURE MODES AND PREDICTIVE ANALYTICAL TECHNIQUES
FOR COMPOSITE MATERIAL PROPERTIES OF TRANSVERSE
STRENGTH AND STIFFNESS*

Failure of a structural element may be stated to have taken place when it ceases to perform satisfactorily.¹⁸ Internal damage in the composite component under transverse tensile load is common prior to changes in the macroscopic appearance and behavior. Verification of internal damage or fracture includes such evidence as:

- A. Breakage of fibers
- B. Microcracking of the fibers
- C. Debond - separation of the matrix and fiber.
- D. Delamination - separation of the lamina

Failure in a composite is defined as when the laminate stress exceeds the proportional limit such that the stress strain behavior may be not predicted from the initial material properties.

Composite material properties in the transverse direction are dominated by the type and consistency of the matrix and interfacial bond to the reinforcement. Initially, a review of the possible failure modes for a composite material under a transverse tensile or compressive load will be discussed. Then, a summary of the predictive analytical techniques for transverse strength and stiffness will be reviewed.

FAILURE MODES OF COMPOSITES UNDER TRANSVERSE TENSILE LOAD

The failure mode of unidirectional composites under a transverse tensile load is commonly a combination of a matrix tensile failure and a constituent debond often with additional fiber splitting as may be seen in the reference figure 12A. This type of failure is a matrix dominated, thereby sensitive to stress concentrations on the fibers which are perpendicular to the load direction. Another primary influence is the type and consistency of the application of the interfacial sizing to the matrix, providing a key location for matrix notch sensitivity.

FAILURE MODES FOR COMPOSITES UNDER TRANSVERSE COMPRESSIVE LOAD

The failure mode of a unidirectional composite under a transverse compression load is frequently a shear failure of the matrix, followed by crushing of the constituent fiber and subsequent matrix debond as may be seen in the reference figure 12B. It should be noted that observed behavior indicates the failure surface is initiated through the debond of the fiber from the matrix, further emphasizing the requirement of interfacial adhesion. In practice, if the test specimen is constrained to prevent deformation perpendicular to the load axis, then the experimental data of the transverse compression strength approaches the material property of the longitudinal compression strength.

FIGURE 12 A

Failure Modes of Unidirectional Composites: Transverse

[source: Chamis, 32]

Photomicrographs of unidirectional composites subjected to transverse tensile load show (a) fracture surface of high-modulus graphite fiber composite and (b) fracture surface of high-tensile-strength graphite-fiber composite.

Failure of unidirectional composite under transverse tensile load.

FIGURE 12 B

Shear Failure of Unidirectional Composite Subjected to Transverse Compressive Load

[source: Chamis, 32]

(Continued)

Shear failure of unidirectional composite subjected to transverse compressive load.

FIGURE 12 C

Photographs Showing Shear Failure of Unconstrained Unidirectional Carbon Fiber Reinforced Plastics Subjected to Transverse Compressive Loads

[source: Chamis, 32]

(a) Type 1 fibre composite

(b) Type 2 fibre composite

In-plane shear failure of unidirectional composite.

PREDICTIVE ANALYSIS OF TRANSVERSE STRENGTH AND STIFFNESS

Transverse tension, compression, and in plane shear of a unidirectional composite is a matrix dominated failure. Predictive analytical methods resulting from application of elasticity principles to ascertain the failure is difficult due to the complex stress field. Several influences on these composite properties includes matrix to filament adhesion and effects of void content.

The predictive models may be summarized by:

- A. Bounding technique
- B. Exact solutions
- C. Self - consistent model

Research into the bounding technique was initiated by Paul.¹⁹

Paul, who employed a bounding technique for intermediate fiber volume composite materials in which the upper bound was determined through the minimum potential energy and the lower bound was determined through the minimum complimentary energy, resulted in bounds too vast to be useful. Rosen and Hashin improved the bounding technique during their development. The predicted transverse modulus which lay on an upper bound is compared to experimental data on a carbon-carbon composite system as may be seen in the reference in figure 13.²⁰

Research into an exact solution where the fibers are arranged into a periodic array surrounded by matrix material, developed into an elasticity problem in search of a rigorous numerical solution. Among the methods of numerical solutions included a

complex variable technique and a finite difference method which was first introduced by Adams and Doner.³³ Predicted values for transverse modulus and longitudinal shear modulus were in good agreement with experimental results.²¹ Shu and Rosen which further developed plasticity methods in 1967 were followed by more rigorous computational finite element techniques by Chen and Lin in 1969.²⁹ Then, in the early 1970's, Halpin and Tsai determined a simplified computational method to estimate the properties of composite through micromechanics analysis.²² This self - consistent model assumes parametric constants which indicate a measure of the reinforcement based on fiber geometry, packing geometry, and loading conditions of the composite. The estimates of transverse modulus were in relatively good agreement with experimental data within the variation of the manufacturing process.

Research into the determination of the transverse strength of a composite has been reviewed by several authors. Transverse strength is limited by the constraints of the fiber on the matrix thereby causing strain and the stress concentration of the matrix adjacent to the fibers. Due to these limitations, the composite fails at a lower strain than an unrestrained matrix material. Contrary to the analytical expectation of the longitudinal strength and stiffness and the transverse modulus, the effective transverse strength is reduced by fiber content. Predictive techniques to determine the transverse strength of a composite have been developed through two avenues; a strength of materials approach and advanced elasticity method employing numerical solutions.²³ In both techniques, the transverse strength is reduced below the matrix strength by a factor which is dependant on the relative properties of the fibers, matrix, and volume fractions.

FIGURE 13

Predictive Techniques - Bounding

Predicted and Experimental Values of Longitudinal Compressive Strength

[source: Rosen, 29]

FIGURE 14

Maximum Principal Stress as a Function of Constituent Stiffness Ratio

[source: Adams and Doner, 33]

Normalized maximum principal stress in matrix for circular filaments in square array subjected to average transverse normal tensile stress component only ($\nu_f = 0.20, \nu_m = 0.35$).

VARIABILITY OF TRANSVERSE STRENGTH AND STIFFNESS

Since the matrix material properties are of prime importance to the capabilities of the unidirectional composite in the transverse plane, the consistency of the manufacture, application, and subsequent cure profile of the composite hardware is essential.²⁴ Duci in studies of the graphite epoxy system employed on a production missile system have identified critical manufacturing parameters, which include:

- A. Stiochiometric tolerances on precursor materials
- B. Filming process parameters.
- C. Wet out characteristics of the prepregging procedure.
- D. Cure cycle window for final composite part process.

The variation of the precursor materials is carefully monitored and controlled with the usage of statistical process control of critical parameters. The process control assessment of these critical in process production control parameters ensures the quality of the B-staged composite material system.²⁵

These attributes effect the consistency of the composite hardware degree of cure and there by impact the capability of attaining these material properties. For example, the composite elongation, δ_c , in the direction of the load is the sum of the elongation of the fiber, δ_f , and the elongation of the matrix, δ_m , such that:

$$\delta_c = \delta_f + \delta_m$$

Further, it is known that the product of the strain and its cumulative thickness identified as the localized elongation of the material.

$$\delta_c = \epsilon_c t_c$$

$$\delta_f = \epsilon_f t_f$$

$$\delta_m = \epsilon_m t_m$$

The resulting expression after trivial algebraic manipulation reveals that the composite strain may be written as:

$$\epsilon_c = \epsilon_f V_f + \epsilon_m V_m$$

The state of stress in the composite is the same as found in the matrix and fiber and therefore may be written as:

$$E_c^{-1} = V_f / E_f + V_m / E_m$$

or may be expressed as a summation of the plies of the materials in the composite:

$$E_c = \sum_{i=1,n} [V_i / E_i]$$

where: "i" indicates the ply Elastic modulus as a volume percentage.

It should be noted that the fiber volume is less effective in raising the transverse composite modulus than the longitudinal composite modulus. Further, the effectiveness of the fiber in raising the transverse modulus decreases with the ratio of fiber modulus to the matrix modulus as may be seen in the referenced figure 17. Results of the predictions from the Halpin - Tsai equation for the transverse compression modulus which is given by:

$$[E_t / E_m] = [(1 + \eta \zeta V_f) / (1 - \eta V_f)]$$

where: η is a measure of the reinforcement, dependant on the packing geometry and loading conditions

FIGURE 15

Stoichiometric Tolerances of Constituent Materials

[source: Duci, 24]

Resin and Prepreg HPLC Reactant Ratio Versus Stoichiometry

FIGURE 16

Solid State Rheological Profile of the 976 - 1 Laminate

[source: Duci, 24]

FIGURE 17

Effect of Fiber Modulus on Directional Moduli

[source: Broutman, 16]

CONCLUSIONS

The capability to define the failure of structural member fabricated with composite materials is critical to the design process. In order to correctly utilize the directional properties of composite materials, an accurate knowledge of the failure modes along with assimilation of predictive analytical techniques must be employed. In this section, a review of these methods which are specific to the failure mode have been outlined, the merit of each prediction technique discussed. These predictive techniques were compared to experimental data when ever possible to assess the accuracy of the prediction. Often times, since the longitudinal property of a unidirectional composite is an order of magnitude greater than the transverse property, the latitude for variation is much smaller for the transverse direction. The bounding technique which was refined by Hashin and Rosen highly improved this predictive technique for transverse modulus and is supported by experimental data for both resinous and carbon based composite material systems.

CHAPTER 4

STATISTICAL CHARACTERIZATION OF STRENGTH AND STRESS

Historically, statistical models of strength of composites was founded with the Griffith theory which states " composites contain strength reducing flaws which reside in the material, weakening it". Upon acceptance of this basic premise by Griffith, then the strength of a given specimen is bounded by the smallest value in a given sample size whereby N is the number of flaws in a volume of material. Therefore, the determination of the material strength as a function of the volume is similar to the study of the distribution of the smallest strength value as a function of volume. Clearly, a great deal of research has been completed in the past sixty years in the study of extreme values, especially minima, in a given sample size. Statistical populations which possess a probability density function, $f(x)$, and its associated cumulative distribution function, $F(x)$, have been the focus of probabilistic methods for composite materials. Of course, the primary interest in minimums, as detailed by Epstein (1948):²⁶

If the statistical population possesses a continuous probability density function, $f(x)$, and has an associated cumulative distribution function $F(x)$,

$$F(X) = \sum_{i = -\infty, x} f(x) dx$$

then the distribution of the smallest value in a sample size drawn from this population is given by the probability density function, $g_n(x)$,

$$g_n(x) = n f(x) \{ [1 - F(x)] \}^{n-1}$$

having a cumulative distribution function, $G_n(x)$:

$$G_n(x) = \int_{-\infty}^x g_n(x) dx = 1 - [1 - F(x)]^n$$

The most probable value of the smallest value found in the sample size is determined by the maxima of $g_n(x)$. If the solution exists, then it may be written as:

$$f'(x_n) = [1 - F(x_n)]^{n-1}$$

This equation which is employed implicitly and explicitly by all authors in description of the weakest link phenomena. Other conclusion made by Epstein during his early research include:

- A. Rectangular distribution implies that strength is not independent of volume, which is in variance to observed behavior.
- B. Cauchy distribution leads to results which are in variance to observed behavior.
- C. Laplace, Gauss (normal), and Weibull distributions imply the strength decrease with increase in volume.

Therefore, Epstein related the distribution of strengths due to flaws inherent in the material as:

$$f(x) = A \exp (- B [x - u]^{**p})$$

where the most probable value of the smallest value in a given sample size, M, must decrease as $\{ (\log M)^{** [1/p]} \}$ and the distribution of the smallest values must be negatively skewed.

The history of research into the statistical distributions of strength of composite materials began in 1926 with Pierce who initiated the study of mathematical minima with the Gaussian distribution. Kontorova furthered this effort into the Gaussian distribution in 1940. In parallel, Weibull had developed a probability of failure of a unit volume as a function of stress by:

$$F_o(\sigma) = 1 - \exp [-(\sigma / \sigma_o)^{**n}]$$

where: σ and n are material parameters which are determined during test.²⁸

To conclude, given that the physical phenomena of the weakest link hypothesis is true, then there is a statistical compulsion for a skewed distribution of strengths of samples of the same size and a semilog dependance on the most probable value of strength on the size of specimen and the number of places a failure may occur.²⁷ This thesis accounts for the skewed distribution and the semilog relationship in the study of the strength of materials.

FAILURE CRITERIA

Predictive analysis techniques for non-isotropic materials have historically relied on the micromechanics approach to determine composite material properties. The prediction of strength and stiffness of a multi-oriented laminate is commonly based on the general mechanical behavior of unidirectional lamina. Of course, the failure criteria has developed to bring theory in line with observed behavior and experimental test data.

The most rational approach was presented by Ho in 1966 which defined the probability of failure of anisotropic materials under uniaxial state of stress assuming a Weibull distribution and a maximum stress criterion as may be seen in the referenced figure 18. Ho described the total risk of rupture as a probability of failure surface, in which the combined state of stress for tension, compression, and shear is given as

$$B = B_X + B_Y + B_{XY}$$

$$= \int_V K \left[\frac{\sigma_x - \sigma_u}{\sigma_0'} \right]^n dV + \int_V K' \left[\frac{\sigma_v' - \sigma_u'}{\sigma_0'} \right]^{m'} dV + \int_V K'' \left[\frac{\sigma_{xy} - \sigma_u''}{\sigma_0''} \right]^{m''} dV$$

Where:

$$\sigma_x \geq \sigma_u \geq 0, \quad \sigma_v' \leq \sigma_u' \leq 0 \text{ (compression)}, \quad |\sigma_{xy}| \geq |\sigma_u''| \geq 0$$

FIGURE 18

Failure Criterion: Multi-Axial Failure Surface, Maximum Stress State

[source: Halpin, 34]

$$B = B_x + B_y' + B_{xy}$$

$$= \int_V K \left[\frac{\sigma_x - \sigma_u}{\sigma_0'} \right]^m dV + \int_V K' \left[\frac{\sigma_y' - \sigma_u'}{\sigma_0'} \right]^{m'} dV + \int_V K'' \left[\frac{\sigma_{xy} - \sigma_u''}{\sigma_0''} \right]^{m''} dV$$

$$\sigma_x \geq \sigma_u \geq 0, \quad \sigma_y' \leq \sigma_u' \leq 0 \text{ (compression)}, \quad |\sigma_{xy}| \geq |\sigma_u''| \geq 0$$

Then, Tsai developed the first ply failure theory in 1964 in which the quadratic form of the combined state of stress indicates the onset of failure of the composite. Petit's research in 1967 lead to a maximum strain criteria applied to the principal axis. Failure was defined as a yield surface obtained via super position of the failure surfaces on to the lamina stress coordinates. More recent work Tsai which was completed with Hill in the later 1960's lead to the Tsai - Hill criteria which is given by:

$$E_{11} = E_f v_f + E_m v_m$$

$$\nu_{12} = \nu_f v_f + \nu_m v_m$$

$$\begin{aligned} \left[\frac{P}{P_m} \right] &= \frac{(1 + \eta \zeta \nu_f)}{(1 - \eta \nu_f)} \\ &= \{ [P_f / P_m - 1] / [(P_f / P_m) + \eta] \} \end{aligned}$$

where: $\bar{P}$ is the composite moduli, E_{22} , G_{12} , or G_{23}
 P_f is the fiber modulus, E_f , G_f , ν_f respectively
 P_m is the matrix modulus, E_m , G_m , or ν_m respectively
 η is a measure of reinforcement which is dependant on the boundary conditions

Experimental validation of analysis by Scop was completed in 1967 in which the tensile strength of a laminate was found to be in good agreement with the ideal strength of the lamina. The weakening effect of flaws in the individual lamina ply was muted by the laminate for the longitudinal tensile failure.

The methods of incorporating a statistical variability of the material properties into a failure criterion which is reflective of the composite system material properties has been a point of study by many previous authors. In most cases, theoretical expressions which are not easily solved by use of computational methods have been simplified to provide a failure criterion which reflects the experimental data. The subsequent section will address current techniques of probabilistic micromechanics methods and implications of material variability on the calculation of design margins performed for production hardware.

FIGURE 19

Comparison of the Halpin-Tsai Calculation

[source: Ashton, Halpin, Petit, 35]

Comparison of Halpin-Tsai calculation, solid circle, with Foye's calculations for the transverse stiffness of a composite containing rectangularly shaped fibers.

Comparison of Halpin-Tsai calculation, solid circle, with Foye's calculation for longitudinal shear stiffness of composite containing rectangularly shaped fibers.

PREDICTION TECHNIQUES EMPLOYING MICROMECHANICS

Methods of probabilistic composite micromechanics analysis were developed to simulate expected uncertainties found in oriented lamina composite material properties. Composite material properties are dependant on the properties of the constituent materials, the distribution and orientation of the reinforcement, and the final state of the matrix material. Since composite laminates are composed of multiple oriented plies of a defined configuration, composite micromechanics methods are the basis for the prediction of ply behavior; the analysis in which is commonly employed is based on the volume and orientation of the constituent with specific material properties.

Probabilistic methods in the past have been used to incorporate Monte Carlo simulations in order to address the statistical variation of the sub-ply material properties.

Lamination theory which is defined as the integration of the ply properties in a laminate is used to determine if the laminate configuration is suitable for a particular design and service life. Several software packages are currently used in industry include ICAN, development sponsored by NASA; MICMAC, development sponsored jointly through Springer and Tsai; and DCAP, development jointly sponsored by the Navy and Rosen.

These analytical codes were developed for a specific composite system to understand the impacts of material variation on the quality of the end item hardware. The ICAN package was developed to present a probabilistic approach of the variation of the constituent materials, its predicted sub-ply properties may be seen in the reference in figure 20. The MICMAC package from Springer and Tsai relates to the product line variability of the pre-impregnated, B-staged thermoset resin system materials to the resulting composite mechanical behavior with the assumptions reviewed in Chapter 3. Finally, the package DCAP which was developed by Rosen was developed to address the constituent

material variability of carbon fiber preforms on the resulting carbon-carbon thermal/mechanical behavior.

PREDICTION TECHNIQUES EMPLOYING MACROMECHANICS

With the ever increasing use of computer intensive analysis codes which numerically assist in the solutions of bodies under a specified loading conditions, new versions of finite element modelers will continue to be refined and enhanced to investigate engineering problems. Many military contractors frequently select the finite element analysis package which best suits the application at hand, for instance NASTRAN is often preferred for structural analysis where as ANSYS is preferred for thermal and modal analysis. At Lockheed Missiles and Space Company the proprietary analysis software, called DIAL, incorporates the primary constituent equations for many engineering problems including structural, thermal, vibrational, non rigid body static and dynamic analysis to name a few. The structural analysis technique which examines any engineering problem should be by definition a reflection of a failure criterion that correlates well with the experimental data available. In the case of continuous fiber resinous composite such as the graphite epoxy system, T300/976, the failure criterion used is a piece wise, linear maximum state of stress criterion where the first ply failure is assumed to indicate hardware failure. For the extent of this study on a probabilistic approach to the reliability of composite hardware, the micromechanics analysis will have statistical input that is intended to reflect the sensitivity of the laminate to manufacturing variability. In this manner, the prediction of laminate failure due to the identified production variability will assist in the assessment of the impact of this variability on the reliability of the hardware.

FIGURE 20

Sample Results from ICAN Micromechanics Analysis

[source: Stock and Bellini, 36]

Fig. 1 - Conventional Model

Fig. 2 - Substructure Model

Sampling results for Longitudinal Elastic Modulus

Sampling results for Transverse Elastic Modulus

CONCLUSIONS

Through the past forty five years, a number of authors have addressed statistical characterization techniques of material strength and stress by several different approaches. Epstein was the first to identify the Weibull population as a reflection of nature's own law of strength and its probability distribution. In review of current micromechanics analysis, which has been restricted to a sub ply model in the research completed by Bellini and Stock, is limited in its approach and assumptions. The methods of practicality, Halpin and Tsai have brought forth through the MICMAC software, a micromechanics analysis of standard composite systems accessible to any design engineer. The Halpin-Tsai equation, which has several assumptions detailed earlier in this section, has been demonstrated to correlate well with experimental data.

PART II: THESIS PROJECT: RELIABILITY EVALUATION OF COMPOSITE HARDWARE :

A PROBABILISTIC MICROMECHANICS APPROACH

CHAPTER 5

SCOPE OF THE STUDY

A drawback in the characterization of structural failure of composite hardware is the inadequate evaluation techniques which provide the assessment of the impacts of constituent material and process variability on the quality of the hardware produced. In this manner, the true design margins for the service life of the hardware may be attained.

The scope of this project is to develop the design parameter sensitivity study which related the variability of the constituent material properties and fabrication window to the final laminate mechanical characteristics. The parameters studied which simulated the expected intrinsic variability in the manufacture and service life of the composite part include the part temperature, the part moisture content, the layup configuration, and the deterministic load. The plan by which this study was executed is outlined in figure 18, the design parameters which were included in the study is outlined in the reference in figure 19.

As may be seen in the referenced figure 19, the scope of the design parameters to be studied included four layup configurations, referenced through experimental test data

found in Table 2. This composite system, T300/976 graphite epoxy, was tested through a characterization test matrix for the thermal / mechanical behavior. Further, both temperature as well as moisture hygroscopic effects are investigated individually and simultaneously for its impact on the reliability of the material property. The total combination of all the design parameters of interest in this study results in over four hundred and eighty independent case studies of the reliability of the composite system due to intrinsic material and process variability.

For a case in point, assuming a unidirectional, eight ply laminate in which a deterministic load of twelve thousand pound in compression is applied. Since this example is intended as a baseline, the temperature and moisture effects are assumed to be zero. The implementation of this particular case, one of the four hundred and eighty reviewed in this study, proceeded along the following avenue. The laminate model was generated with the code ADVLAM which details the number of plies, the orientation, et cetera concerning the details of the laminate. Then, the random sampling of material properties which reflects the significant database from the characterization effort for the T300/976 composite system, selects the properties required to perform the analysis. The ADVLAM code then determines the lamina state of stress ply by ply, compares the ply stress to the failure criterion which is set to be a maximum stress state, and then documents if the laminate in fact is predicted to fail. Statistical methods are then used to calculate the parameter estimates of the material properties employed in the ADVLAM lamination theory analysis. Parameter sensitivities are also calculated for each permutation of the design parameters study to determine areas which indicate a greater need for further study of impacts of these variables in the design.

Project Assumptions of Fracture Characterization

Complete characterization of fracture properties of these composite materials commonly includes the development of strength criterion as well as fatigue, toughness, and fracture mechanics data where ascertained necessary. Characterization test matrices contain a large percentage of off axis layup configurations such that strength transitions may be determined. The generation of a mechanical property database where the composite system is tested in the environmental conditions expected during service is well specified by several texts. In each case, a great deal of care must be taken in the details of the design and implementation of each test for consistency; test procedures should be documented for completeness. One of the many details involved in the implementation of a material characterization program concerns the consistency of the composite material fabrication and its subsequent test method. Variability of the constituent materials and the fabrication process window is commonly controlled through limits set in internal documentation such as the appropriate material and process specifications; variability of test method is frequently controlled through internal testing procedures which refine the ASTM and industry standards. During this development study where the thermal/mechanical properties of the T300/976 graphite epoxy composite system were being generated, the standard methods of control of the aforementioned variables have been implemented to reduce where ever possible the coefficient of variation of the data generated. At all times, the failure mode for each test was documented, records and test specimens for each test were kept in an archive to provide the necessary documentation trail for possible future efforts.

Project Assumptions of Statistical Characterization of Strength

This investigation included the study of a graphite epoxy material system which has been used on many applications where the hot, wet compression strength of the composite system is of prime importance. Further, this material is available in several product forms including a unidirectional tape and an eight harness satin cloth through Imperial Chemicals Incorporated, Fiberite Materials Division. Due to the excessive usage of this composite system by the aerospace industry, a significant database of material properties is available to the community; the primary composite ply properties are shown for this material system in Table 2.²⁴

Project Assumptions of Failure Criteria

For this study, the Maximum Stress and the Hoffman plane stress failure criteria were chosen as the select failure criteria; these failure criteria provide good agreement with experimental data of this material system.

Project Assumptions of Micromechanics Prediction Techniques

ADVLAM is a Lockheed proprietary software code which predicts the micromechanics behavior of composite laminates. The lamination theory employed assumes a composite laminate, defined as plate of shell finite elements which may be resolved into identifiable sets of different lamina, each with distinct material and geometric properties. Interaction between the lamina, or plies, is accounted for by the 2D compatibility requirement of the thin shell elasticity theory in which plane sections remain plane

during local deformation. ADVLAM however does not take into account the 3D effects which may occur at the interface between lamina or other geometric discontinuities. The failure theories which are accessible in this software package includes:

- A. Tsai - Wu
- B. Hoffman
- C. Tsai - Hill
- D. Maximum Stress
- E. Maximum Strain

Although these failure criteria provide the analyst with the latitude to incorporate different theory comparisons, only Maximum Stress was employed in the initial implementation of the project of study.

TABLE 3

Statistical Representation of T300 / 976 Graphite Epoxy Composite System

[source: Blackson, 39]

COMPRESSION PROPERTY	TEMPERATURE	STRENGTH	COEFFICIENT OF VARIATION
	[F]	[KSI]	[%]
SIGMA 1	76	96.5	9.5
SIGMA 2	76	92.9	9.7
SIGMA 1	250	80.9	8
SIGMA 2	250	79.9	8.1
SIGMA 1	350	66.1	7
SIGMA 2	350	63.7	7.1
TENSION PROPERTY	TEMPERATURE	STRENGTH	COEFFICIENT OF VARIATION
	[F]	[KSI]	[%]
SIGMA 1	76	79.6	12.7
SIGMA 2	76	79.3	12.4
SIGMA 1	250	89.7	6.9
SIGMA 2	250	88.8	5.6
SIGMA 1	350	88	4.7
SIGMA 2	350	87.7	4.6

FIGURE 21

Plan of Design Sensitivity Algorithm

[source: Blackson, 40]

FOR ALL PERMUTATIONS OF DESIGN PARAMETERS:

FAILURE CRITERIA, LAYUP CONFIGURATION, DETERMINISTIC LOAD CASE & LOAD
PART TEMPERATURE EFFECTS, PART MOISTURE EFFECTS

- DEFINE THE MODEL
ASSUME: Probability distribution through data
Equations of interest - failure criteria
- COMPUTER GENERATED RANDOM SAMPLING
SELECT independent variables, MATERIAL PROPERTIES
- CALCULATE THE DEPENDANT VARIABLES
DETERMINE the LAMINA STRESS STATE
- ESTIMATE THE REGRESSION PARAMETERS
- REPLICATE EXPERIMENT with "N" cases
with new randomly selected input variables
- STATISTICAL METHODS
CALCULATE parameter estimates

DIFFERENTIATE ALL RATES

DETERMINE parameter sensitivities

FIGURE 22

Scope of Design Parameters to Study

[source: Blackson, 40]

FAILURE CRITERIA [2]

maximum stress
Hoffman criteria

LAYUP CONFIGURATION [4]

unidirectional, six ply
unidirectional, eight ply
quasi - isotropic, eight ply
quasi - isotropic, twelve ply

DETERMINISTIC LOAD CASE [2]

tension
compression

DETERMINISTIC LOAD [5]

$p1 = 0.$
 $p2 = 10$ kips
 $p3 = 12$ kips
 $p4 = -12$ kips
 $p5 = -14$ kips

TEMPERATURE EFFECTS [3]

$t1 = 76$ F
 $t2 = 250$ F
 $t3 = 350$ F

MOISTURE EFFECTS [2]

$m1 = 0\%$
 $m2 = 1\%$

The total combinations of design parameter variation is four hundred and eighty (480) different cases.

PROJECT IMPLEMENTATION

This design parameter sensitivity study encompassed over four hundred and eighty different parameter permutations of layup configuration, deterministic load case, deterministic load, failure criteria, thermal and moisture content effects. The lamination code, ADVLAM, was executed for each design parameter combination described above, generating a ply-by-ply stress analysis for the laminate in the described service environment. The results of each stress analysis was summarized into a spread sheet format; Monte Carlo simulations were executed to demonstrate the reliability level of hardware which employs material of this known degree of property variability. Since the material properties are unique to the temperature and humidity regime, independent versions of the Monte Carlo simulation case studies were used to reflect this hygroscopic dependance. The initial generation of the reliability analysis was based on three thousand test cases, although higher sensitivity of five thousand test cases were used in more sensitive parameter combination to increase the probabilistic base. The strength distributions seen in the appendices were generated with one thousand test cases for ease of visual display and computer access time.

FIGURE 23

Sample Probabilistic Micromechanics Analysis Code Printout

[source: Blackson, 41]

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*****
          A D V L A M   VERSION - December 1984
*****

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OUTTER SHELL LAYUP CONFIGURATION

Analysis type: LINEAR 3-D

Run time: 20-MAR-1989 13:25:01.77

NLAYER = 12 NMATER = 1 SYMFLG = T IFAIL = 4

PRINT(I) = T T T T F

Composite thickness = 1.7796E-01

Layer no.	Layer Material no.	Layup angle THETA (deg)	Thickness H	Midplane distance Z
1	1	30.00	1.4830E-02	-8.1565E-02
2	1	-30.00	1.4830E-02	-6.6735E-02
3	1	30.00	1.4830E-02	-5.1905E-02
4	1	-30.00	1.4830E-02	-3.7075E-02
5	1	0.00	1.4830E-02	-2.2245E-02
6	1	0.00	1.4830E-02	-7.4150E-03
7	1	0.00	1.4830E-02	7.4150E-03
8	1	0.00	1.4830E-02	2.2245E-02
9	1	-30.00	1.4830E-02	3.7075E-02
10	1	30.00	1.4830E-02	5.1905E-02
11	1	-30.00	1.4830E-02	6.6735E-02
12	1	30.00	1.4830E-02	8.1565E-02

Elastic material property data for material 1:

N	E1	E2	E3	G12	G13	G23	PR12	PR13	PR23	ALPHA1	ALPHA2	BETA1	BETA2	T	M
1	8.8000E+06	8.6000E+06	1.4400E+06	8.9000E+05	3.0000E+05	3.0000E+05									
1	0.095	0.530	0.530	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00

MAX. STRESS strength property data for material 1:

XT	XC	YT	YC	S	TEMP	MOIST
8.1000E+04	9.7000E+04	8.1800E+04	9.3200E+04	1.8000E+04	7.5000E+01	0.0000E+00

Integrated thermal loads NX, NY, NXY, MX, MY, and MXY:

1	2	3	4	5	6
0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00

Integrated hygroscopic loads NX, NY, NXY, MX, MY, and MXY:

1	2	3	4	5	6
0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00

Total hygrothermal loads NX, NY, NXY, MX, MY, and MXY:

1	2	3	4	5	6
0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00

Composite laminate extensional properties:

EX = 6.5193E+06	EY = 6.3992E+06	EZ = 1.4400E+06
GXY = 2.4333E+06	GXZ = 3.0000E+05	GYZ = 3.0000E+05
PRXY = 0.3303	PRXZ = 0.3922	PRYZ = 0.3948

1	2	3	4	5	6
0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00

Composite laminate extenslonal properties:

EX = 6.5193E+06 EY = 6.3992E+06 EZ = 1.4400E+06
 GXY = 2.4333E+06 GXZ = 3.0000E+05 GYZ = 3.0000E+05
 PRXY = 0.3303 PRXZ = 0.3922 PRYZ = 0.3948

Composite 3-D elastic stiffness matrix:

	1	2	3	4	5	6
1	7.8512E+06	2.9166E+06	9.3927E+05	0.0000E+00	0.0000E+00	0.0000E+00
2	2.9166E+06	7.7152E+06	9.3803E+05	0.0000E+00	0.0000E+00	0.0000E+00
3	9.3927E+05	9.3803E+05	1.6047E+06	0.0000E+00	0.0000E+00	0.0000E+00
4	0.0000E+00	0.0000E+00	0.0000E+00	3.0000E+05	0.0000E+00	0.0000E+00
5	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	3.0000E+05	0.0000E+00
6	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	2.4333E+06

Composite membrane-bending (ABD) stiffness matrix:

	1	2	3	4	5	6
1	1.2994E+06	4.2133E+05	0.0000E+00	1.0254E-02	1.7090E-03	0.0000E+00
2	4.2133E+05	1.2754E+06	0.0000E+00	1.7090E-03	9.7656E-03	0.0000E+00
3	0.0000E+00	0.0000E+00	4.3303E+05	0.0000E+00	0.0000E+00	2.6855E-03
4	1.0254E-02	1.7090E-03	0.0000E+00	3.1000E+03	1.4341E+03	1.4405E+02
5	1.7090E-03	9.7656E-03	0.0000E+00	1.4341E+03	3.0509E+03	-1.3493E+02
6	0.0000E+00	0.0000E+00	2.6855E-03	1.4405E+02	-1.3493E+02	1.4650E+03

Composite membrane-bending (ABD^-1) flexibility matrix:

	1	2	3	4	5	6
1	8.6194E-07	-2.8474E-07	-3.5487E-21	-3.7450E-12	2.2143E-12	5.7220E-13
2	-2.8474E-07	8.7812E-07	3.4609E-21	2.2000E-12	-3.7101E-12	-5.5805E-13
3	-3.5487E-21	3.4609E-21	2.3093E-06	3.6802E-13	-3.6330E-13	-4.3030E-12
4	-3.7450E-12	2.2000E-12	3.6802E-13	4.1729E-04	-1.9878E-04	-5.9341E-05
5	2.2143E-12	-3.7101E-12	-3.6330E-13	-1.9878E-04	4.2380E-04	5.8581E-05
6	5.7220E-13	-5.5805E-13	-4.3030E-12	-5.9341E-05	5.8581E-05	6.9384E-04

Composite coefficients of thermal expansion AX, AY, AXY, KX, KY, and KXY:

1	2	3	4	5	6
0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00

Composite coefficients of hygroscopic expansion BX, BY, BXY, KX, KY, and KXY:

1	2	3	4	5	6
0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00

LODFLG(I) = T T T T T T

Applied stress resultants NX, NY, NXY, MX, MY, and MXY:

1	2	3	4	5	6
-1.4000E+04	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00

Mid-plane strains and curvatures EX, EY, GXY, KX, KY and KXY:

	1	2	3	4	5	6
	-1.2067E-02	3.9864E-03	4.9681E-17	5.2430E-08	-3.1000E-08	-8.0108E-09

Transverse shears VX and VY:

1	2
0.0000E+00	0.0000E+00

Antiplane stresses SZ, TYZ and TXZ:

1	2	3
0.0000E+00	0.0000E+00	0.0000E+00

Lamina stresses in laminate coordinate system:

LAY	K	SigX	SigY	SigZ	SigYZ	SigXZ	SigXY
1	1	-6.608E+04	-1.232E+04	0.000E+00	0.000E+00	0.000E+00	-2.181E+04
1	2	-6.608E+04	-1.232E+04	0.000E+00	0.000E+00	0.000E+00	-2.181E+04
2	1	-6.608E+04	-1.232E+04	0.000E+00	0.000E+00	0.000E+00	2.181E+04
2	2	-6.608E+04	-1.232E+04	0.000E+00	0.000E+00	0.000E+00	2.181E+04
3	1	-6.608E+04	-1.232E+04	0.000E+00	0.000E+00	0.000E+00	-2.181E+04
3	2	-6.608E+04	-1.232E+04	0.000E+00	0.000E+00	0.000E+00	-2.181E+04
4	1	-6.608E+04	-1.232E+04	0.000E+00	0.000E+00	0.000E+00	2.181E+04

1 2 3
0.0000E+00 0.0000E+00 0.0000E+00

Lamina stresses in laminate coordinate system:

LAY	K	SigX	SigY	SigZ	SigYZ	SigXZ	SigXY
1	1	-6.608E+04	-1.232E+04	0.000E+00	0.000E+00	0.000E+00	-2.181E+04
1	2	-6.608E+04	-1.232E+04	0.000E+00	0.000E+00	0.000E+00	-2.181E+04
2	1	-6.608E+04	-1.232E+04	0.000E+00	0.000E+00	0.000E+00	2.181E+04
2	2	-6.608E+04	-1.232E+04	0.000E+00	0.000E+00	0.000E+00	2.181E+04
3	1	-6.608E+04	-1.232E+04	0.000E+00	0.000E+00	0.000E+00	-2.181E+04
3	2	-6.608E+04	-1.232E+04	0.000E+00	0.000E+00	0.000E+00	-2.181E+04
4	1	-6.608E+04	-1.232E+04	0.000E+00	0.000E+00	0.000E+00	2.181E+04
4	2	-6.608E+04	-1.232E+04	0.000E+00	0.000E+00	0.000E+00	2.181E+04
5	1	-1.039E+05	2.464E+04	0.000E+00	0.000E+00	0.000E+00	2.115E-04
5	2	-1.039E+05	2.464E+04	0.000E+00	0.000E+00	0.000E+00	1.057E-04
6	1	-1.039E+05	2.464E+04	0.000E+00	0.000E+00	0.000E+00	1.057E-04
6	2	-1.039E+05	2.464E+04	0.000E+00	0.000E+00	0.000E+00	-1.222E-11
7	1	-1.039E+05	2.464E+04	0.000E+00	0.000E+00	0.000E+00	-1.222E-11
7	2	-1.039E+05	2.464E+04	0.000E+00	0.000E+00	0.000E+00	-1.057E-04
8	1	-1.039E+05	2.464E+04	0.000E+00	0.000E+00	0.000E+00	-1.057E-04
8	2	-1.039E+05	2.464E+04	0.000E+00	0.000E+00	0.000E+00	-2.115E-04
9	1	-6.608E+04	-1.232E+04	0.000E+00	0.000E+00	0.000E+00	2.181E+04
9	2	-6.608E+04	-1.232E+04	0.000E+00	0.000E+00	0.000E+00	2.181E+04
10	1	-6.608E+04	-1.232E+04	0.000E+00	0.000E+00	0.000E+00	-2.181E+04
10	2	-6.608E+04	-1.232E+04	0.000E+00	0.000E+00	0.000E+00	-2.181E+04
11	1	-6.608E+04	-1.232E+04	0.000E+00	0.000E+00	0.000E+00	2.181E+04
11	2	-6.608E+04	-1.232E+04	0.000E+00	0.000E+00	0.000E+00	2.181E+04
12	1	-6.608E+04	-1.232E+04	0.000E+00	0.000E+00	0.000E+00	-2.181E+04
12	2	-6.608E+04	-1.232E+04	0.000E+00	0.000E+00	0.000E+00	-2.181E+04

Lamina stresses in material coordinate system:

LAY	K	Sig1	Sig2	Sig3	Sig23	Sig13	Sig12
1	1	-7.153E+04	-6.873E+03	0.000E+00	0.000E+00	0.000E+00	1.237E+04
1	2	-7.153E+04	-6.873E+03	0.000E+00	0.000E+00	0.000E+00	1.237E+04
2	1	-7.153E+04	-6.873E+03	0.000E+00	0.000E+00	0.000E+00	-1.237E+04
2	2	-7.153E+04	-6.873E+03	0.000E+00	0.000E+00	0.000E+00	-1.237E+04
3	1	-7.153E+04	-6.873E+03	0.000E+00	0.000E+00	0.000E+00	1.237E+04
3	2	-7.153E+04	-6.873E+03	0.000E+00	0.000E+00	0.000E+00	1.237E+04
4	1	-7.153E+04	-6.873E+03	0.000E+00	0.000E+00	0.000E+00	-1.237E+04
4	2	-7.153E+04	-6.873E+03	0.000E+00	0.000E+00	0.000E+00	-1.237E+04
5	1	-1.039E+05	2.464E+04	0.000E+00	0.000E+00	0.000E+00	2.115E-04
5	2	-1.039E+05	2.464E+04	0.000E+00	0.000E+00	0.000E+00	1.057E-04
6	1	-1.039E+05	2.464E+04	0.000E+00	0.000E+00	0.000E+00	1.057E-04
6	2	-1.039E+05	2.464E+04	0.000E+00	0.000E+00	0.000E+00	-1.222E-11
7	1	-1.039E+05	2.464E+04	0.000E+00	0.000E+00	0.000E+00	-1.222E-11
7	2	-1.039E+05	2.464E+04	0.000E+00	0.000E+00	0.000E+00	-1.057E-04
8	1	-1.039E+05	2.464E+04	0.000E+00	0.000E+00	0.000E+00	-1.057E-04
8	2	-1.039E+05	2.464E+04	0.000E+00	0.000E+00	0.000E+00	-2.115E-04
9	1	-7.153E+04	-6.873E+03	0.000E+00	0.000E+00	0.000E+00	1.237E+04
9	2	-7.153E+04	-6.873E+03	0.000E+00	0.000E+00	0.000E+00	-1.237E+04
10	1	-7.153E+04	-6.873E+03	0.000E+00	0.000E+00	0.000E+00	1.237E+04
10	2	-7.153E+04	-6.873E+03	0.000E+00	0.000E+00	0.000E+00	1.237E+04
11	1	-7.153E+04	-6.873E+03	0.000E+00	0.000E+00	0.000E+00	-1.237E+04
11	2	-7.153E+04	-6.873E+03	0.000E+00	0.000E+00	0.000E+00	-1.237E+04
12	1	-7.153E+04	-6.873E+03	0.000E+00	0.000E+00	0.000E+00	1.237E+04
12	2	-7.153E+04	-6.873E+03	0.000E+00	0.000E+00	0.000E+00	1.237E+04

Lamina failure criteria:

LAY	K	Sig1	Sig2	Sig12	FAIL
1	1	-7.1526E+04	-6.8730E+03	1.2373E+04	OK
1	2	-7.1526E+04	-6.8730E+03	1.2373E+04	OK
2	1	-7.1526E+04	-6.8730E+03	-1.2373E+04	OK
2	2	-7.1526E+04	-6.8730E+03	-1.2373E+04	OK
3	1	-7.1526E+04	-6.8730E+03	1.2373E+04	OK
3	2	-7.1526E+04	-6.8730E+03	1.2373E+04	OK
4	1	-7.1526E+04	-6.8730E+03	-1.2373E+04	OK
4	2	-7.1526E+04	-6.8730E+03	-1.2373E+04	OK
5	1	-1.0385E+05	2.4641E+04	2.1146E-04	FAILED
5	2	-1.0385E+05	2.4641E+04	1.0573E-04	FAILED
6	1	-1.0385E+05	2.4641E+04	1.0573E-04	FAILED
6	2	-1.0385E+05	2.4641E+04	-1.2223E-11	FAILED
7	1	-1.0385E+05	2.4641E+04	-1.2223E-11	FAILED
7	2	-1.0385E+05	2.4641E+04	-1.0573E-04	FAILED
8	1	-1.0385E+05	2.4641E+04	-1.0573E-04	FAILED
8	2	-1.0385E+05	2.4641E+04	-2.1146E-04	FAILED
9	1	-7.1526E+04	-6.8730E+03	-1.2373E+04	OK
9	2	-7.1526E+04	-6.8730E+03	-1.2373E+04	OK
10	1	-7.1526E+04	-6.8730E+03	1.2373E+04	OK
10	2	-7.1526E+04	-6.8730E+03	1.2373E+04	OK
11	1	-7.1526E+04	-6.8730E+03	-1.2373E+04	OK
11	2	-7.1526E+04	-6.8730E+03	-1.2373E+04	OK
12	1	-7.1526E+04	-6.8730E+03	1.2373E+04	OK
12	2	-7.1526E+04	-6.8730E+03	1.2373E+04	OK

7	2	-1.039E+05	2.464E+04	0.000E+00	0.000E+00	0.000E+00	-1.057E-04
8	1	-1.039E+05	2.464E+04	0.000E+00	0.000E+00	0.000E+00	-1.057E-04
8	2	-1.039E+05	2.464E+04	0.000E+00	0.000E+00	0.000E+00	-2.115E-04
9	1	-6.608E+04	-1.232E+04	0.000E+00	0.000E+00	0.000E+00	2.181E+04
9	2	-6.608E+04	-1.232E+04	0.000E+00	0.000E+00	0.000E+00	2.181E+04
10	1	-6.608E+04	-1.232E+04	0.000E+00	0.000E+00	0.000E+00	-2.181E+04
10	2	-6.608E+04	-1.232E+04	0.000E+00	0.000E+00	0.000E+00	-2.181E+04
11	1	-6.608E+04	-1.232E+04	0.000E+00	0.000E+00	0.000E+00	2.181E+04
11	2	-6.608E+04	-1.232E+04	0.000E+00	0.000E+00	0.000E+00	2.181E+04
12	1	-6.608E+04	-1.232E+04	0.000E+00	0.000E+00	0.000E+00	-2.181E+04
12	2	-6.608E+04	-1.232E+04	0.000E+00	0.000E+00	0.000E+00	-2.181E+04

Lamina stresses in material coordinate system:

LAY	K	Sig1	Sig2	Sig3	Sig23	Sig13	Sig12
1	1	-7.153E+04	-6.873E+03	0.000E+00	0.000E+00	0.000E+00	1.237E+04
1	2	-7.153E+04	-6.873E+03	0.000E+00	0.000E+00	0.000E+00	1.237E+04
2	1	-7.153E+04	-6.873E+03	0.000E+00	0.000E+00	0.000E+00	-1.237E+04
2	2	-7.153E+04	-6.873E+03	0.000E+00	0.000E+00	0.000E+00	-1.237E+04
3	1	-7.153E+04	-6.873E+03	0.000E+00	0.000E+00	0.000E+00	1.237E+04
3	2	-7.153E+04	-6.873E+03	0.000E+00	0.000E+00	0.000E+00	1.237E+04
4	1	-7.153E+04	-6.873E+03	0.000E+00	0.000E+00	0.000E+00	-1.237E+04
4	2	-7.153E+04	-6.873E+03	0.000E+00	0.000E+00	0.000E+00	-1.237E+04
5	1	-1.039E+05	2.464E+04	0.000E+00	0.000E+00	0.000E+00	2.115E-04
5	2	-1.039E+05	2.464E+04	0.000E+00	0.000E+00	0.000E+00	1.057E-04
6	1	-1.039E+05	2.464E+04	0.000E+00	0.000E+00	0.000E+00	1.057E-04
6	2	-1.039E+05	2.464E+04	0.000E+00	0.000E+00	0.000E+00	-1.222E-11
7	1	-1.039E+05	2.464E+04	0.000E+00	0.000E+00	0.000E+00	-1.222E-11
7	2	-1.039E+05	2.464E+04	0.000E+00	0.000E+00	0.000E+00	-1.057E-04
8	1	-1.039E+05	2.464E+04	0.000E+00	0.000E+00	0.000E+00	-1.057E-04
8	2	-1.039E+05	2.464E+04	0.000E+00	0.000E+00	0.000E+00	-2.115E-04
9	1	-7.153E+04	-6.873E+03	0.000E+00	0.000E+00	0.000E+00	1.237E+04
9	2	-7.153E+04	-6.873E+03	0.000E+00	0.000E+00	0.000E+00	-1.237E+04
10	1	-7.153E+04	-6.873E+03	0.000E+00	0.000E+00	0.000E+00	1.237E+04
10	2	-7.153E+04	-6.873E+03	0.000E+00	0.000E+00	0.000E+00	1.237E+04
11	1	-7.153E+04	-6.873E+03	0.000E+00	0.000E+00	0.000E+00	-1.237E+04
11	2	-7.153E+04	-6.873E+03	0.000E+00	0.000E+00	0.000E+00	-1.237E+04
12	1	-7.153E+04	-6.873E+03	0.000E+00	0.000E+00	0.000E+00	1.237E+04
12	2	-7.153E+04	-6.873E+03	0.000E+00	0.000E+00	0.000E+00	1.237E+04

Lamina failure criteria:

LAY	K	Sig1	Sig2	Sig12	FAIL
1	1	-7.1526E+04	-6.8730E+03	1.2373E+04	OK
1	2	-7.1526E+04	-6.8730E+03	1.2373E+04	OK
2	1	-7.1526E+04	-6.8730E+03	-1.2373E+04	OK
2	2	-7.1526E+04	-6.8730E+03	-1.2373E+04	OK
3	1	-7.1526E+04	-6.8730E+03	1.2373E+04	OK
3	2	-7.1526E+04	-6.8730E+03	1.2373E+04	OK
4	1	-7.1526E+04	-6.8730E+03	-1.2373E+04	OK
4	2	-7.1526E+04	-6.8730E+03	-1.2373E+04	OK
5	1	-1.0385E+05	2.4641E+04	2.1146E-04	FAILED
5	2	-1.0385E+05	2.4641E+04	1.0573E-04	FAILED
6	1	-1.0385E+05	2.4641E+04	1.0573E-04	FAILED
6	2	-1.0385E+05	2.4641E+04	-1.2223E-11	FAILED
7	1	-1.0385E+05	2.4641E+04	-1.2223E-11	FAILED
7	2	-1.0385E+05	2.4641E+04	-1.0573E-04	FAILED
8	1	-1.0385E+05	2.4641E+04	-1.0573E-04	FAILED
8	2	-1.0385E+05	2.4641E+04	-2.1146E-04	FAILED
9	1	-7.1526E+04	-6.8730E+03	-1.2373E+04	OK
9	2	-7.1526E+04	-6.8730E+03	-1.2373E+04	OK
10	1	-7.1526E+04	-6.8730E+03	1.2373E+04	OK
10	2	-7.1526E+04	-6.8730E+03	1.2373E+04	OK
11	1	-7.1526E+04	-6.8730E+03	-1.2373E+04	OK
11	2	-7.1526E+04	-6.8730E+03	-1.2373E+04	OK
12	1	-7.1526E+04	-6.8730E+03	1.2373E+04	OK
12	2	-7.1526E+04	-6.8730E+03	1.2373E+04	OK

<CL> PNS exhausted

ENDRUN called by CLIP

FORTTRAN STOP

*DCL-W-SKPDAT, image data (records not beginning with "\$") ignored

FIGURE 24

Sample of Statistical T300/976 Material Property Strength Distribution

[source: Blackson, 39]

RESULTS OF STUDY

The results of this design parameter sensitivity study proved insightful into the uses of this material system in design and fabrication of composite hardware. The study was easily segmented by the deterministic load case and specific load and therefore the review of the results of the program will be discussed in this manner.

The first to be addressed is the tensile load cases, which is well known to be a fiber dominated failure. Conceptually, the composite material properties should be sensitive to the fiber properties, the variation in geometric orientation of the reinforcement, and the processing window which ensures load transfer from the matrix into the fiber. As expected by these concepts, the tensile load cases were indeed very sensitive to the relatively high coefficient of variation of the ply tensile data and the scatter associated with the test method. These test procedures which were briefly touched upon in Chapter 3, explain the test methods used which control the coefficient of variation of the data. The control of these variable involve the consistency of many sub-processes such as panel cut and layup, cured composite specimen machining, as well as test equipment accuracy and calibration. To summarize, the study indicates that the identified attributes which affect the ply properties under tensile load do in fact impact the reliability of that property on component service life.

The second deterministic load case, compression, is known to be a matrix dominated failure. Conceptually, the composite material properties should be sensitive to the consistency of the matrix, the fiber matrix interface, and the hygroscopic effects of elevated temperature and moisture content. Consistent with expectation, the

compression ply properties as determined through this study are indeed sensitive to temperature, which has a significant impact as the part temperature approaches the glass transition temperature of the matrix material. Moisture content in the composite system which is known to plasticize the matrix material also shows this hygroscopic sensitivity. It should be noted that the sensitivity of the materials system to hygroscopic effects is constantly reviewed through the production monitors which have been proven effective in the procurement of quality B-staged pre-impregnated material.

FIGURE 25 A

Reliability Evaluation of T300/976 Material Properties in Composite Laminates

[source: Blackson, 40]

FIGURE 25 B

Reliability Evaluation of T300/976 Material Properties in Composite Laminates

[source: Blackson, 40]

FIGURE 25 C

Reliability Evaluation of T300/976 Material Properties in Composite Laminates

[source: Blackson, 40]

Table 4

Reliability Evaluation of Design Parameter Sensitivity Study for
T300/976 Composite Material System

[source: Blackson, 40]

DATASET NUMBER	SIGMA 1	SIGMA 2	DATASET NUMBER	SIGMA 1	SIGMA 2
111211	100	90.1	1112112	100	89.6
111311	100	52.4	1113112	100	50.2
112411	100	84.8	1124112	100	81.3
112511	100	19.7	1125112	100	17.1
122411	100	100	1224112	100	100
122511	76.1	75.8	1225112	72.5	71.4
1112121	100	100	1112122	100	100
1113121	100	98	1113122	100	92.3
1124121	100	84	1124122	100	80.1
1125121	100	19.7	1125122	100	12.5
1224121	100	100	1224122	100	100
1225121	75	76.1	1225122	70.3	71.2
1112131	100	100	1112132	100	100
1113131	100	98.9	1113132	100	91.1
1224131	99.4	99.3	1224132	93.1	94.6
1225131	100	84.3	1225132	100	76.5

Impacts on Research and Current Design Methods

In an effort to identify the design procedures which incorporate the intrinsic material variability into the material requirements, several procedures must be added. Initially, the vehicle mission defines the material requirements needed for the baseline design concept. Once the material system has been selected which supports the requirements of the mission, thermal and mechanical property evaluation must be completed. The resulting data may then be manipulated to develop the extreme value statistics for the expected service environment of component. As these statistics are attained, the uncertainty of the material property may be ascertained through the use of Monte Carlo simulations. These simulations employed in conjunction with lamina analysis for the specific part, layup configuration, and thermal / mechanical profile, the uncertainty of the reliability for the part may then be properly evaluated. In this manner, the material model reflects a failure criterion which reflects the intrinsic material variability in the composite system.

Conclusions and Summary

The need for materials of special capability which not only provide ease of manufacture but also cost effectiveness has been identified and addressed with the usage of composite material systems in current designs. Although composite systems provide the flexibility in design where the material employed may be optimized to support stringent and directional property requirements; they are also highly sensitive to the consistency of the constituent materials, the method of processing, and the methods of post fabrication finishing and assembly. Once the impact of this variation on the quality of the finished part has been identified and evaluated, an assessment of these sensitivities on the true design margins may be completed.

It was shown in this study that analytical methods currently exist which assist in the determination of the impacts of material and process variability on the reliability of the composite hardware. Predictive techniques which relate the variability of constituent materials to the thermal/mechanical properties of the final composite material system requires further development and integration into current design methods.

The scope of the future research on the predictive analytical techniques which incorporates the material variability of a composite system into an appropriate failure criterion needs to be addressed. Since each composite system is sensitive to the constituent materials, the processing window, and the test method employed, the development of an anisotropic failure criteria is not a trivial task. With a well characterized composite system such as graphite epoxy, T300/976, such a failure

criterion could be completed with minimal effort. To complete this activity, multiple parts would required lamina and structural analysis, Monte Carlo simulations specific to the part load case, fabrication of replicate parts for each load case, and subsequent mechanical test of these parts. Correlation of the data to the analysis and the ascertained realibility of the hardware may then be developed.

APPENDIX

Statistical Representation Experimental Data of T300/976 Material Properties
Room Temperature Compression, Sigma 22

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# 6792E+05 ( 2) xxxi | | | | | | | | | |
# 6909E+05 ( 0) | | | | | | | | | |
# 7026E+05 ( 1) xxi | | | | | | | | | |
# 7143E+05 ( 1) xxi | | | | | | | | | |
# 7260E+05 ( 7) xxxxxxxxxxxxi | | | | | | | | | |
# 7377E+05 ( 7) xxxxxxxxxxxxi | | | | | | | | | |
# 7494E+05 ( 10) xxxxxxxxxxxxi | | | | | | | | | |
# 7611E+05 ( 7) xxxxxxxxxxxxi | | | | | | | | | |
# 7728E+05 ( 14) xxxxxxxxxxxxxxxxxxxxi | | | | | | | | | |
# 7846E+05 ( 16) xxxxxxxxxxxxxxxxxxxxxxxxxxxxi | | | | | | | | | |
# 7963E+05 ( 24) xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxi | | | | | | | | | |
# 8080E+05 ( 24) xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxi | | | | | | | | | |
# 8197E+05 ( 32) xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxi | | | | | | | | | |
# 8314E+05 ( 33) xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxi | | | | | | | | | |
# 8431E+05 ( 47) xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxi | | | | | | | | | |
# 8548E+05 ( 46) xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxi | | | | | | | | | |
# 8665E+05 ( 34) xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxi | | | | | | | | | |
# 8782E+05 ( 49) xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxi | | | | | | | | | |
# 8899E+05 ( 47) xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxi | | | | | | | | | |
# 9017E+05 ( 46) xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxi | | | | | | | | | |
# 9134E+05 ( 56) xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxi | | | | | | | | | |
# 9251E+05 ( 49) xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxi | | | | | | | | | |
# 9368E+05 ( 43) xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxi | | | | | | | | | |
# 9485E+05 ( 51) xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxi | | | | | | | | | |
# 9602E+05 ( 40) xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxi | | | | | | | | | |
# 9719E+05 ( 52) xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxi | | | | | | | | | |
# 9836E+05 ( 20) xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxi | | | | | | | | | |
# 9953E+05 ( 39) xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxi | | | | | | | | | |
# 1007E+05 ( 35) xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxi | | | | | | | | | |
# 1019E+05 ( 25) xxxxxx> xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxi | | | | | | | | | |
# 1030E+05 ( 24) xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxi | | | | | | | | | |
# 1042E+05 ( 20) xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxi | | | | | | | | | |
# 1054E+05 ( 26) xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxi | | | | | | | | | |
# 1066E+05 ( 10) xxxxxxxxxxxxxxxxxxxxi | | | | | | | | | |
# 1077E+05 ( 13) xxxxxxxxxxxxxxxxxxxxxxxxxxxxi | | | | | | | | | |
# 1089E+05 ( 14) xxxxxxxxxxxxxxxxxxxxxxxxxxxxi | | | | | | | | | |
# 1101E+05 ( 6) xxxxxxxxxxxxi | | | | | | | | | |
# 1112E+05 ( 6) xxxxxxxxxxxxi | | | | | | | | | |
# 1124E+05 ( 2) xxxi | | | | | | | | | |
# 1136E+05 ( 3) xxxxi | | | | | | | | | |
# 1148E+05 ( 3) xxxxi | | | | | | | | | |
# 1159E+05 ( 1) xxi | | | | | | | | | |
# 1171E+05 ( 1) xxi | | | | | | | | | |

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Room Temperature Tension, Sigma 11

[illegible]

Statistical Representation Experimental Data of T300/976 Material Properties

Room Temperature Tension, Sigma 22

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.8551E+05 ( 1) XXXI
.8558E+05 ( 4) XXXXXXXXII
.8765E+05 ( 4) XXXXXXXXII
.8872E+05 ( 9) XXXXXXXXXXXXXXXXII
.8978E+05 ( 9) XXXXXXXXXXXXXXXXII
.9085E+05 ( 4) XXXXXXXXII
.9192E+05 (11) XXXXXXXXXXXXXXXXII
.9299E+05 (15) XXXXXXXXXXXXXXXXII
.9405E+05 (15) XXXXXXXXXXXXXXXXII
.9512E+05 (17) XXXXXXXXXXXXXXXXII
.9619E+05 (15) XXXXXXXXXXXXXXXXII
.9726E+05 (32) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXII
.9832E+05 (25) XXXXXXXXXXXXXXXXII
.9939E+05 (34) XXXXXXXXXXXXXXXXII
.9946E+05 (35) XXXXXXXXXXXXXXXXII
.9953E+05 (38) XXXXXXXXXXXXXXXXII
.9959E+05 (28) XXXXXXXXXXXXXXXXII
.9966E+05 (35) XXXXXXXXXXXXXXXXII
.9973E+05 (37) XXXXXXXXXXXXXXXXII
.9980E+05 (41) XXXXXXXXXXXXXXXXII
.9987E+05 (37) XXXXXXXXXXXXXXXXII
.9993E+05 (46) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXII
.9998E+05 (44) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXII
.9999E+05 (35) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXII
.9999E+05 (38) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXII
.9999E+05 (38) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXII
.9999E+05 (34) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXII
.9999E+05 (48) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXII
.9999E+05 (33) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXII
.9999E+05 (26) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXII
.9999E+05 (29) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXII
.9999E+05 (28) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXII
.9999E+05 (17) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXII
.9999E+05 (23) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXII
.9999E+05 (19) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXII
.9999E+05 (19) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXII
.9999E+05 (17) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXII
.9999E+05 (9) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXII
.9999E+05 (13) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXII
.9999E+05 (6) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXII
.9999E+05 (18) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXII
.9999E+05 (8) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXII
.9999E+05 (3) XXXXXXXXII
.9999E+05 (2) XXXXII
.9999E+05 (1) XXXI
.9999E+05 (2) XXXXII
.9999E+05 (3) XXXXXXXXII
.9999E+05 (1) XXXI
.9999E+05 (1) XXXI

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Statistical Representation Experimental Data of T300/976 Material Properties

250 F Compression, Sigma 11

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#.6881E+05 ( 2) XXXI | | | | | | | | | |
#.6899E+05 ( 2) XXXI | | | | | | | | | |
#.6918E+05 ( 2) XXXI | | | | | | | | | |
#.6296E+05 ( 2) XXXI | | | | | | | | | |
#.6395E+05 ( 1) XI | | | | | | | | | |
#.6493E+05 ( 1) XI | | | | | | | | | |
#.6591E+05 ( 4) XXXXXXI | | | | | | | | | |
#.6690E+05 ( 18) XXXXXXXXXXXXXI | | | | | | | | | |
#.6788E+05 ( 13) XXXXXXXXXXXXXXXX | | | | | | | | | |
#.6886E+05 ( 9) XXXXXXXXXXXX | | | | | | | | | |
#.6985E+05 ( 19) XXXXXXXXXXXXXXXXXXXXXI | | | | | | | | | |
#.7083E+05 ( 26) XXXXXXXXXXXXXXXXXXXXXXXX | | | | | | | | | |
#.7182E+05 ( 28) XXXXXXXXXXXXXXXXXXXXXXXX | | | | | | | | | |
#.7280E+05 ( 48) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX | | | | | | | | | |
#.7378E+05 ( 38) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX | | | | | | | | | |
#.7477E+05 ( 54) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX | | | | | | | | | |
#.7575E+05 ( 51) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX | | | | | | | | | |
#.7673E+05 ( 41) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX | | | | | | | | | |
#.7772E+05 ( 59) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX | | | | | | | | | |
#.7870E+05 ( 53) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX | | | | | | | | | |
#.7969E+05 ( 68) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX | | | | | | | | | |
#.8067E+05 ( 53) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX | | | | | | | | | |
#.8165E+05 ( 54) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX | | | | | | | | | |
#.8264E+05 ( 52) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX | | | | | | | | | |
#.8362E+05 ( 55) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX | | | | | | | | | |
#.8460E+05 ( 42) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX | | | | | | | | | |
#.8559E+05 ( 42) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX | | | | | | | | | |
#.8657E+05 ( 35) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX | | | | | | | | | |
#.8756E+05 ( 35) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX | | | | | | | | | |
#.8854E+05 ( 26) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX | | | | | | | | | |
#.8952E+05 ( 26) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX | | | | | | | | | |
#.9051E+05 ( 16) XXXXXXXXXXXXXXXXXXXXXXXX | | | | | | | | | |
#.9149E+05 ( 14) XXXXXXXXXXXXXXXX | | | | | | | | | |
#.9247E+05 ( 14) XXXXXXXXXXXXXXXX | | | | | | | | | |
#.9346E+05 ( 18) XXXXXXXXXXXXXI | | | | | | | | | |
#.9444E+05 ( 4) XXXXXI | | | | | | | | | |
#.9543E+05 ( 3) XXXXI | | | | | | | | | |
#.9641E+05 ( 3) XXXXI | | | | | | | | | |
#.9739E+05 ( 1) XI | | | | | | | | | |
#.9838E+05 ( 1) XI | | | | | | | | | |
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Statistical Representation Experimental Data of T300/976 Material Properties

250 F Compression, Sigma 22

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# 5948E+05 ( 4) XXXXXI I I I I I I I I I I
# 6037E+05 ( 1) XI I I I I I I I I I I
# 6135E+05 ( 2) XXXI I I I I I I I I I I
# 6232E+05 ( 1) XI I I I I I I I I I I
# 6338E+05 ( 1) XI I I I I I I I I I I
# 6427E+05 ( 1) XI I I I I I I I I I I
# 6524E+05 ( 7) XXXXXXXXXI I I I I I I I I I I
# 6622E+05 ( 10) XXXXXXXXXXXXXI I I I I I I I I I I
# 6719E+05 ( 12) XXXXXXXXXXXXXXXI I I I I I I I I I I
# 6816E+05 ( 10) XXXXXXXXXXXXXI I I I I I I I I I I
# 6914E+05 ( 19) XXXXXXXXXXXXXXXXXXXXXI I I I I I I I I I I
# 7011E+05 ( 25) XXXXXXXXXXXXXXXXXXXXXXXXXI I I I I I I I I I I
# 7109E+05 ( 29) XXXXXXXXXXXXXXXXXXXXXXXXXXI I I I I I I I I I I
# 7206E+05 ( 35) XXXXXXXXXXXXXXXXXXXXXXXXXXI I I I I I I I I I I
# 7303E+05 ( 46) XXXXXXXXXXXXXXXXXXXXXXXXXXI I I I I I I I I I I
# 7401E+05 ( 49) XXXXXXXXXXXXXXXXXXXXXXXXXXI I I I I I I I I I I
# 7498E+05 ( 47) XXXXXXXXXXXXXXXXXXXXXXXXXXI I I I I I I I I I I
# 7595E+05 ( 48) XXXXXXXXXXXXXXXXXXXXXXXXXXI I I I I I I I I I I
# 7693E+05 ( 60) XXXXXXXXXXXXXXXXXXXXXXXXXXI I I I I I I I I I I
# 7790E+05 ( 55) XXXXXXXXXXXXXXXXXXXXXXXXXXI I I I I I I I I I I
# 7888E+05 ( 64) XXXXXXXXXXXXXXXXXXXXXXXXXXI I I I I I I I I I I
# 7985E+05 ( 50) XXXXXXXXXXXXXXXXXXXXXXXXXXI I I I I I I I I I I
# 8082E+05 ( 54) XXXXXXXXXXXXXXXXXXXXXXXXXXI I I I I I I I I I I
# 8180E+05 ( 51) XXXXXXXXXXXXXXXXXXXXXXXXXXI I I I I I I I I I I
# 8277E+05 ( 57) XXXXXXXXXXXXXXXXXXXXXXXXXXI I I I I I I I I I I
# 8374E+05 ( 37) XXXXXXXXXXXXXXXXXXXXXXXXXXI I I I I I I I I I I
# 8472E+05 ( 42) XXXXXXXXXXXXXXXXXXXXXXXXXXI I I I I I I I I I I
# 8569E+05 ( 33) XXXXXXXXXXXXXXXXXXXXXXXXXXI I I I I I I I I I I
# 8667E+05 ( 34) XXXXXXXXXXXXXXXXXXXXXXXXXXI I I I I I I I I I I
# 8764E+05 ( 26) XXXXXXXXXXXXXXXXXXXXXXXXXXI I I I I I I I I I I
# 8861E+05 ( 27) XXXXXXXXXXXXXXXXXXXXXXXXXXI I I I I I I I I I I
# 8959E+05 ( 14) XXXXXXXXXXXXXXXXXI I I I I I I I I I I
# 9056E+05 ( 13) XXXXXXXXXXXXXXXXXI I I I I I I I I I I
# 9153E+05 ( 15) XXXXXXXXXXXXXXXXXI I I I I I I I I I I
# 9251E+05 ( 9) XXXXXXXXXXXXXI I I I I I I I I I I
# 9348E+05 ( 4) XXXXXI I I I I I I I I I I
# 9446E+05 ( 3) XXXXI I I I I I I I I I I
# 9543E+05 ( 3) XXXI I I I I I I I I I I
# 9640E+05 ( 1) XI I I I I I I I I I I
# 9737E+05 ( 1) XI I I I I I I I I I I

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250 F Tension, Sigma 11

[illegible]

Statistical Representation Experimental Data of T300/976 Material Properties

250 F Tension, Sigma 22

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# .7055E+05 ( 0) | | | | | | | | | |
# .7157E+05 ( 0) | | | | | | | | | |
# .7259E+05 ( 4) XXXXI | | | | | | | | | |
# .7362E+05 ( 1) XI | | | | | | | | | |
# .7464E+05 ( 3) XXXI | | | | | | | | | |
# .7566E+05 ( 1) XI | | | | | | | | | |
# .7668E+05 ( 3) XXXI | | | | | | | | | |
# .7771E+05 ( 18) XXXXXXXXXXXXI | | | | | | | | | |
# .7873E+05 ( 17) XXXXXXXXXXXXXXXXI | | | | | | | | | |
# .7975E+05 ( 16) XXXXXXXXXXXXXXXXI | | | | | | | | | |
# .8077E+05 ( 34) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXI | | | | | | | | | |
# .8180E+05 ( 38) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXI | | | | | | | | | |
# .8282E+05 ( 60) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXI | | | | | | | | | |
# .8384E+05 ( 66) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXI | | | | | | | | | |
# .8486E+05 ( 63) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXI | | | | | | | | | |
# .8589E+05 ( 78) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXI | | | | | | | | | |
# .8691E+05 ( 77) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXI | | | | | | | | | |
# .8693E+05 ( 98) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXI | | | | | | | | | |
# .8795E+05 ( 62) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXI | | | | | | | | | |
# .8798E+05 ( 75) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXI | | | | | | | | | |
# .8891E+05 ( 76) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXI | | | | | | | | | |
# .8933E+05 ( 45) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXI | | | | | | | | | |
# .8976E+05 ( 51) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXI | | | | | | | | | |
# .9018E+05 ( 43) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXI | | | | | | | | | |
# .9061E+05 ( 35) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXI | | | | | | | | | |
# .9103E+05 ( 23) XXXXXXXXXXXXXXXXXXXXXXXXI | | | | | | | | | |
# .9146E+05 ( 20) XXXXXXXXXXXXXXXXXXXXXXXXI | | | | | | | | | |
# .9189E+05 ( 15) XXXXXXXXXXXXXXXXI | | | | | | | | | |
# .9231E+05 ( 4) XXXXI | | | | | | | | | |
# .9274E+05 ( 3) XXXXI | | | | | | | | | |
# .9316E+05 ( 4) XXXXI | | | | | | | | | |
# .9359E+05 ( 1) XI | | | | | | | | | |

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Statistical Representation Experimental Data of T300/976 Material Properties

350 F Compression, Sigma 11

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0.5180E+05 ( 0)          |          |          |          |          |          |          |          |
0.5179E+05 ( 4)  XXXXX| |          |          |          |          |          |          |
0.5257E+05 ( 2)  XXX| |          |          |          |          |          |          |
0.5336E+05 ( 2)  XXX| |          |          |          |          |          |          |
0.5414E+05 ( 1)  X| |          |          |          |          |          |          |
0.5493E+05 ( 1)  X| |          |          |          |          |          |          |
0.5571E+05 ( 7)  XXXXXXXX| |          |          |          |          |          |          |
0.5650E+05 ( 14) XXXXXXXXXXXXXXXX| |          |          |          |          |          |          |
0.5728E+05 ( 9)  XXXXXXXXXXXX| |          |          |          |          |          |          |
0.5807E+05 ( 20) XXXXXXXXXXXXXXXXXXXXXXXX| |          |          |          |          |          |          |
0.5885E+05 ( 29) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX| |          |          |          |          |          |          |
0.5964E+05 ( 23) XXXXXXXXXXXXXXXXXXXXXXXX| |          |          |          |          |          |          |
0.6042E+05 ( 45) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX| |          |          |          |          |          |          |
0.6121E+05 ( 49) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX| |          |          |          |          |          |          |
0.6199E+05 ( 60) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX| |          |          |          |          |          |          |
0.6277E+05 ( 50) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX| |          |          |          |          |          |          |
0.6356E+05 ( 60) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX| |          |          |          |          |          |          |
0.6434E+05 ( 61) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX| |          |          |          |          |          |          |
0.6513E+05 ( 75) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX| |          |          |          |          |          |          |
0.6591E+05 ( 59) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX| |          |          |          |          |          |          |
0.6670E+05 ( 63) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX| |          |          |          |          |          |          |
0.6748E+05 ( 56) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX| |          |          |          |          |          |          |
0.6827E+05 ( 66) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX| |          |          |          |          |          |          |
0.6905E+05 ( 39) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX| |          |          |          |          |          |          |
0.6984E+05 ( 47) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX| |          |          |          |          |          |          |
0.7062E+05 ( 36) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX| |          |          |          |          |          |          |
0.7141E+05 ( 30) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX| |          |          |          |          |          |          |
0.7219E+05 ( 30) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX| |          |          |          |          |          |          |
0.7298E+05 ( 16) XXXXXXXXXXXXXXXXXXXXX| |          |          |          |          |          |          |
0.7376E+05 ( 14) XXXXXXXXXXXXXXXX| |          |          |          |          |          |          |
0.7455E+05 ( 16) XXXXXXXXXXXXXXXX| |          |          |          |          |          |          |
0.7533E+05 ( 7)  XXXXXXXX| |          |          |          |          |          |          |
0.7611E+05 ( 3)  XXXX| |          |          |          |          |          |          |
0.7690E+05 ( 3)  XXXX| |          |          |          |          |          |          |
0.7768E+05 ( 3)  XXXX| |          |          |          |          |          |          |
0.7847E+05 ( 1)  X| |          |          |          |          |          |          |
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Statistical Representation Experimental Data of T300/976 Material Properties

350 F Compression, Sigma 22

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# 4775E+05 ( 0)      |      |      |      |      |      |      |      |
# 4851E+05 ( 0)      |      |      |      |      |      |      |      |
# 4927E+05 ( 4)  XXXXX|      |      |      |      |      |      |      |
# 5003E+05 ( 1)  X|      |      |      |      |      |      |      |
# 5079E+05 ( 2)  XXX|      |      |      |      |      |      |      |
# 5154E+05 ( 1)  X|      |      |      |      |      |      |      |
# 5230E+05 ( 1)  X|      |      |      |      |      |      |      |
# 5306E+05 ( 3)  XXXX|      |      |      |      |      |      |      |
# 5382E+05 ( 9)  XXXXXXXXXXXX|      |      |      |      |      |      |
# 5458E+05 ( 15) XXXXXXXXXXXXXXXX|      |      |      |      |      |      |
# 5533E+05 ( 10) XXXXXXXXXXXXX|      |      |      |      |      |      |
# 5609E+05 ( 20) XXXXXXXXXXXXXXXXXXXX|      |      |      |      |      |
# 5685E+05 ( 27) XXXXXXXXXXXXXXXXXXXXXXXXXXXX|      |      |      |      |
# 5761E+05 ( 37) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX|      |      |      |
# 5837E+05 ( 36) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX|      |      |      |
# 5912E+05 ( 53) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX|      |      |
# 5988E+05 ( 60) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX|      |
# 6064E+05 ( 49) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX|      |
# 6140E+05 ( 63) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX|
# 6216E+05 ( 62) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX|
# 6291E+05 ( 74) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX|
# 6367E+05 ( 59) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX|
# 6443E+05 ( 59) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX|
# 6519E+05 ( 55) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX|
# 6595E+05 ( 57) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX|
# 6670E+05 ( 42) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX|
# 6746E+05 ( 47) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX|
# 6822E+05 ( 36) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX|
# 6898E+05 ( 28) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX|
# 6974E+05 ( 31) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX|
# 7049E+05 ( 14) XXXXXXXXXXXXXXXXXXXX|      |      |      |      |
# 7125E+05 ( 15) XXXXXXXXXXXXXXXXXXXX|      |      |      |      |
# 7201E+05 ( 13) XXXXXXXXXXXXXXXX|      |      |      |      |
# 7277E+05 ( 7)  XXXXXXXX|      |      |      |      |
# 7353E+05 ( 3)  XXXX|      |      |      |      |
# 7428E+05 ( 3)  XXXX|      |      |      |      |
# 7504E+05 ( 3)  XXXX|      |      |      |      |
# 7580E+05 ( 1)  X|      |      |      |      |

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Statistical Representation Experimental Data of T300/976 Material Properties

350 F Tension, Sigma 11

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#.#7831E+05 ( 0)      |      |      |      |      |      |      |      |      |
#.#7130E+05 ( 0)      |      |      |      |      |      |      |      |      |
#.#7229E+05 ( 0)      |      |      |      |      |      |      |      |      |
#.#7328E+05 ( 0)      |      |      |      |      |      |      |      |      |
#.#7427E+05 ( 0)      |      |      |      |      |      |      |      |      |
#.#7526E+05 ( 5)  XXXXXI |      |      |      |      |      |      |      |      |
#.#7625E+05 ( 3)  XXXI  |      |      |      |      |      |      |      |      |
#.#7724E+05 ( 1)  XI    |      |      |      |      |      |      |      |      |
#.#7823E+05 ( 6)  XXXXXI |      |      |      |      |      |      |      |      |
#.#7922E+05 ( 10) XXXXXXXXXXXXXI |      |      |      |      |      |      |      |      |
#.#8021E+05 ( 16) XXXXXXXXXXXXXI |      |      |      |      |      |      |      |      |
#.#8120E+05 ( 36) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX |      |      |      |      |      |      |
#.#8219E+05 ( 46) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX |      |      |      |      |      |      |
#.#8318E+05 ( 64) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX |      |      |      |      |      |      |
#.#8417E+05 ( 82) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX |      |      |      |      |      |      |
#.#8516E+05 ( 74) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX |      |      |      |      |      |      |
#.#8615E+05 ( 87) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX |      |      |      |      |      |      |
#.#8714E+05 ( 106) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX |      |      |      |      |      |      |
#.#8813E+05 ( 78) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX |      |      |      |      |      |      |
#.#8912E+05 ( 83) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX |      |      |      |      |      |      |
#.#9011E+05 ( 78) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX |      |      |      |      |      |      |
#.#9110E+05 ( 63) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX |      |      |      |      |      |      |
#.#9209E+05 ( 47) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX |      |      |      |      |      |      |
#.#9308E+05 ( 41) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX |      |      |      |      |      |      |
#.#9407E+05 ( 26) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX |      |      |      |      |      |      |
#.#9506E+05 ( 29) XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX |      |      |      |      |      |      |
#.#9605E+05 ( 10) XXXXXXXX |      |      |      |      |      |      |      |      |
#.#9704E+05 ( 5)  XXXXXI |      |      |      |      |      |      |      |      |
#.#9803E+05 ( 4)  XXXXI |      |      |      |      |      |      |      |      |
#.#9902E+05 ( 1)  VI    |      |      |      |      |      |      |      |      |
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350 F Tension, Sigma 22

[illegible]

Statistical Representation Experimental Data of T300/976 Material Properties

Room Temperature Shear, Tau 12

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# .1526E+05 ( 8)      |      |      |      |      |      |      |      |
# .1546E+05 ( 8)      |      |      |      |      |      |      |      |
# .1566E+05 ( 8)      |      |      |      |      |      |      |      |
# .1585E+05 ( 8)      |      |      |      |      |      |      |      |
# .1605E+05 ( 8)      |      |      |      |      |      |      |      |
# .1624E+05 ( 2)  x1  |      |      |      |      |      |      |      |
# .1644E+05 ( 8)      |      |      |      |      |      |      |      |
# .1663E+05 ( 8)      |      |      |      |      |      |      |      |
# .1683E+05 ( 24)  xxxxxx|      |      |      |      |      |      |      |
# .1703E+05 ( 38)  xxxxxxxxxxxxxxxxxxxxxxx|      |      |      |      |      |      |
# .1722E+05 ( 55)  xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx|      |      |      |      |      |
# .1742E+05 ( 89)  xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx|      |      |      |      |      |
# .1761E+05 ( 126) xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx|      |      |      |      |      |
# .1781E+05 ( 158) xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx|      |      |      |      |      |
# .1800E+05 ( 162) xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx|      |      |      |      |      |
# .1820E+05 ( 127) xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx|      |      |      |      |      |
# .1840E+05 ( 97)  xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx|      |      |      |      |      |
# .1859E+05 ( 52)  xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx|      |      |      |      |      |
# .1879E+05 ( 35)  xxxxxxxxxxxxxxxxxxxxxxx|      |      |      |      |      |
# .1898E+05 ( 15)  xxxxxxxx|      |      |      |      |      |
# .1918E+05 ( 8)   xxxxx|      |      |      |      |      |
# .1937E+05 ( 3)   xxi|      |      |      |      |      |
# .1957E+05 ( 1)  xi|      |      |      |      |      |
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