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REENTRY VEHICLE NOSETIP STRESS ANALYSIS

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Air Force Materials Laboratory
Wright-Patterson Air Force Base, Ohio

August 1975

AFML-TR-75-76

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SPACE AND MISSILES BRANCH
SYSTEMS SUPPORT DIVISION

AUGUST 1975

TECHNICAL REPORT AFML-TR-75-76

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Clarence A Pratt

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Space and Missiles Branch
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FOR THE DIRECTOR

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER AFML-TR-75-76	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) REENTRY VEHICLE NOSETIP STRESS ANALYSIS		5. TYPE OF REPORT & PERIOD COVERED 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) ROBERT M. JONES AND JOHN R. KOENIG		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS CIVIL AND MECHANICAL ENGINEERING DEPARTMENT SOUTHERN METHODIST UNIVERSITY INSTITUTE OF TECHNOLOGY, DALLAS, TEXAS 75275		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 7381 738102
11. CONTROLLING OFFICE NAME AND ADDRESS AIR FORCE MATERIALS LABORATORY/MXS		12. REPORT DATE August 1975 13. NUMBER OF PAGES 36
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release; Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Graphite, Carbon/Carbon, Composite Materials, Stress Analysis, Orthotropy, Anisotropy, Material Modeling

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The design analysis problems for graphite and carbon/carbon reentry vehicle nosetips in ballistic and maneuvering trajectories are outlined. The ultimate objective is computer programs for prediction of the thermal and mechanical stress behavior of such nosetips. The steps for qualifying computer programs to attain the objective are discussed in the context of necessary laboratory experiments through flight tests. Present nosetip stress analysis computer programs are characterized, and material behavioral characteristics not properly treated are identified. Some of the problem areas are different tensile and (Cont'd)

20. Abstract (cont'd)

compressive moduli; nonlinear orthotropic behavior including biaxial softening (substantially increased strains under biaxial tensile loading opposed to uniaxial loading); macroscopic inhomogeneity and asymmetry of carbon/carbon nosetips; incompletely characterized materials; and inadequate failure criteria. Future nosetip stress analysis capabilities are speculatively predicted.

FOREWORD

This report was prepared under the auspices of the Space and Missiles Branch, System Support Division, Project 7381, "Materials Applications Useful in USAF Weapons Systems," Task 738102, "Space, Missile, and Propulsion Systems Material and Component Evaluation."

This report is based on a presentation at the Conference on Brittle Fracture of Graphites and Carbon/Carbon Composites, Asilomar, Pacific Grove, California, 27 February - 1 March 1973.

This report was prepared by Dr. Robert M. Jones, Consultant to AFML and Associate Professor of Solid Mechanics at SMU Institute of Technology, Dallas, Texas 75275 and Captain John R. Koenig of the Space and Missiles Branch of AFML, now Associate Engineer, Southern Research Institute, Birmingham, Alabama 35205. The report was released by the authors in March 1975. The authors gratefully acknowledge the advice and support of Clarence A. Pratt, project monitor.

TABLE OF CONTENTS

LIST OF FIGURES

1. INTRODUCTION

The stress analysis problems inherent to reentry vehicle nosetip design were discussed in general by Jones [1] in 1967 along with numerous specific problems by other authors in the same conference proceedings volume. Since then nosetip stress analysis technology has been periodically reviewed. In 1970, results of the aborted Graphite Advanced Development Plan were summarized from a stress analysis and material modeling point of view [2]. Shortly thereafter, an extremely valuable interagency conference was held under the auspices of the Atomic Energy Commission [3]. More recently, Schneider et al. [4] described some current thermodynamic and elastic stress analysis procedures for reentry vehicle nosetips.

The objective of this report is to review current reentry vehicle nosetip stress analysis capabilities and to identify material behavior characteristics that are not correctly treated. We ultimately aim to establish the material behavior principles necessary for adequate engineering treatment of reentry vehicle nosetip stress analysis problems. In doing so, we hope to motivate desperately needed research in material behavior phenomena. Also, we will identify many facets of material modeling that must be brought to bear on the problem. Obviously, we cannot define a precise material model now, but we will lay out the path.

In accomplishing this objective, we will first discuss some of the systemic motivations that generate reentry vehicle nosetip stress analysis problems. We will then describe current nosetip analysis capabilities. Next, we will examine some of the current problem areas that have been identified in the past few years. Finally, we will predict some of the nosetip analysis capabilities that we expect to exist within the next five years.

2. SYSTEMIC MOTIVATION

The first category of reentry vehicles that should be described is ballistic reentry vehicles as shown in Fig. 1. Ballistic reentry vehicles are subjected to, if they operate at zero angle of attack, an essentially axisymmetric pressure and temperature state. Therefore, the material properties are axisymmetric if originally they were axisymmetric. In addition, the pressure and temperature loading increases essentially monotonically as we progress along the trajectory. The second category of reentry vehicles is maneuvering reentry vehicles, also shown in Fig. 1. They are subjected to asymmetric pressure and temperature and therefore have asymmetric material properties and asymmetric geometry. In addition, they are subjected to cyclic loading due to maneuvering of the vehicle during flight.

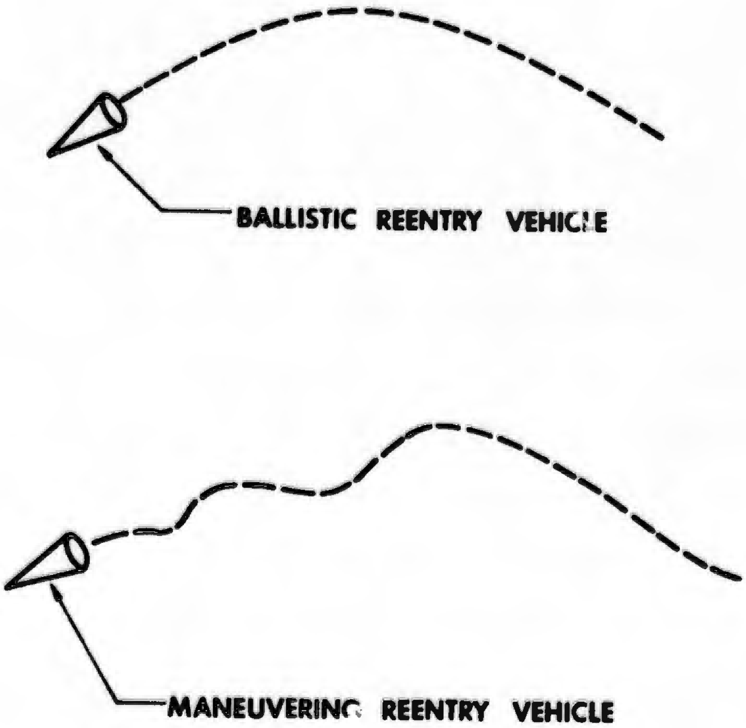

FIGURE 1 BALLISTIC AND MANEUVERING REENTRY VEHICLES

Reentry vehicle nosetips must be designed to meet five major requirements: (1) avoidance of failure due to thermal and mechanical stresses arising from rapid reentry as well as blast loads and maneuvering; (2) avoidance of burn-through due to ablation; (3) accuracy of the vehicle trajectory; (4) hardness against exoatomospheric nuclear encounter; and (5) resistance to particle encounter such as rain, dust, and ice. In this report, we will concentrate on the thermal and mechanical stress problem with some perspective added by discussion of pertinent trends from ablation analysis.

The geometries common for nosetips are shown in Fig. 2. First of all, a shell tip generally has very high thermal stresses because of a thick transition region from the solid body to the shell region. A shell tip is also quite susceptible to burning through because of the thin walls. Thermodynamicists would like as much material as possible in the nosetip to prevent burn-through whereas thermal stress analysts want as little material as possible to avoid thermal stresses. These two diverse and contrasting requirements are the reason for needing very precise prediction capabilities for nosetip design. For example, the design of a shell tip is changed by realigning the internal contour

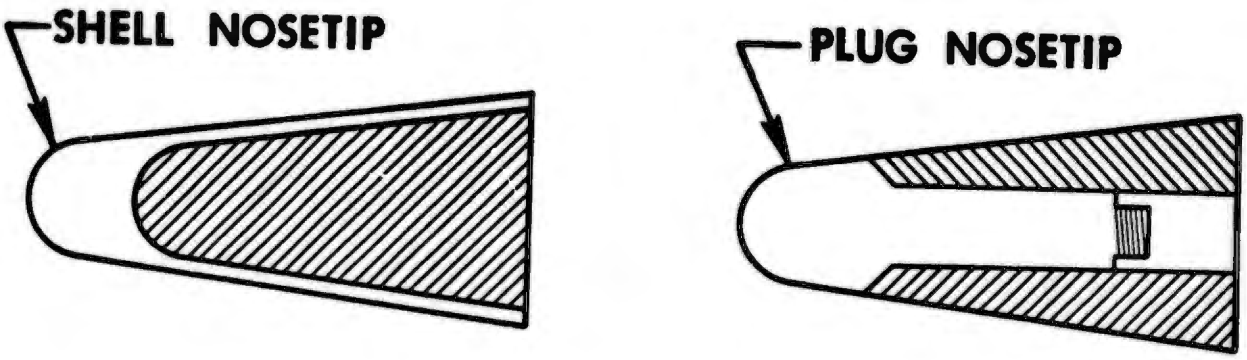

FIGURE 2 NOSETIP GEOMETRIES

as shown in Fig. 2 to lessen the susceptibility to thermal stress failure and, at the same time, not to violate the ablation requirements.

Plug tips are generally subjected to less severe thermal stresses than shell tips. However, shell tips are more effective in resisting side (aerodynamic) loads during manuevering and have higher hardness than plug tips. The capability for redesigning plug tips to survive a trajectory from a thermal stress versus ablation point of view is much wider than for shell tips. For example, with plug tips, we would expect to decrease the exposed length of the plug (the "overhang") to decrease thermal stresses. We might increase the shank diameter (although it is generally fixed by heatshield thickness requirements due to ablation) and simultaneously we might change the angle of the interface between the plug and the heat shield material (carbon phenolic, carbon/carbon, quartz phenolic, etc.) surrounding it.

The principal nosetip materials under consideration are graphites and carbon/carbons. Graphites are macroscopically homogeneous, transversely isotropic, and generally fail in a brittle manner. The stress-strain diagram shown in Fig. 3 is nonlinear to failure. A typical modulus versus temperature relationship is also shown in Fig. 3 wherein the modulus actually increases from its room temperature value until a temperature of about 3500°F is reached and subsequently decreases to nearly zero as graphite approaches sublimation. In addition, at all temperatures, the axial modulus is lower than the modulus in the circumferential and radial directions. On the other hand, carbon/carbon materials are macroscopically inhomogeneous because of large fibers in, for example, the axial direction of the nosetip. These materials can be characterized as orthotropic if the fibers are in orthogonal directions but can be anisotropic when fibers at other than 90° are inserted in the material. Carbon/carbon fails in a progressive manner as shown in the stress-

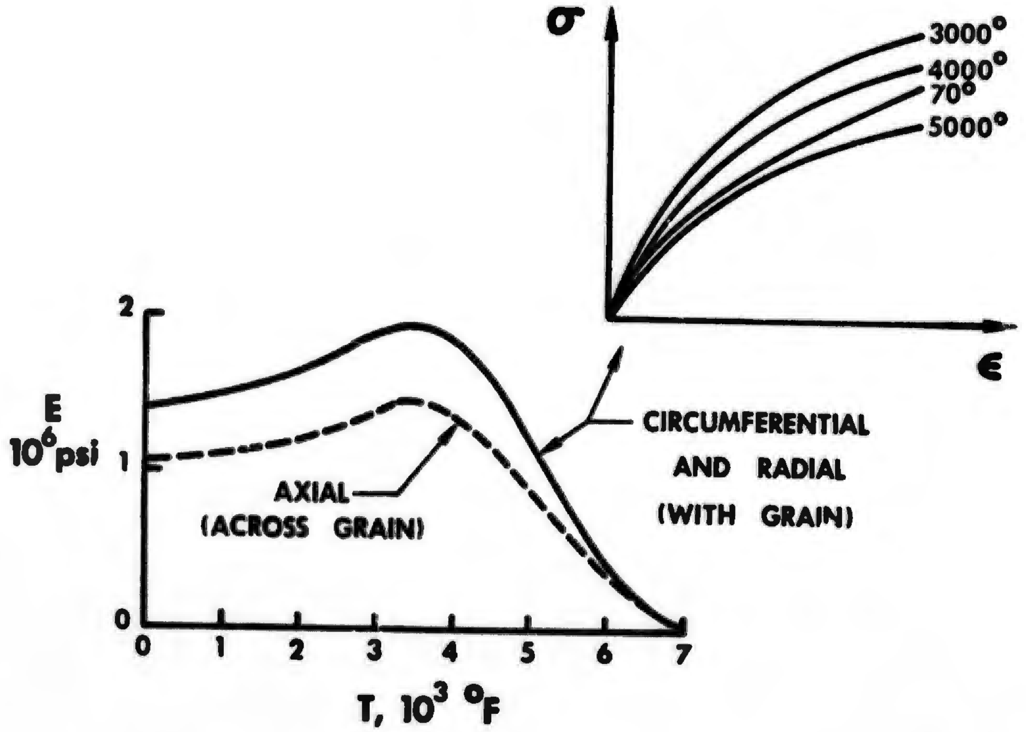

FIGURE 3 TYPICAL GRAPHITE NOSETIP MATERIAL (ATJ-S(WS) in Compression

strain diagram of Fig. 4. In this figure, the material is stressed in the direction of some substantial axial fibers which apparently slip relative to the matrix material as stress is applied. The modulus versus temperature relationship is shown for the circumferential and radial directions in Fig. 4. The three curves shown are interpretations of the same experimental data by different people. Thus, there is considerable disagreement as to the actual modulus versus temperature relationship. Note that the axial modulus for this particular carbon/carbon material is about twice the circumferential modulus. Such a relationship is not unexpected when you realize that there are such large fibers in the axial direction.

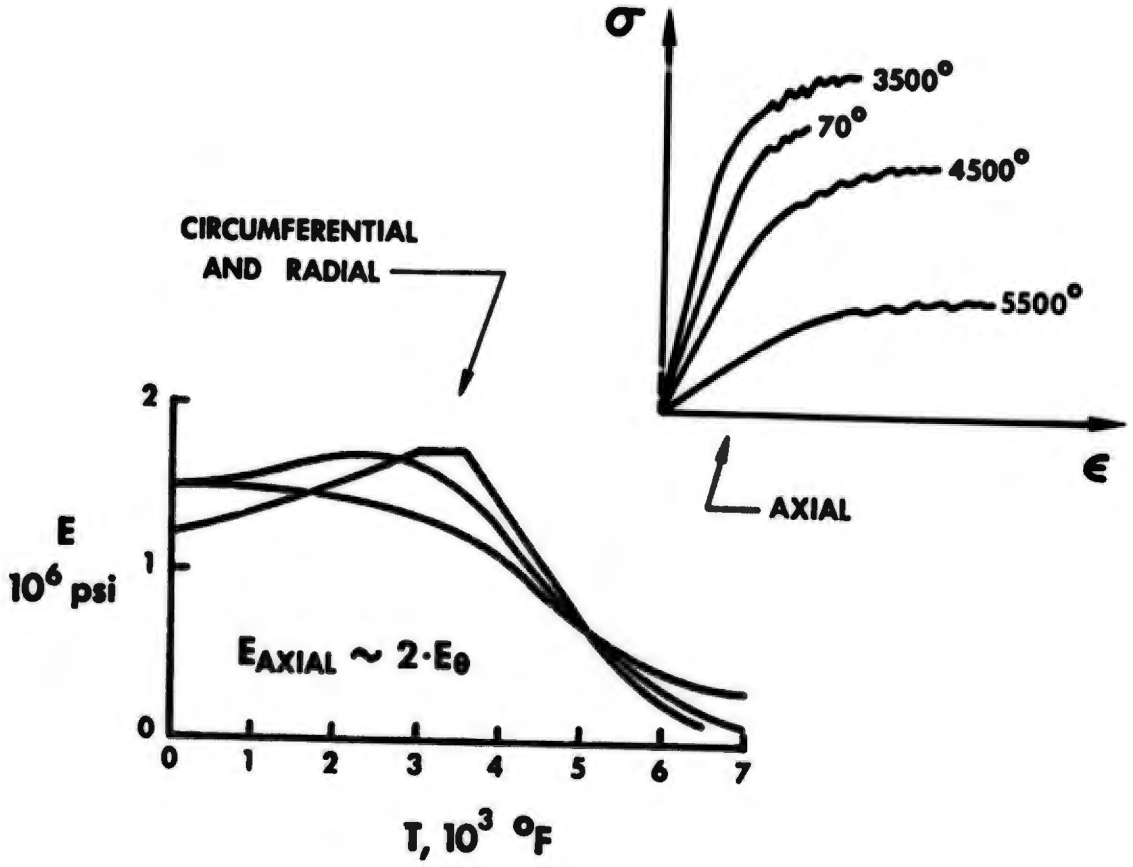

FIGURE 4 TYPICAL CARBON/CARBON NOSETIP MATERIAL (MOD III in Compression)

3. PRESENT ANALYSIS CAPABILITY

The objective of current nosetip stress analysis efforts is to be able to predict the behavior of both graphite and carbon/carbon nosetips in ballistic as well as maneuvering trajectories. In order to accomplish this objective, we must have an appropriate hierarchy of computer programs for use in reentry vehicle development during three phases of design: (1) preliminary design analysis where many parametric studies are made, (2) intermediate design analysis, and (3) final design analysis where we expect all the required characteristics of behavior modeling for a particular system to be taken into account.

The criteria to select computer programs for these three design analysis phases are based on three factors. First, the sophistication of the program (the appropriateness of the material model to the problem). Second, the ease of use which involves the availability of the program, our familiarity with its use, and finally the number of man hours to implement the computer programs. The last factor is the cost of using the computer. The balancing of the three factors is different for each of the three stages of design analysis. For example, crude (i.e., unsophisticated) programs that are easy to use and inexpensive to run would be used in preliminary design analysis. There, the sophistication of problem modeling is sacrificed in order to use programs that require little effort and expense, thereby accomplishing parametric studies for many configurations. In final design analysis, on the other hand, all stops would be pulled out, and the most sophisticated modeling necessary would be used even if the number of man hours for input and the computer cost are both high. The balance of factors for intermediate design analysis is more nebulously defined as being somewhere between the two extremes just discussed. A major point is that only when we know the correct material behavior in detail from having used the most sophisticated programs can we use the simplified programs intelligently. That is, an integrated learning process must be undergone to effectively accomplish a nosetip design.

The interactions that occur in the nosetip design process between the disciplines of materials, thermodynamics, aerodynamics, stress analysis, failure analysis, and design are shown in Fig. 5. Generally, the materials people provide properties to the stress analysts and to the thermodynamicists. The aerodynamicists provide heat rates and pressures to the thermodynamicists and pressures and shears to the stress analysts. In turn, the thermodynamicists provide temperatures to the stress analysts, who are then in a position to determine the stresses and strains in the nosetip. Those stresses and strains are then evaluated with some failure criterion. If the design is judged to be prone to failure, then changes must be made. The first type of change that is usually attempted is specification of a new internal geometry for a shell tip or a new overhang for a plug tip. The thermodynamicists then do their job over again, and so on through another stress analysis and application of the failure criterion. Another possibility in design is that perhaps a new mate-

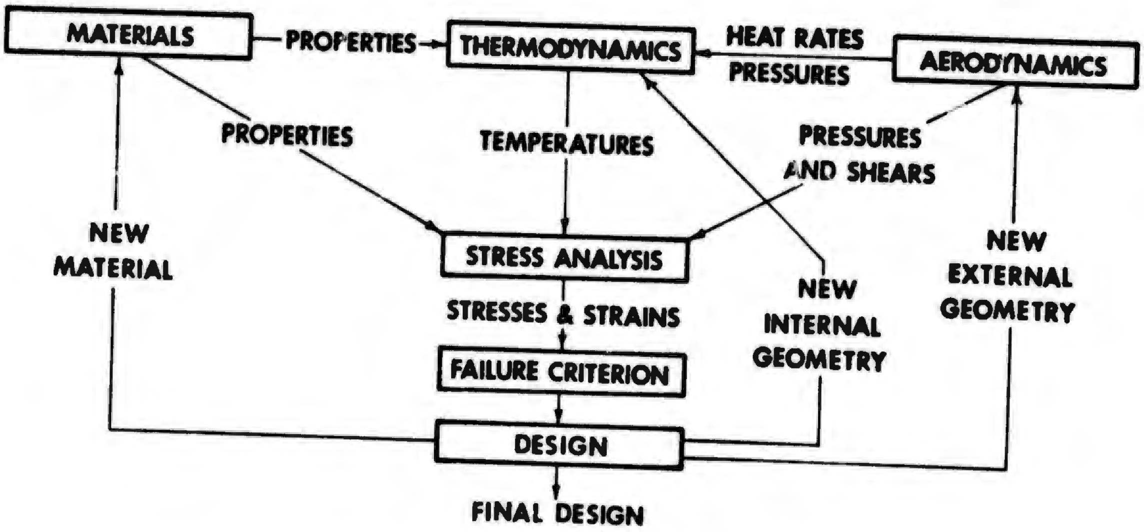

FIGURE 5 DISCIPLINARY INTERACTIONS

rial or a modification of the old material would be judged more suitable for this particular nosetip, and the entire process would start all over again. The final and least likely alternative is that new external geometry (e.g., a new half cone angle or nosetip radius) would be specified and everybody, including the aerodynamicists, would do their job all over again. The net result of cycling through the various interactions shown in Fig. 5 is that an acceptable design is generated. An acceptable design, however, may be quite difficult (and perhaps impossible) to obtain if we have trouble providing enough material to avoid burn-through yet little enough material to avoid excessive thermal stresses.

In order to make nosetip behavior prediction a rational process, we must have appropriate stress analysis tools and failure criteria. We will not discuss further those other disciplines with which we interact; rather, we will emphasize that for the purpose of stress analysis and the overall prediction of nosetip behavior, we must have a prediction tool that is verified by use of simple laboratory tests; complex laboratory tests (uniaxial through biaxial or triaxial tests); proof tests of various types including ground facility tests, such as the Philco-Ford hydrogen-fluorine facility; and on up through flight tests. Thus, we qualify a nosetip behavior prediction tool for the use through an integrated testing and analysis procedure. Only through this procedure can we be confident that we have an adequate prediction tool.

We would like to distinguish between the two types of stress analysis necessary for nosetip materials. The first is a continuum or macromechanical approach wherein the characteristic length of the material, such as the grain size in graphite or the fiber spacing in carbon/carbon, is very much smaller than the dimension over which stresses change rapidly. This type of analysis is more typically applicable to graphites than carbon/carbons because of the obvious relation between the physical characteristics of those materials and their application in nosetips. The second approach is the noncontinuum or micromechanical approach wherein the material characteristic length is about the same order of magnitude as the dimension over which the stresses change rapidly. This type of analysis may be required for carbon/carbon materials.

We have shown a one-sentence description of the nosetip continuum stress analysis problem in Fig. 6. In the braces are listed adjectives in increasing order of complexity as we read down to the highest degree of sophistication believed applicable to the problem. We have boxed in those adjectives that represent our present capability. That is, we can now perform stress analysis of inhomogeneous orthotropic elastic axisymmetric bodies subjected to static axisymmetric thermal and mechanical loads. To a limited extent, we can also consider plastic effects, but not simultaneously with asymmetric bodies under asymmetric loads.

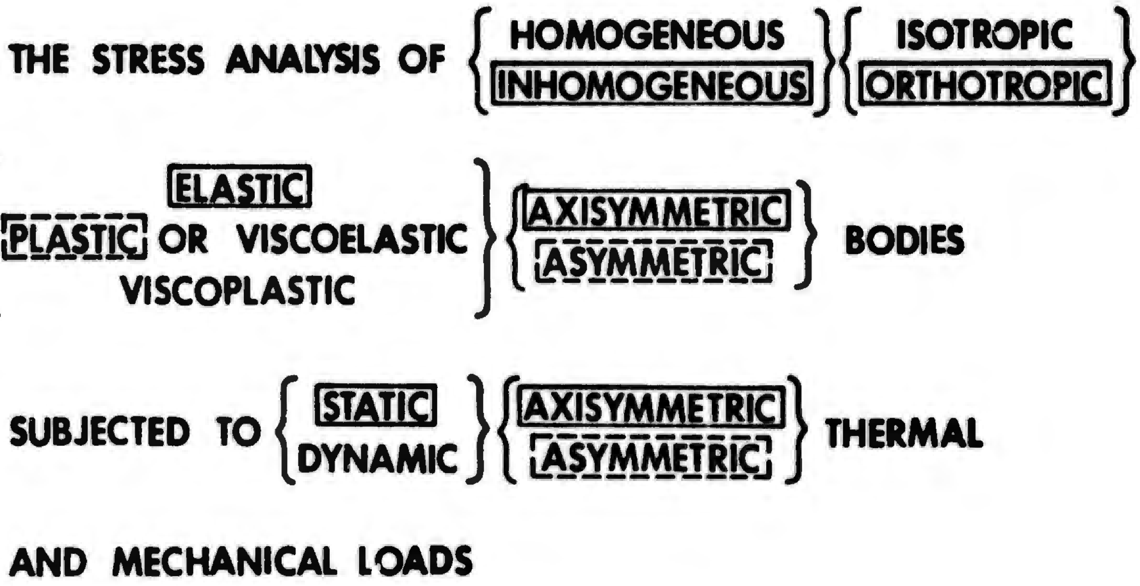

FIGURE 6 NOSETIP CONTINUUM STRESS ANALYSIS

The nosetip noncontinuum stress analysis problem is described by use of the sentence in Fig. 7. There, we have added two new features: first, a two-phase or multiphase material must be treated, and, also, that material might be anisotropic. None of the adjectives are boxed in because no program exists for analysis of a nosetip with more than one material phase. Thus, we have a long way to go to solve the real nosetip noncontinuum stress analysis problem.

The generally available nosetip thermostructural computer programs are listed in Fig. 8 along with their characterization according to material model, type of body, and type of loading. All programs apply to inhomogeneous bodies under static load. The SAAS III program [5] has an elastic material model with an approximate deformation theory of plasticity of an axisymmetric body under axisymmetric load. The SAAS III program is the basis for nosetip stress analysis efforts by most reentry vehicle design contractors. Many contractors modified various versions of SAAS to, for example, automate the changing external boundary of the nosetip during reentry. The DOASIS program [6] has an improved deformation plasticity model over SAAS III for the same type of body

$$\text{THE STRESS ANALYSIS OF} \begin{Bmatrix} \text{TWO-PHASE} \\ \text{MULTIPHASE} \end{Bmatrix} \begin{Bmatrix} \text{HOMOGENEOUS} \\ \text{INHOMOGENEOUS} \end{Bmatrix}$$

$$\begin{Bmatrix} \text{ISOTROPIC} \\ \text{ORTHOTROPIC} \\ \text{ANISOTROPIC} \end{Bmatrix} \begin{Bmatrix} \text{ELASTIC} \\ \text{PLASTIC OR VISCOELASTIC} \\ \text{VISCOPLASTIC} \end{Bmatrix} \begin{Bmatrix} \text{AXISYMMETRIC} \\ \text{ASYMMETRIC} \end{Bmatrix}$$

$$\text{BODIES SUBJECTED TO} \begin{Bmatrix} \text{STATIC} \\ \text{DYNAMIC} \end{Bmatrix} \begin{Bmatrix} \text{AXISYMMETRIC} \\ \text{ASYMMETRIC} \end{Bmatrix} \text{THERMAL}$$

$$\text{AND MECHANICAL LOADS}$$

FIGURE 7 NOSETIP NONCONTINUUM STRESS ANALYSIS

PROGRAM	CHARACTERIZATION		
	MATERIAL MODEL	BODY	LOADING
SAAS III	DEFORMATION PLASTICITY	AXISYMMETRIC	AXISYMMETRIC
DOASIS	DEFORMATION PLASTICITY	AXISYMMETRIC	AXISYMMETRIC
OASIS	INCREMENTAL PLASTICITY	AXISYMMETRIC	AXISYMMETRIC
ASAAS	ELASTIC	ASYMMETRIC	ASYMMETRIC
SAFE 3D	ELASTIC	ASYMMETRIC	ASYMMETRIC

ALL TREAT AN INHOMOGENEOUS BODY UNDER STATIC LOAD

FIGURE 8 AVAILABLE NOSETIP STRESS ANALYSIS PROGRAMS

and the same loading. On the other hand, the OASIS program [7] has an incremental plasticity model for axisymmetric bodies under axisymmetric loads. The ASAAS program [8,9] has an elastic material model for asymmetric bodies (asymmetric material properties, but axisymmetric geometry) under asymmetric loading. The asymmetric material properties of the body are expanded in a Fourier series in the circumferential direction. A more rigorous approach to that very complex problem is given in the version of the SAFE 3-D program adapted for nosetip analysis [10]. The material model there is also elastic for asymmetric bodies built up of tetrahedra under asymmetric loading. Crose and McKinley [11] show that predictions with the ASAAS program agree favorably with SAFE 3-D results and are obtained at much lower cost. General purpose programs such as NASTRAN, ASKA, etc., including other versions of SAFE 3-D, are not set up for nosetips although they do have other important modeling capabilities that could be brought to bear on the nosetip problem. Other nosetip programs are available such as the ROHM & HAAS program, the ORTHOSAFE and ASYM programs of General Electric Reentry Systems Division, the FINE program of Philco-Ford, and the NDAT program of Lockheed Missiles and Space Co.

4. CURRENT PROBLEM AREAS

Numerous problems have arisen in the modeling of the complex response of graphitic materials (graphites or carbon/carbons) during design analysis for various nosetip environments. The choice of graphitic materials for nosetips was based primarily on nonstructural considerations. Moreover, as is often the case, design technology was required before it was "ready". The lack of a design technique was also evident in the lack of criteria by which selection and/or improvement of materials could be accomplished. Programs were started to define the material responses and the implications of the environment in those responses. However, indications of critical areas of study came bit by bit and were incorporated in the overall design procedure. Before discussing these effects in particular, we will address the implications of the dilemma in which this enforced approach has placed us.

Clearly, the predictive computer program, as the mathematical analog of a material, is only as accurate as the model it contains. However, we cannot claim that with each additional effect accounted for, the prediction will be quantitatively more accurate, because other effects, as yet unaccounted for, may be acting in the "opposite direction". This dilemma establishes the need for validation tests under thermal loads. These tests can occur on a laboratory scale where the deformation and/or failure level is measured with precision instrumentation. Or, the tests can involve full-scale simulation in a rocket nozzle exhaust where reentry conditions are approached (but are never achieved!). However, in full-scale tests, the only information determined is the time to failure, i.e., the analysis is required to prove the analysis. With this perspective, we proceed to discuss the different phenomena that are known and must be incorporated in a precise design technology.

4.1 Orthotropic Material Properties

The first area of concern in developing a model for graphitic materials is the generation of basic data in a manner in which the material is "doing its own thing". That is, artificial bias must not be imposed by the testing procedure. Note that the response of both graphite and carbon/carbons under load is the result of complex interactions of elastic straining, tearing mechanisms, matrix flow, a-b plane slip and opening as well as other phenomena. With the orthotropic nature of the material and these mechanisms in mind, we are not surprised that the bulk response of these materials cannot be modeled by classical elastic or elastic-plastic constitutive relations. Therefore, the interpretation of the data derived from tension and compression tests is insufficient to characterize the response.

Great care must be used in interpreting even basic tension and compression data. Two considerations which must be included in the reduction of such data for input to the nosetip behavior program are (1) the model used and its relation to the nature of the loading in real application and (2) the type of test and instrumentation from which the data were derived. For example, in elastic and bilinear elastic-plastic models, compression data should be input not as the data to failure, but only up to a stress-strain level experienced by the nosetip. To attempt to directly use modulus data obtained in a flexure test would be equally erroneous because such data, as classically reduced, contain assumptions of classical elasticity with the same tension and compression behavior. A further example is a nosetip for which the response is sensitive to the Poisson's ratios, i.e., a reasonable range in variations of the Poisson's ratios leads to significant changes in the results of the analysis. Typical Poisson's ratios data are generated on specimens for which the precision of the instrumentation is of the same order as the signal itself. Therefore, higher quality data than presently available must be generated. Moreover, we must truly know the behavior of the material before we can reliably measure its properties.

Variations in reported material properties may be from both real and unreal sources. Examples of unreal sources come very often when the data have been generated at different sources or by inaccurate or inappropriate testing techniques. We must, as a prerequisite to analysis, determine the quality of the data we are using. Real variations can often be minimized by using data from the same billet as the nosetip and, since the number of specimens would then be far too limited, data from the same batch of billets. Eventually, we hope, improved characterization based on microstructural studies and nondestructive testing procedures will aid in determining the correct data to be used. In any case, materials with such complex constituents and processing as graphites and carbon/carbons will have significant variability; limited data packages should be used only for screening and preliminary analysis. Before the nosetip design phase for a selected material, complete characterization must be accomplished and quality control testing must be continued on all new batches of material received.

Another area of major concern at present is the material properties in general. First of all, some engineers are still not convinced that nosetip materials are actually orthotropic and that a principal consequence of the orthotropy is that the various shear moduli are independent of each other and independent of the Young's moduli and Poisson's ratios in a given coordinate system (relations between moduli can be obtained if rotations of, for example, forty-five degrees are made). Moreover, some engineers still don't understand that the Poisson's ratios are independent and not bounded by the value of 1/2. That value of 1/2 is valid only for isotropic incompressible materials. An incompressible orthotropic material does not have Poisson's ratios of 1/2;

moreover, graphite is not an incompressible material. Generally, we must insist that properties be reported in principal material directions instead of at some angle to those directions. We should anticipate that a series of uniaxial, biaxial, and triaxial tests be utilized to characterize materials as elastic, plastic, viscoelastic, or whatever is necessary to adequately describe the material. In the process, we need stress-strain curves to failure over the full range of nosetip operating temperatures.

4.2 Different Moduli in Tension and Compression

Many nosetip materials exhibit different elastic moduli in tension than in compression, as shown in Fig. 9. The nonlinear stress-strain curve has essentially different slopes under tensile stresses than under compressive stresses. Note that the actual behavior is continuous through a zero stress level, but, given the requirement to have a simple stress-strain curve in a computer program, use of bilinear model does require different tension and compression moduli. For graphites, we find that the differences between the tension and compression moduli are about ±20%. For carbon/carbons, a very realistic appraisal of the difference between tension and compression moduli

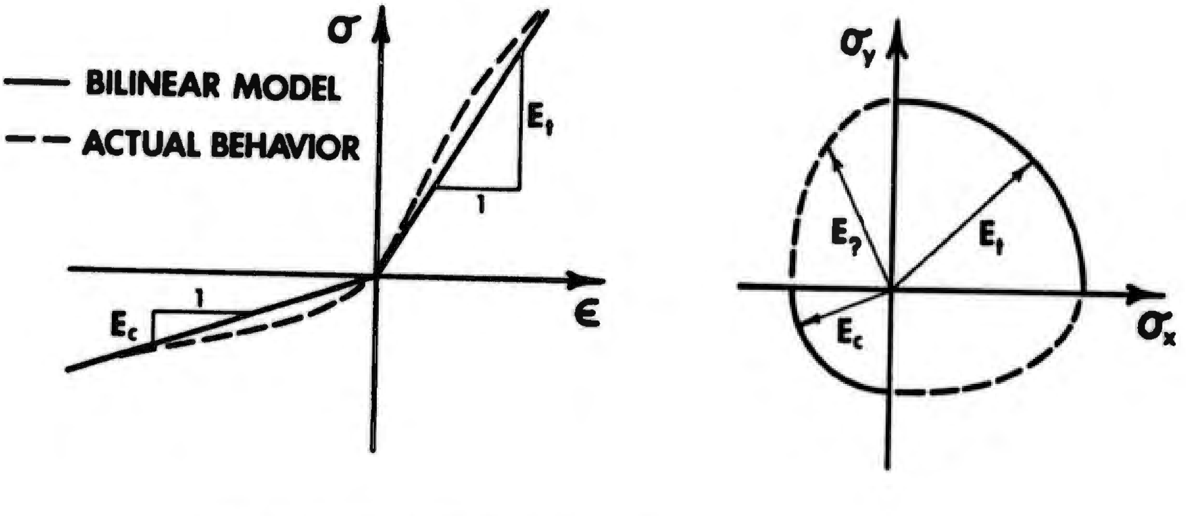

FIGURE 9 DIFFERENT MODULI IN TENSION AND COMPRESSION

may be on the order of a factor of two. Some data are reported wherein differences of up to factors of three to five occur.

One of the many problems involved in analyzing materials with different moduli in tension and compression is not very well illustrated by the simple uniaxial stress-strain curve on the left of Fig. 9. On the right is a sketch of a biaxial stress plot where in the all-tension quadrant we can easily appreciate that the tension modulus must be used. However, in the mixed tension and compression stress state, we really don't know what modulus to use; perhaps more importantly, we don't know what Poisson's ratios to use. That is, the problem is generally one in which we are faced with an orthotropic material under a multiaxial stress state, and the moduli depend on the stress level in an unknown manner. Models for materials with different moduli in tension and compression are discussed by Jones [12] and by Crose and Jones [5].

4.3 Nonlinear Orthotropic Behavior of Graphite

Graphite exhibits nonlinear orthotropic behavior as shown in Fig. 10. Weng [3] obtained a stress intensity - strain intensity relation that passes through experimental data for uniaxial and biaxial loading. Because the material is orthotropic, the dilatation or expansion of the material cannot take place without distortion and vice versa. Therefore, the imposition of a hydrostatic pressure changes the yield stress of the material; this behavioral phenonmenon renders classical plasticity invalid for use with graphites.

A more recently identified characteristic of graphites is called "biaxial softening." In Fig. 11, a stress-strain curve obtained under uniaxial loading is sketched alongside a stress-strain curve obtained under biaxial loading. For the same stress level, the strains are much larger for the biaxial stress state than for the uniaxial stress state. Ordinarily, with the usual Poisson effects, we would expect the biaxial curve to fall to the left of the uniaxial

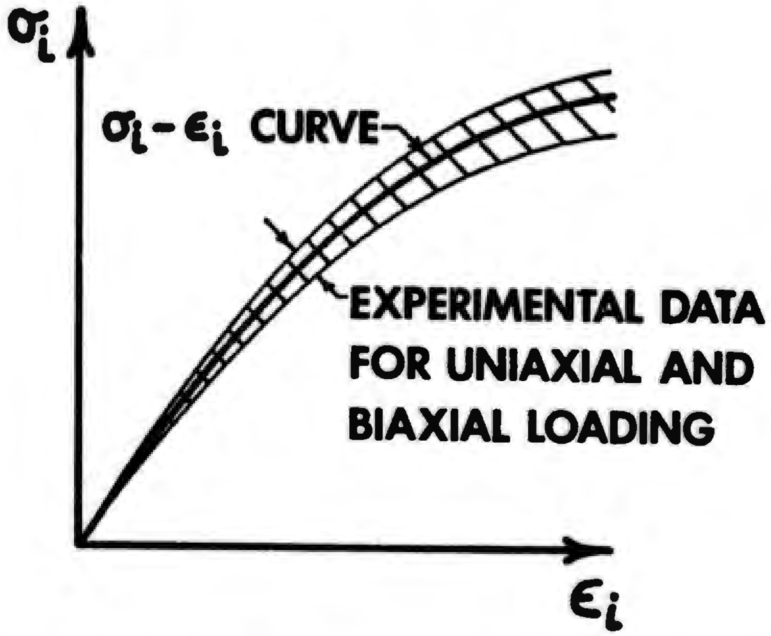

FIGURE 10 NONLINEAR ORTHOTROPIC BEHAVIOR OF GRAPHITE

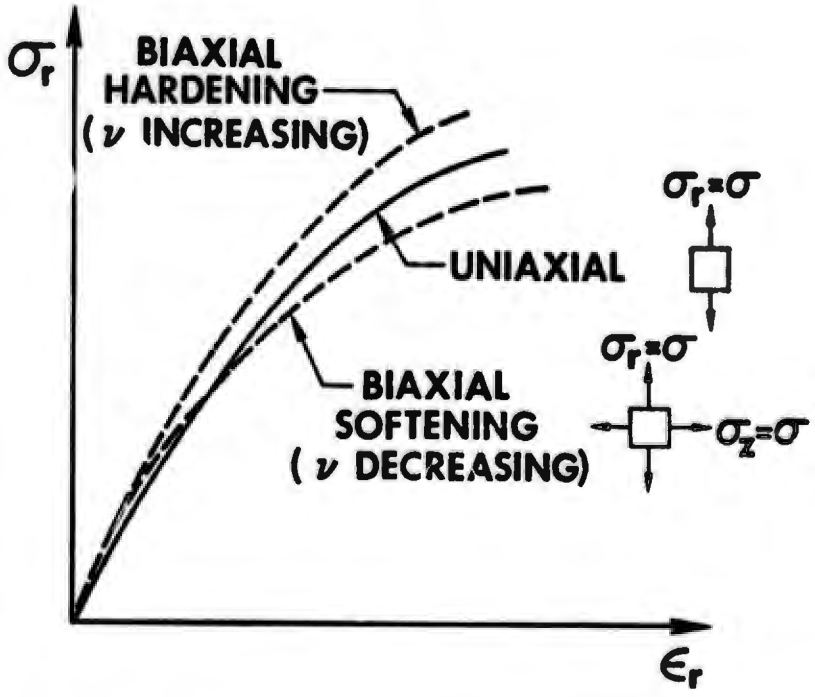

FIGURE 11 BIAXIAL SOFTENING OF GRAPHITE

curve. This behavioral phenomenon (which, strictly speaking, should be called "multiaxial softening") is attributed to plastic volume change due to microcracking or tearing. The fact that a plastic volume change occurs is another reason for rejecting classical plasticity theory for graphites.

Another way of looking at the biaxial softening problem is shown in Fig. 12 where biaxial strain states are plotted for hollow tubular ATJ-S graphite specimens loaded at 70°F [13]. In all cases, the maximum principal stress is 3,550 psi. The experimental data are denoted by open circles and are connected by straight lines for various stress ratios. The SAAS II computer program [14] was used to evaluate the strains under a very similar maximum principal stress state (3,500 psi), but note that the predicted strains are much less than the measured strains. In fact, the actual strains are nearly 30% higher than the SAAS II prediction in which a bilinear approximation to the nonlinear behavior was used and, perhaps more important, in which an inappropriate yield function was used. The intermediate result using superposition of uniaxial stress-strain data is only an approximation to the real behavior and would not be expected to agree with the experimental data.

Other possibly relevent material characteristics which should be, and to some extent are being, addressed include (1) the effect of rapid heating on overall material response, (2) the effect of stress state on free expansion, and (3) the inaccuracy inherent to applying deformation theories of plasticity to what is more correctly an incremental problem.

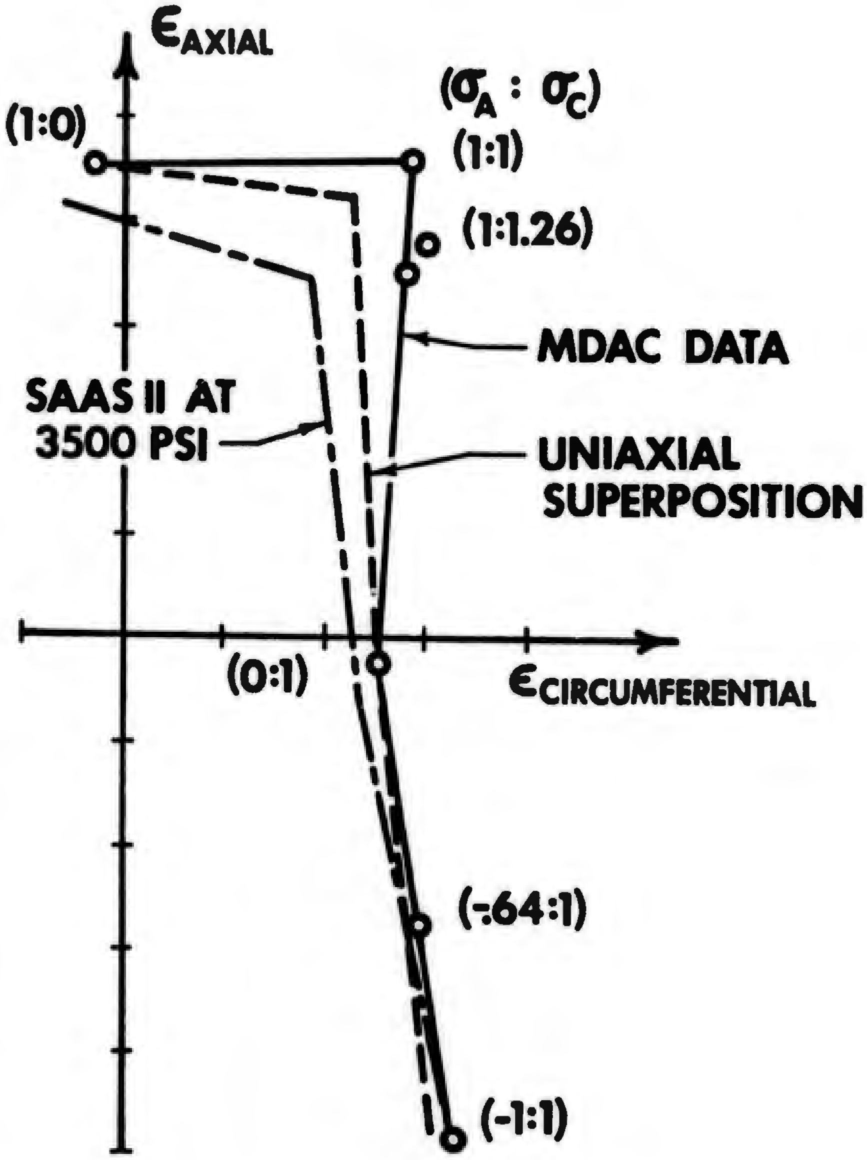

FIGURE 12 BIAXIAL SOFTENING RESULTS FOR ATJ-S GRAPHITE

4.4 Carbon/Carbon Nosetips

Carbon/carbon nosetips are made in both shell and plug styles. A typical plug nosetip is shown in Fig. 13. This type of nosetip has been examined for thermal stress resistance in the Philco-Ford hydrogen-flourine facility [15]. Note that this particular nosetip has large axial fibers that you can detect as the multiple streaks at the very tip of the nose. Obviously, carbon/carbon nosetips are macroscopically inhomogeneous. We also see from the pattern of axial reinforcement that we could not describe the material as axisymmetric. Moreover, the stress field is discontinuous because of the large axial fibers. Thus, if we use an axisymmetric nosetip stress analysis, we predict grossly averaged stresses. Accordingly, we might require a three-dimensional finite element stress analysis program for micromechanical stress analysis, although perhaps a combination of a two-dimensional program and a three-dimensional program or a pseudo-three-dimensional program such as ASAAS [8] might suffice.

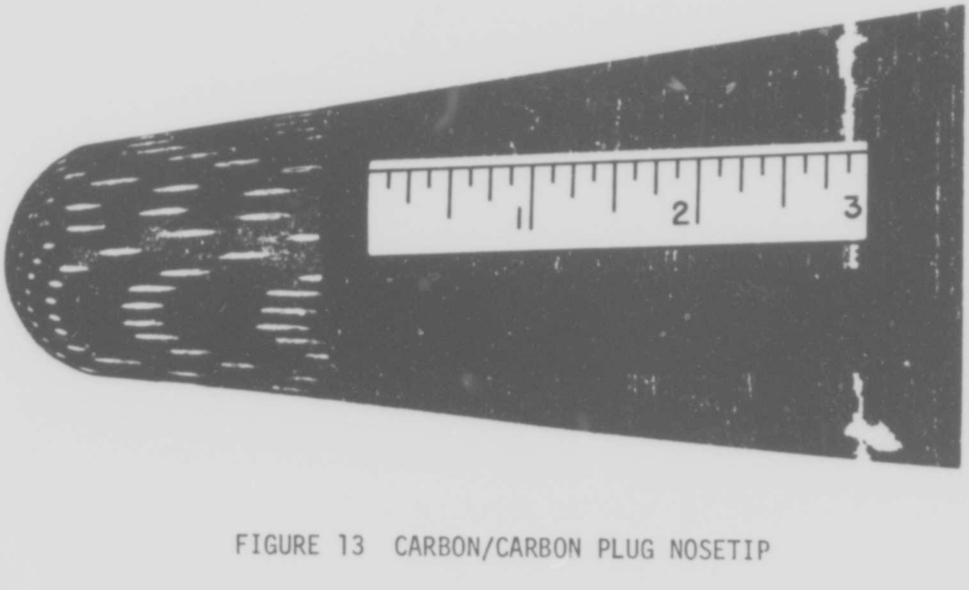

FIGURE 13 CARBON/CARBON PLUG NOSETIP

Another facet of carbon/carbons is their drastically different tension and compression moduli. Moreover, currently, the general material property characterization is quite inadequate; recall Fig. 4 where the modulus versus temperature relationship was interpreted in three different fashions from the same data. Thus, carbon/carbon design analysis technology is in its infancy. Another interesting problem associated with carbon/carbon nosetips is that for short tension specimens in the axial direction of the nosetip material, the fibers will actually pull out if the specimens are less than about eight inches long. However, nosetips are much less than eight inches long. Accordingly, the stress gradients are very severe and are accompanied by a difficult-to-represent physical mechanism for fiber motion relative to the matrix.

4.5 Failure Criteria

Failure criteria are yet another significant problem area. Two types of failure occur for nosetips. First, instantaneous failure is typified by graphite; almost every crack that reaches a critical length is catastrophic since it propagates in an essentially instantaneous manner. Such cracks propagate either completely through the tip or to some degree than renders the tip most unlikely to survive subsequent loading. The other type of nosetip failure is a progressive failure; that is, the cracking is not catastrophic immediately, but the cracks can progress with time to cause failure of the nosetip. Also, progressive failure cracks degrade the material's capability to endure subsequent loading. Progressive failure is often exhibited by carbon/carbons.

Several methods exist for predicting instantaneous failure: a maximum principal stress or strain criterion, a generalized distortional energy theory (although orthotropic materials generally have distortional energy coupled to dilatational energy) commonly referred to as the Tsai-Hill Theory [16], and, finally, a tensor failure theory such as the Tsai-Wu theory [17]. The methods of predicting progressive failure generally involve fracture mechanics to study the initiation and propagation of cracks in a nonhomogeneous material.

All failure theories require the generation of data which are currently obtained in a stress loading test. However, the thermal stress state in a nosetip actually leads to deformation loading. Thus, techniques must be found to account for this very real distinction. Also, failure theories with multi-dimensional failure surfaces might prove useful in an engineering sense when suitable data are available to confirm them for nosetip materials. However, such failure theories are usually based on a continuum assumption rather than on a description of the actual complex nature of the material. Moreover, a failure criterion established for "mean" failure cannot necessarily be extrapolated to a high confidence level based on statistical distributions of uniaxial data. That is, the multi-dimensional criterion may vary with the failure probability level.

Progressive failure is more difficult to describe quantitatively than instantaneous failure because both the loading behavior and failure surface are functions of time (and perhaps thermochemical reactions) as well as of stress-strain-temperature relations. Such a phenomenological description is far too complex for the current state of technology (and for the economic resources available for the problem). Thus, an engineering solution will most likely come from a fracture mechanics approach based on limiting assumptions of the imposed loading during reentry.

4.6 Material Model - Failure Criterion Interaction

An interesting interaction exists between the material model used and the failure criterion applied. For example, a few years ago when we performed only elastic analyses, we typically used a strain-based failure criterion. A linear-elastic stress-strain curve is sketched as a dashed line in Fig. 14

along with a solid curve that more accurately represents a typical graphite. Note that the over-predicted stresses lead to unnecessarily conservative failure predictions. However, if we use the maximum strain failure criterion, we will generally be in about the correct ballpark for failure of the material, despite our inaccurate stress prediction. On the other hand, if we are able to use a plastic analysis, we will follow the actual nonlinear stress-strain curve and predict more accurate stresses. Therefore, in such cases, a stress-based failure criterion is reasonable. Finally, for an analysis in which a zero plastic volume change is inherent, we know we cannot predict the strains very accurately and must use a stress-based failure criterion. However, the current stress-to-failure data are much more consistent than the strain-to-failure data. This factor may also influence whether a stress- or a strain-based failure criterion is used in future design analysis.

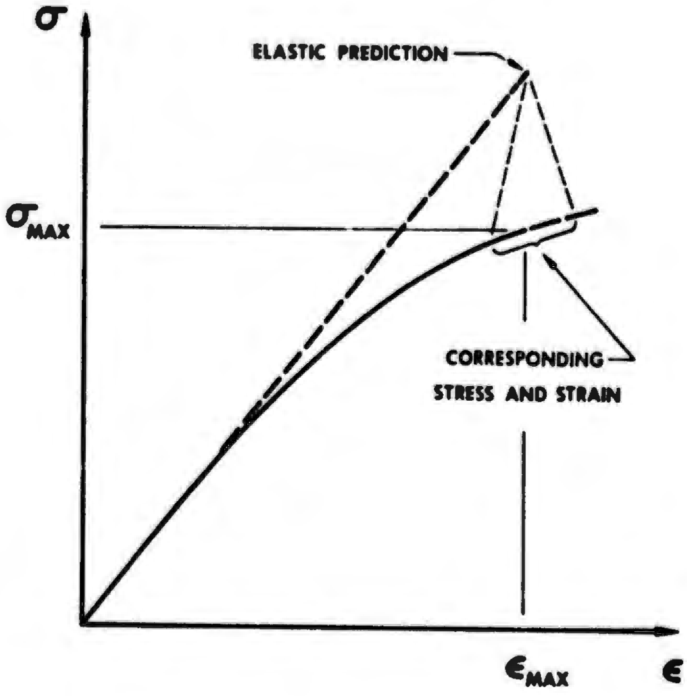

FIGURE 14 MATERIAL MODEL - FAILURE CRITERION INTERACTION

5. FUTURE CAPABILITIES

Most of the problem areas we just discussed will presumably have adequate engineering treatments, if not scientifically acceptable explanations, within the next few years. Currently, research is being done in the area of biaxial softening and nonlinear behavior of graphites. Efforts to define the behavior of composite materials with different moduli in tension and compression are also underway. Exploratory studies are in progress for definition of the many problems associated with understanding and design analysis of carbon/carbon nosetips. Many efforts, sponsored and informal, are being conducted to define effective failure criteria. Across the board, there is an effort to upgrade the understanding of the materials we are trying to use.

Sometime in the near future, perhaps within five years, we anticipate the availability of three-dimensional finite element stress analysis computer programs with very sophisticated material models. These material models will have multiple phases (i.e., a micromechanical approach), incremental nonclassical plasticity, and maybe even strain-rate dependent effects. The stresses predicted with such a program will somehow be coordinated, we presume, with fracture mechanics analysis of multiphase materials wherein both initiation and propagation of a crack with time during the trajectory will be predicted.

6. CONCLUDING REMARKS

In this report, we have been able to clearly identify that if a new class of reentry vehicles and/or a new class of materials is introduced, important new classes of complicated stress analysis and failure problems often simultaneously arise and must be resolved. In addition, our present analysis capability for reentry vehicle nosetips is inadequate for today's problems, much less tomorrow's.

Many new problem areas have been identified such as different tension and compression moduli, nonlinear orthotropic behavior including biaxial softening, carbon/carbon inhomogeneities, and inadequate failure criteria. Efforts are currently underway to obtain an engineering understanding of these phenomena. However, many of the efforts are somewhat fragmented; more interagency cooperation is essential to effectively resolve the very difficult nosetip stress analysis problem. We believe the near future holds three-dimensional finite element stress analysis programs for complex material behavior, including crack propagation. These programs will be used not only in the final design analysis stage, but will also be used to enable intelligent application of less sophisticated computer programs at earlier stages of design analysis.

In order to attain the objective of predicting nosetip behavior, we must have (1) closely integrated testing and analysis programs to characterize the nosetip materials and (2) a rational nosetip design analysis procedure. We must have a rational design analysis procedure because flight tests yield only "go" or "no go" information and hence very little actual nosetip behavior information. That is, flight tests cannot tell us <u>how</u> to <u>redesign</u> a nosetip to survive a specified environment. Redesigning a nosetip to satisfy various goals requires an accurate design analysis procedure; only a design analysis tool has a rationale for redesign. If we change the trajectory or the nosetip configuration, flight tests have to be done all over again; but the ground-based rational design analysis procedure will automatically account for such changes. Of course, a series of flight tests can reveal many points of a specific parameter - performance relationship. However, design analysis efforts are orders of magnitude less costly and have an overwhelming advantage of providing information on geometries and materials vastly different from those flown on necessarily specific flight tests. Thus, the development of rational design analysis procedures for nosetips is imperative.

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