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METCAN - THE METAL MATRIX COMPOSITE ANALYZER

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ABSTRACT

Metal matrix composites (MMC) have recently been the subject of intensive study and are receiving serious consideration for critical structural applications in advanced aerospace systems. The routine application of MMC in aerospace structures will evolve as concurrent developments progress in related areas of processing and fabrication, experimental mechanics, and computational structural analysis and design methodologies. This presentation concerns recent research efforts related to the latter aspect, namely, MMC analysis and design.

Predicting the mechanical and thermal behavior and the structural response of components fabricated from MMC requires the use of a variety of mathematical models. These models, for example, relate stresses to applied forces, stress intensities at the tips of cracks to nominal stresses, buckling resistance to applied force, or vibration response to excitation forces. The models just mentioned require initial tangent and strain-dependent stress-strain relationships. Experimental data indicate that the stress-strain responses of unidirectional MMC are (1) slightly nonlinear in the longitudinal direction, (2) mildly nonlinear in the transverse direction, and (3) highly nonlinear in intralaminar shear. In-service loads on MMC structures can generally be expected to strain the metal matrix nonlinearly. The stress-strain relationships for a laminate may then become load-path dependent, and hence it is important to be able to track the composite behavior throughout its load history. Moreover, the mechanical performance and structural integrity of MMC are ultimately governed by the behavior of the constituents at a local level. In general this behavior is dynamic because of various nonlinearities associated with, for example, (1) large local stress excursions, (2) temperature-dependent material properties, (3) time-dependent effects, and (4) constituent chemical reactions. It is important also then to be able to track behavior at the local level.

This presentation describes the extensive research in computational mechanics methods for predicting the nonlinear behavior of MMC. This research has culminated in the development of the METCAN (metal matrix composite analyzer) computer code.

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OVERVIEW OF STRUCTURAL ANALYSIS

The process of structural analysis can be viewed simplistically as the solution of pertinent governing equations to arrive at estimates of important response variables that are usually of interest in comparison with some limiting values. This is summarized below, where the matrix notation implies solution by a discrete numerical technique such as the finite element method. Nonlinear problems are commonly approached by using a piecewise linear approximation in which the solution becomes an incremental or iterative process. Unique aspects associated with the analysis of a composite structure derive from the additional models required (1) to arrive at a description of the structure characteristics and (2) to determine the localized response, which becomes important for these systems. The additional models are collectively referred to as composite mechanics.

**SYSTEM
EQUATIONS
OF
MOTION**

$$[M] \{\ddot{u}\} + [C] \{\dot{u}\} + [K]\{u\} = \{F(t)\}$$

$$\{u\} \leq \{u_A\}$$

**CONSTITUTIVE
EQUATION**

$$\{\sigma\} = [D][B]\{u\}$$

$$\{\sigma\} \leq \{S_A\}$$

**NATURAL
FREQUENCY
EIGENPROBLEM**

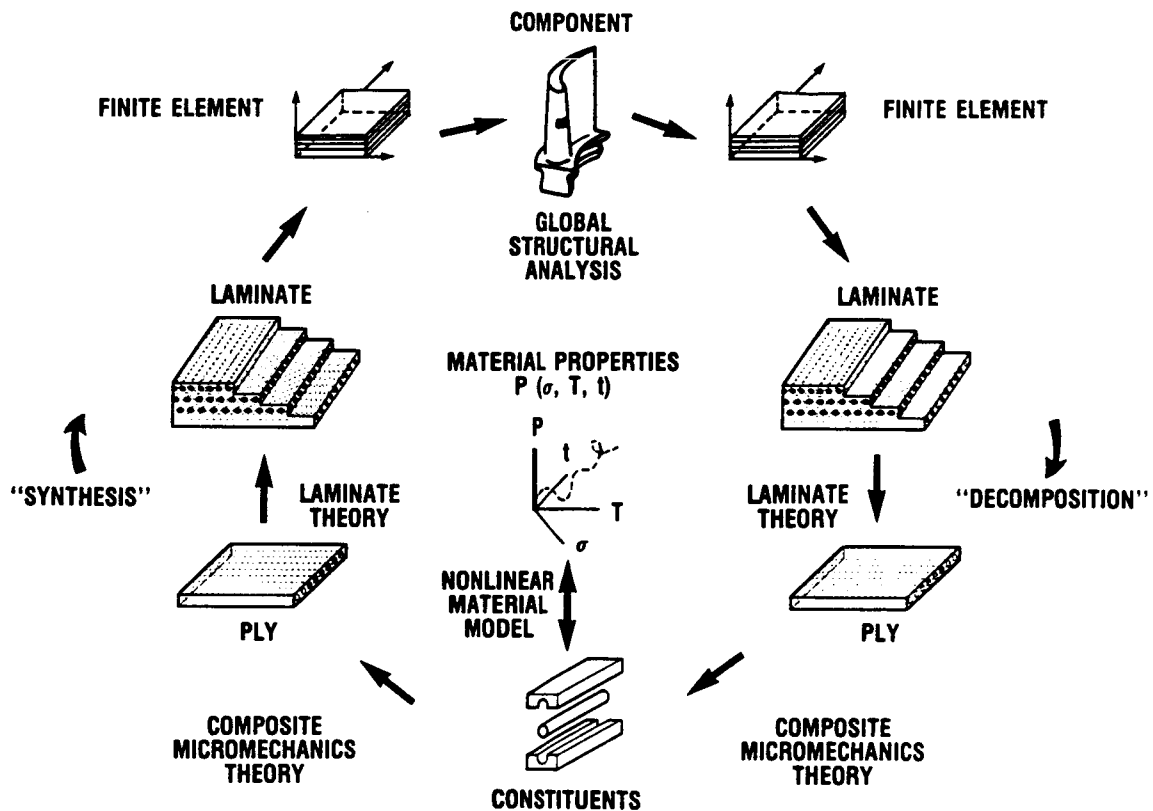
$$([K] - \omega^2[M])\{u\} = \{0\}$$

$$\omega \leq \omega_A$$

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INTEGRATED APPROACH TO METAL MATRIX COMPOSITE ANALYSIS

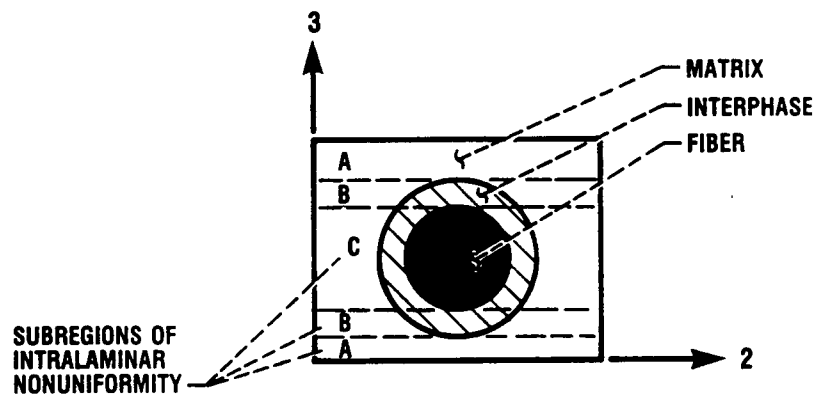
The integrated approach implemented in the METCAN computer code is illustrated in the figure. The cyclic arrangement defines the computational effort for each load increment. Material nonlinearity is treated at the constituent (fiber, matrix, interphase) level, where the current material model describes a time-temperature-stress dependence of a constituent's mechanical and thermal properties at any instant in its "material history space." Characteristic properties of the composite, at the various levels of simulation, are approximated from the instantaneous constituent properties by composite mechanics. This process, termed "synthesis" here, results in a point description of "equivalent pseudo-homogeneous" properties for the composite. These properties could be used, for example, to specify elemental properties for a subsequent global structural analysis by the finite element method. In the reverse or "decomposition" process, global response variables are "decomposed" into localized response, again at the various levels of simulation. The METCAN code, at this point, does not incorporate the global structural analysis capability, and hence "a priori" load histories are specified as part of the input to the code.



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COMPOSITE LOCAL BEHAVIOR AND RESPONSE

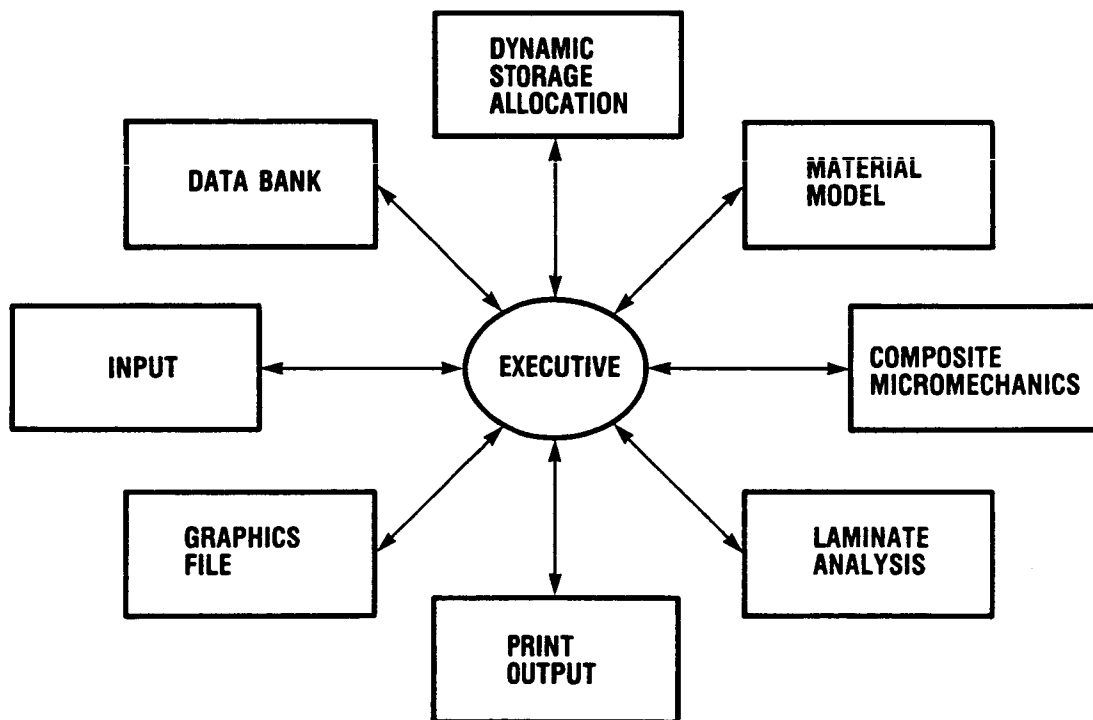
A unique feature of the METCAN computer code is its treatment of the interphase as a separate constituent. This is an important consideration for metal matrix composites in high-temperature applications where the fiber and the matrix may chemically react, forming an interphase. At the most local level constituent behavior and response variables are tracked in the three intralaminar subregions illustrated in the figure.



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MODULAR STRUCTURE OF METCAN

In developing the METCAN computer code priority has been placed on maintaining a modular software structure and providing a user-friendly interface. The code features include (1) a dynamic storage allocation scheme for efficient use of computer resources, (2) a resident data bank of constituent material properties, (3) user-selective control of primary (printed) output, (4) generation of a secondary output file for subsequent graphics postprocessing, and (5) both interactive and batch modes of operation.



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METCAN CURRENT AND FUTURE CAPABILITIES

The current capabilities of the METCAN computer code provide for most of the essential aspects of metal matrix composite analysis and design. The code also serves as a framework within which future capabilities will be developed. The current and planned future capabilities are summarized below.

- **SIMULATED BEHAVIOR AND RESPONSE**
 - MECHANICAL PROPERTIES**
 - THERMAL PROPERTIES**
 - STRESSES AND STRAINS**
 - MICROSTRESSES**
 - FRACTURE STRESSES**
 - FINITE ELEMENT COMPATIBILITY**
- **LOAD AND EFFECT**
 - MONOTONIC LOAD HISTORIES**
 - CYCLIC LOAD HISTORIES**
 - * **INTERPHASE PROPERTIES AND GROWTH**
 - * **STEADY-STATE CREEP**
 - * **THERMAL RATCHETTING**
 - * **CREEP RUPTURE**
 - * **DAMAGE**
 - * **THERMAL SHOCK**
 - * **IMPACT LOADING**

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UNIDIRECTIONAL GRAPHITE/COPPER MMC PROPERTY PREDICTIONS

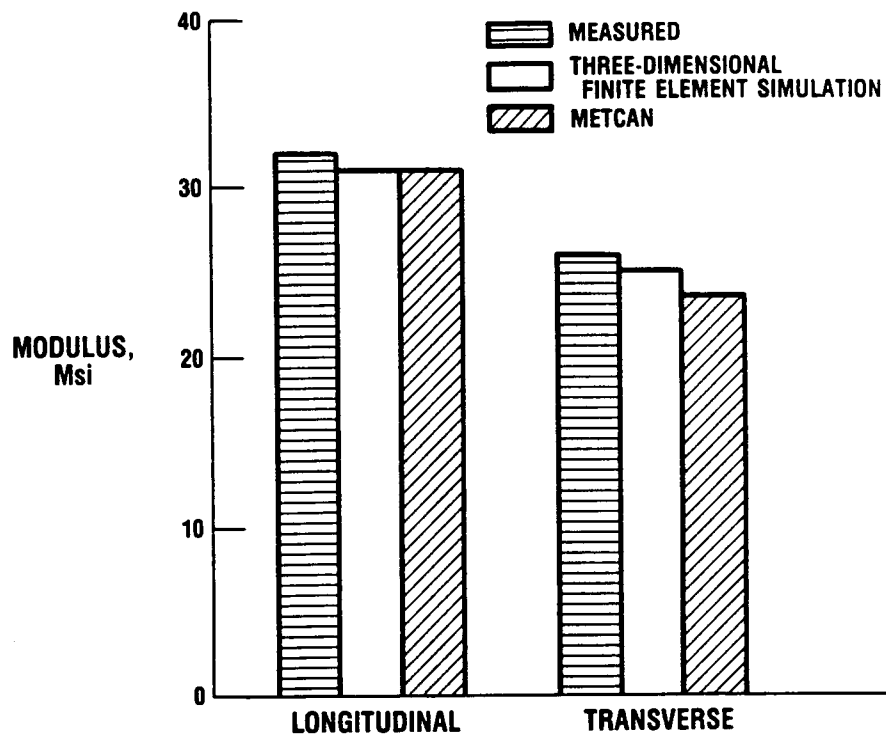
A fairly comprehensive summary of the mechanical and thermal properties for a unidirectional graphite/copper metal matrix composite at several fiber volume fractions is given in the table. The properties were determined (1) by using the METCAN computer code and (2) from a detailed three-dimensional finite element analysis in which both the fiber and the matrix were modeled discretely. The METCAN-predicted properties, based on the simplified composite mechanics equations, show excellent agreement overall with the finite-element-simulated properties.

PROPERTY	FIBER VOLUME FRACTION, PERCENT					
	22.3		46.6		62.2	
	METCAN	FINITE ELEMENT	METCAN	FINITE ELEMENT	METCAN	FINITE ELEMENT
E ₁₁ , Msi	37.3	36.7	58.4	58.0	72.0	71.8
E ₂₂ , Msi	10.2	---	6.5	---	4.6	---
E ₃₃ , Msi	10.2	11.0	6.5	6.9	4.6	5.0
G ₁₂ , Msi	4.5	4.8	3.2	3.4	2.5	2.6
G ₂₃ , Msi	4.2	4.5	2.8	2.7	2.1	1.8
G ₁₃ , Msi	4.5	---	3.2	---	2.5	---
ν ₁₂ , in./in.	0.28	0.30	0.25	0.29	0.24	0.28
ν ₂₃ , in./in.	0.30	0.26	0.30	0.22	0.30	0.19
ν ₁₃ , in./in.	0.30	---	0.30	---	0.24	---
α ₁₁ , ppm	3.0	3.7	0.83	1.40	0.09	0.42
α ₂₂ , ppm	9.6	10.9	9.4	11.1	9.2	10.9
α ₃₃ , ppm	9.6	---	9.4	---	9.2	---
K ₁₁ , Btu in./°F hr in. ²	20.6	---	22.0	---	22.8	---
K ₂₂ , Btu in./°F hr in. ²	20.4	---	21.7	---	22.6	---
K ₃₃ , Btu in./°F hr in. ²	20.4	---	21.7	---	22.6	---

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UNDIRECTIONAL BORSIC/TITANIUM MMC PREDICTED MODULI

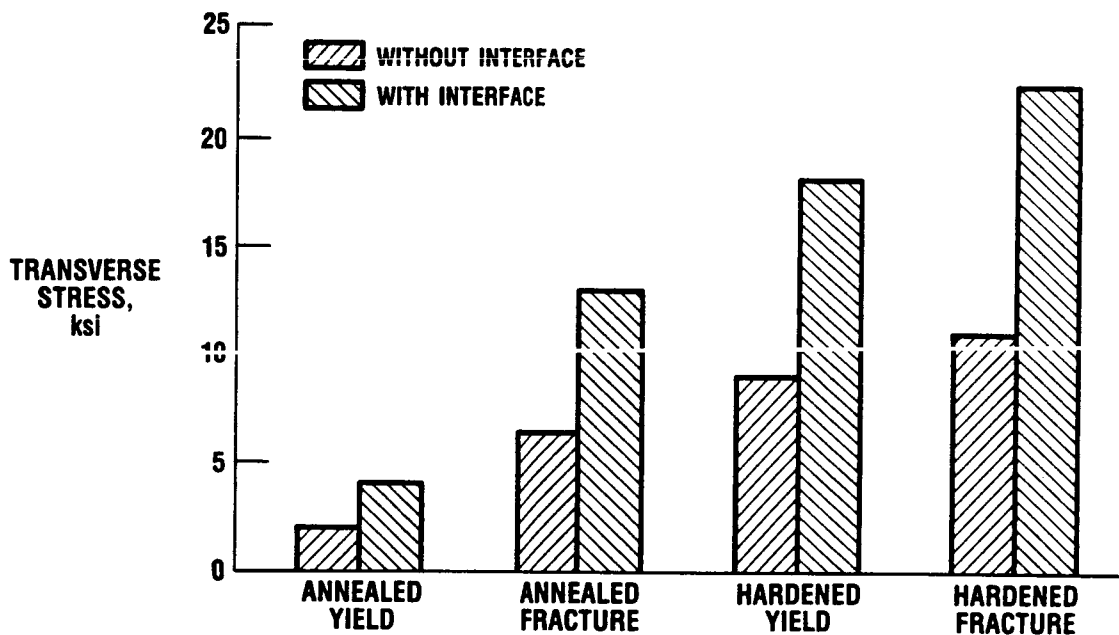
An example of the METCAN computer code's capability for predicting composite material properties is illustrated in the figure. The results shown are the longitudinal and transverse moduli for a unidirectional borsic/titanium metal matrix composite. The results demonstrate an excellent agreement between METCAN predictions, detailed three-dimensional finite element simulations, and experimentally measured values.



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UNIDIRECTIONAL GRAPHITE/COPPER MMC TRANSVERSE STRENGTH BOUNDS

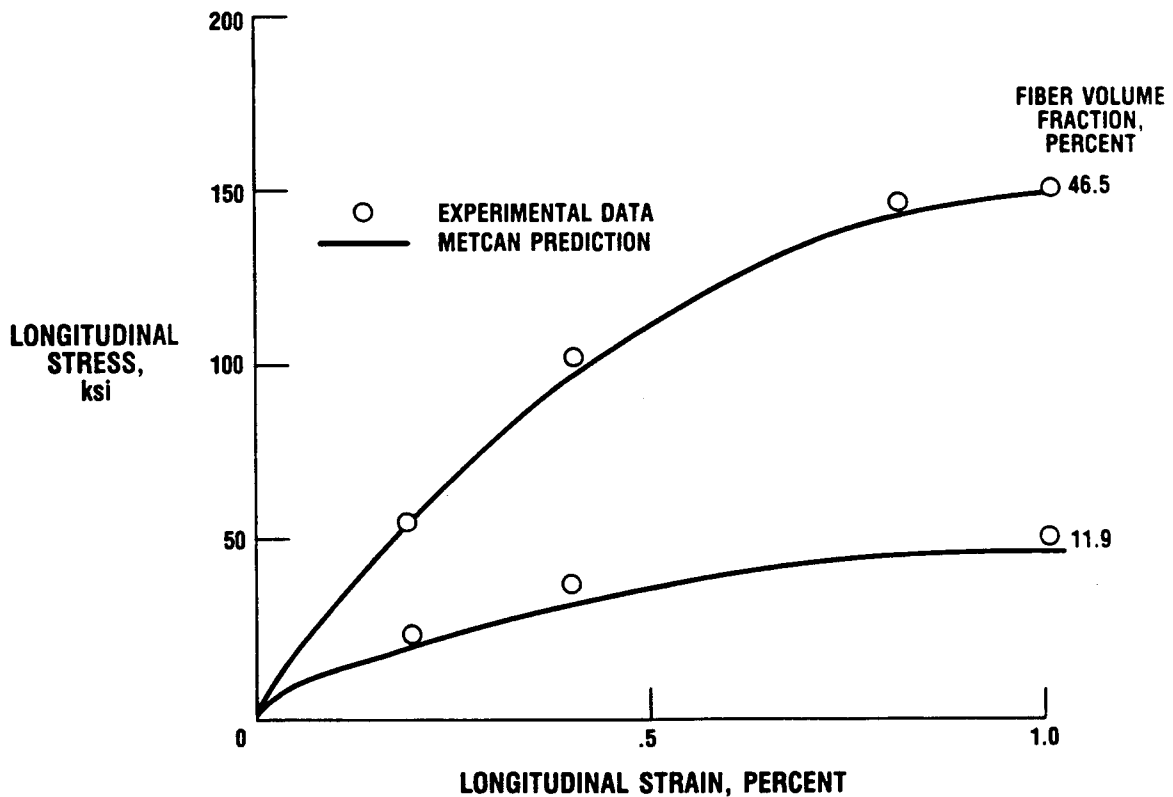
A result of a study of fiber/matrix interface effects (bond quality) on composite transverse strength that used the METCAN computer code is shown in the figure. The yield and fracture stress are presented for a unidirectional graphite/copper metal matrix composite with two different copper matrix treatments (annealed and hardened). Shown are the predicted stress levels without an interface (no bond) and with an interface (perfect bond). The two conditions can be viewed as extremes, or bounds, on the bond quality achieved in actual fabrication. Indeed, experimental data for transverse strength exhibit significant scatter and, although not shown in the figure, generally fall within the bounds predicted by METCAN.



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UNDIRECTIONAL TUNGSTEN/COPPER MMC STRESS-STRAIN RESPONSE

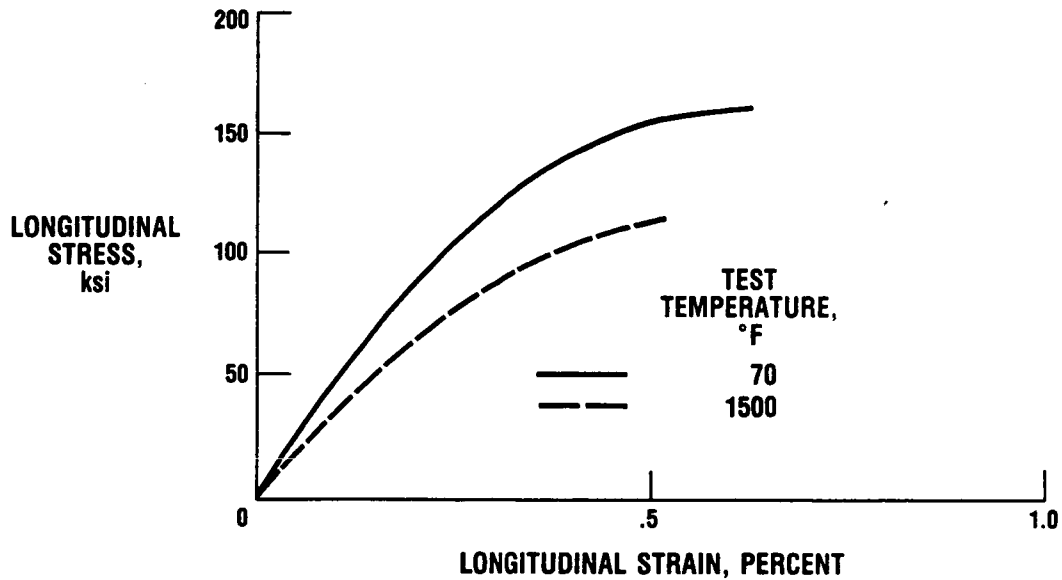
An example of the type of information obtained from the METCAN computer code is given in the figure, which shows the nonlinear stress-strain response due to monotonic loading at room temperature for unidirectional tungsten/copper metal matrix composites with two different fiber volume fractions. Evident from the figure is the excellent agreement between the METCAN-predicted and experimentally measured responses.



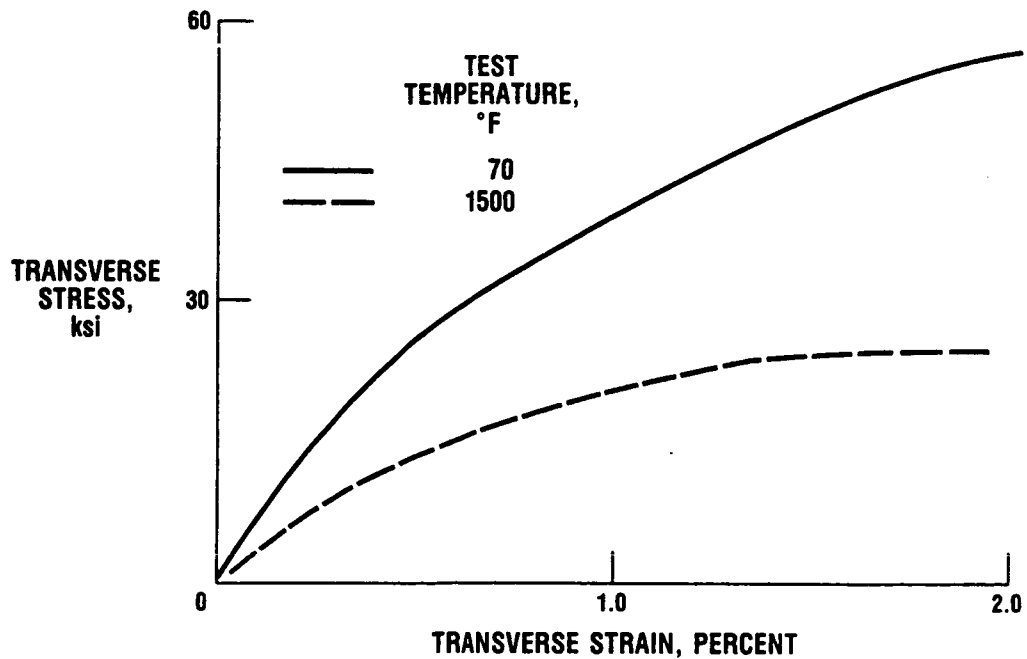
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UNDIRECTIONAL GRAPHITE/COPPER MMC STRESS-STRAIN RESPONSE

Another example of METCAN computer code predictive capability is shown here. The results shown in the figure are the nonlinear stress-strain response to monotonic loading for a unidirectional graphite/copper metal matrix composite at elevated as well as room temperature, and for transverse as well as longitudinal loading direction.



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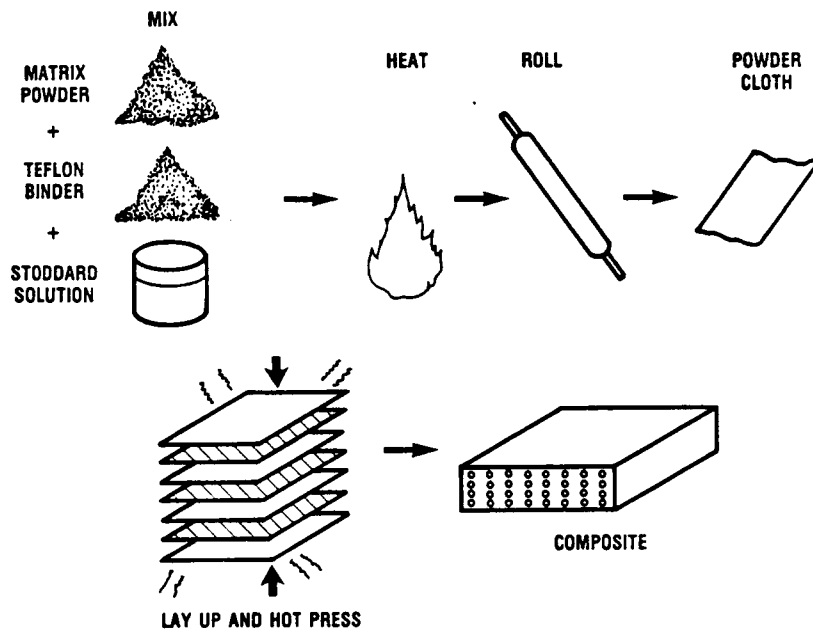


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METAL MATRIX COMPOSITE FABRICATION PROCESS

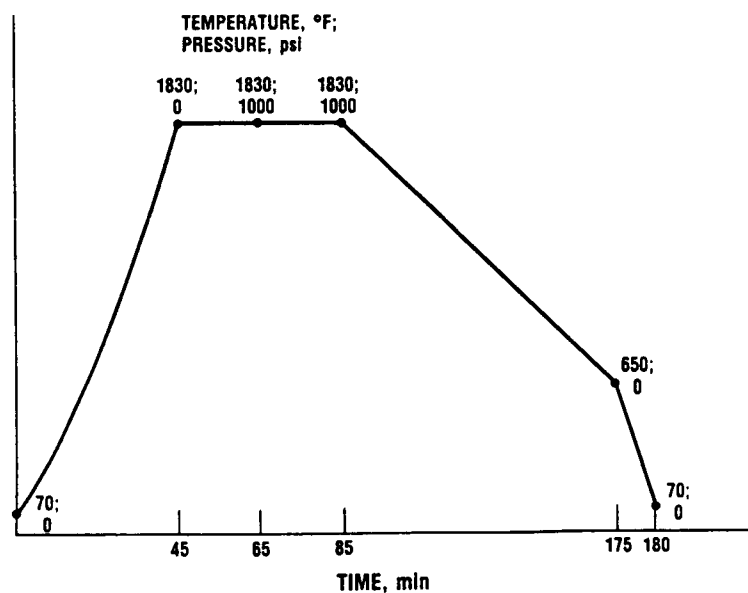
The METCAN computer code has recently been used to investigate the development of residual stresses in a typical fabrication process, as illustrated in the figure. The effect of fabrication residual stresses on subsequent in-service performance of aerospace propulsion structures has also been investigated by using METCAN in conjunction with other global structural analysis computer codes.

METAL-MATRIX COMPOSITE FABRICATION PROCESS



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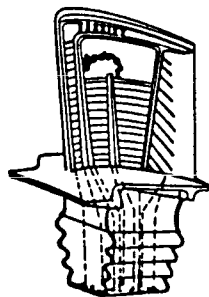
MMC PROCESSING CONDITIONS



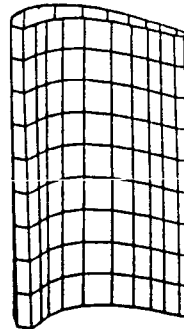
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TUNGSTEN/SUPERALLOY MMC TURBINE BLADE

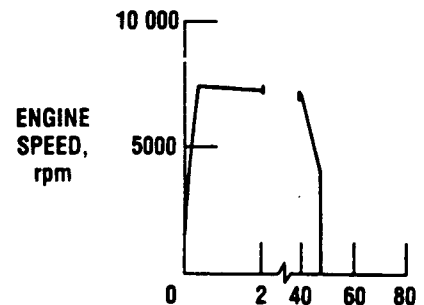
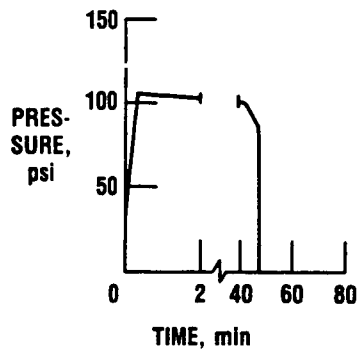
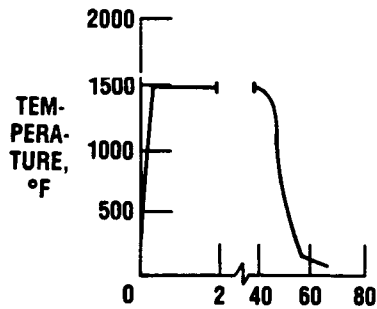
The figure shows a turbine airfoil fabricated from an angle-plyed $[+45^{\circ}/-45^{\circ}]_s$ tungsten/superalloy composite and subjected to hypothetical aircraft engine flight mission conditions.



TURBINE AIRFOIL



FINITE ELEMENT MODEL



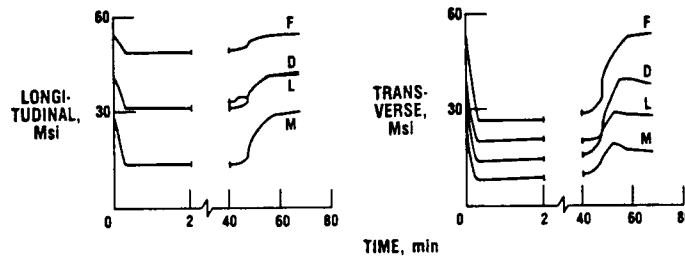
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TUNGSTEN/SUPERALLOY MMC TURBINE AIRFOIL ANALYSIS

The results from a quasi-static incremental analysis of the airfoil model show a variety of behavior and response quantities corresponding to the outermost (exterior surface) ply at the midchord root location on the airfoil (identified by arrow in previous figure). These results were obtained by interfacing the METCAN computer code with the familiar NASTRAN finite element structural analysis computer code.

MODULUS

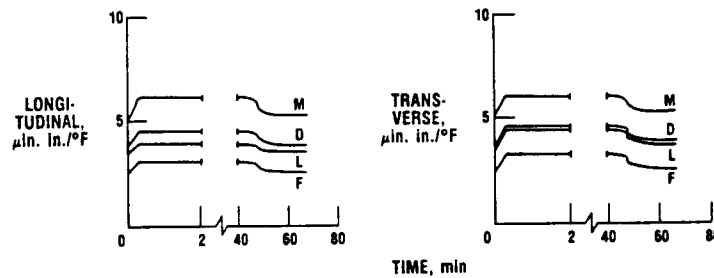
F FIBER
M MATRIX
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THERMAL EXPANSION COEFFICIENT

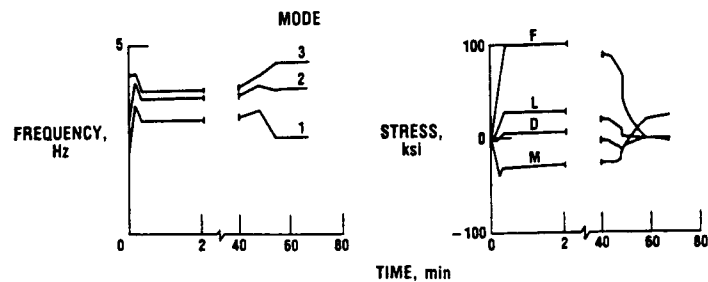
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NATURAL FREQUENCY AND LONGITUDINAL STRESS

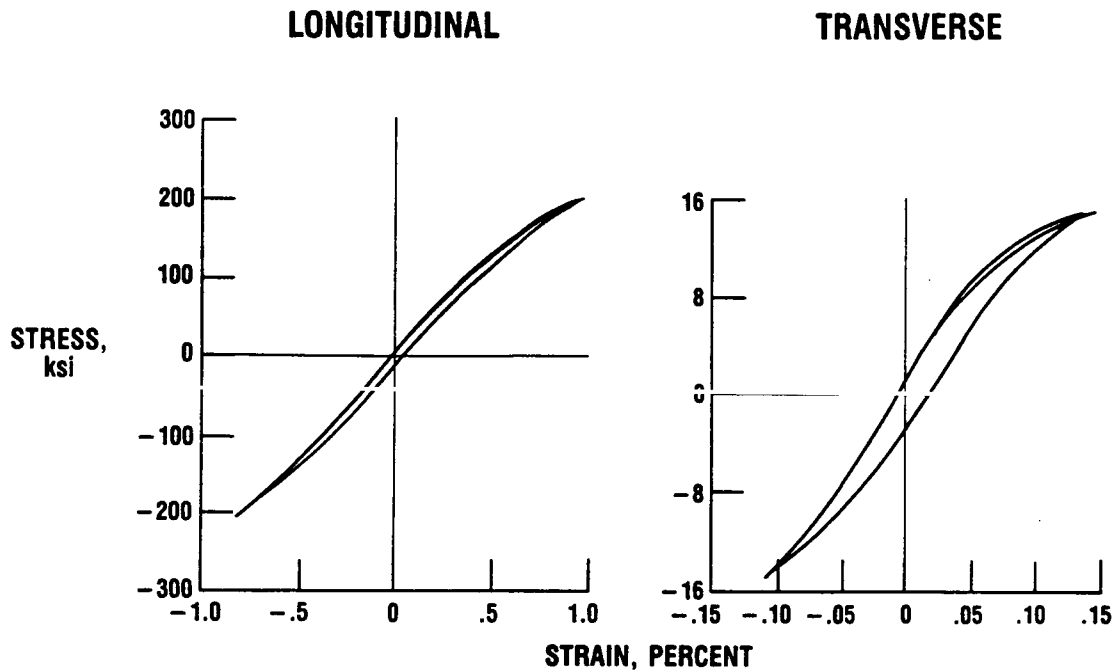
F FIBER
M MATRIX
D INTERPHASE
L PLY



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UNIDIRECTIONAL BORON/ALUMINUM MMC CYCLIC STRESS-STRAIN RESPONSE

An example of planned future capability for the METCAN computer code, which is currently under development, is shown in the figure and represents the predicted nonlinear stress-strain response to cyclic loading for a unidirectional boron/aluminum metal matrix composite, for both longitudinal and transverse loading directions. Further investigation of the nature of unloading at the constituent level is needed before this feature can become a permanent capability of the METCAN computer code.



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SUMMARY

- METCAN PERFORMS MOST ESSENTIAL ASPECTS OF MECHANICS, ANALYSIS, AND DESIGN OF METAL-MATRIX COMPOSITES
- METCAN IS MODULAR, OPEN ENDED, AND USER FRIENDLY
- STANDARD METAL-MATRIX COMPOSITES AS WELL AS INTERPLY HYBRID METAL-MATRIX COMPOSITES CAN BE ANALYZED
- RESPONSE DUE TO DIFFERENT TYPES OF THERMAL AND MECHANICAL LOAD HISTORIES ACCOUNTING FOR THERMOMECHANICAL DEGRADATION CAN BE OBTAINED ROUTINELY
- KEY FEATURES OF METCAN INCLUDE
 - LINEAR AND NONLINEAR ANALYSIS
 - ROOM- AND HIGH-TEMPERATURE PROPERTIES
 - STRESS AND STRAIN INFLUENCE COEFFICIENTS
 - RESIDENT DATA BANK

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