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SUMMARY

Computational procedures are described to simulate the thermal and mechanical behavior of high temperature metal matrix composites (HT-MMC) in the following three broad areas: (1) Behavior of HT-MMCs from micromechanics to laminate via Metal Matrix Composite Analyzer (METCAN), (2) tailoring of HT-MMC behavior for optimum specific performance via Metal Matrix Laminate Tailoring (MMLT), and (3) HT-MMC structural response for hot structural components via High Temperature Composite Analyzer (HITCAN). Representative results from each area are presented to illustrate the effectiveness of computational simulation procedures. The sample case results show that METCAN can be used to simulate material behavior such as strength, stress-strain response, and cyclic life in HT-MMCs; MMLT can be used to tailor the fabrication process for optimum performance such as that for in-service load carrying capacity of HT-MMCs; and HITCAN can be used to evaluate static fracture and fatigue life of hot pressurized metal matrix composite rings.

INTRODUCTION

Composite structural behavior is generally complex because of the multi-inherent scales and behavior coupling in intra- and inter-scales. That, for high temperature metal matrix composite (HT-MMC) structures, is compounded because of the presence of nonlinear dependencies such as those on temperature, stress, and time. Prediction of HT-MMC behavior requires analyses at inherent multiple composite material/structure scales. These analyses need to be integrated progressively from the constituent scale (fiber, matrix, and interphase) to global structural component. The various scales involve micromechanics (intraply), macromechanics (interply), laminate (multiple plies), local region (plate type finite element), and structural component (assemblage of many finite elements). This obviously complicates the task. One approach is to solve the fundamental governing field equations for all the participating variables by employing a computer as an integral part of the solution. Since this approach can be used to simulate the behavior or process as well as a specific event, it is called "Computational Simulation."

Recent research at NASA Lewis Research Center is directed toward the development of computational methodologies and corresponding stand-alone computer codes for predicting the nonlinear behavior of HT-MMCs at all the inherent scales. The simulation starts with constituents and the fabrication process and progresses to determine the effects induced by the severe service loading environments. Based on the fundamental physics of how the material/structure behaves, three computational simulation procedures/ codes have been developed: (1) Behavior of HT-MMCs from micromechanics to laminate via Metal Matrix Composite Analyzer (METCAN); (2) tailoring of HT-MMC behavior for optimum specific performance via

Metal Matrix Laminate Tailoring (MMLT); and (3) HT-MMC structural response for hot structural components via High Temperature Composite Analyzer (HITCAN).

The primary objective of this article is to briefly describe these three computational procedures/codes and present illustrative results from their applications to simulate specific HT-MMC behavior. Select references are cited for that purpose. The secondary objective is to demonstrate the effectiveness of this hierarchical computational capability to predict the material behavior of a SiC/Ti (silicon carbide fiber/titanium matrix) laminate, to tailor the fabrication process of a P100/Copper (graphite fiber/copper matrix) laminate for maximum in-service load carrying capacity, and to predict static/fatigue life of a SiC/Ti composite ring.

BEHAVIOR OF HT-MMC FROM MICROMECHANICS TO LAMINATE

The behavior of HT-MMCs from micromechanics to laminate is computationally simulated using the procedure embedded in the in-house computer code METCAN. The structure of METCAN, its simulation capabilities, and typical results to illustrate the applications of these capabilities, are summarized in this section.

The structure of METCAN parallels the fabrication process of metal matrix composites. A typical fabrication process is schematically illustrated in figure 1. The simulation capability in METCAN is depicted schematically in figure 2. METCAN has the capability to predict all aspects of HT-MMC behavior, including the fabrication process by using room temperature properties for the fiber and matrix. The formalism embedded in METCAN, an initial version, and concepts are demonstrated in reference 1. A detailed description of the micromechanics to represent the simulation at the constituents scale is provided in reference 2. Fundamental to the computational simulation in METCAN is the introduction of the multi-factor interaction model (MFIM) to represent the various nonlinearities and their mutual interactions in the constituents. The equation form of the MFIM and reasons for its selection are summarized in figure 3. A discussion on MFIM's ability to represent constituent material behavior and the subsequent influence of this behavior on the response of structural components made from HT-MMC is presented in reference 3.

The METCAN computational sequence for the simulation of a typical composite behavior starting from the fabrication process is shown in figure 4. The sequence consists of: (1) processing - cool down from processing temperature to room temperature; (2) heat up to use temperature from room temperature; and (3) mechanical load to obtain stress-strain data.

The minimum number of tests for calibrating METCAN for a specific HT-MMC are shown in figure 5. They are: (1) monotonic longitudinal tensile test; (2) monotonic transverse tensile test; (3) interlaminar shear creep rupture test; (4) thermal cyclic test of crossply laminate; and (5) mechanical cyclic test of crossply laminate. Once METCAN has been calibrated with these tests, the entire spectrum of HT-MMC behavior under various thermal and mechanical static and time-dependent loads can be predicted. Obviously, the computational simulation via METCAN minimizes the costly and time consuming experimental effort that would otherwise be required in the absence of a predictive capability.

The verification/validation of the capabilities of METCAN with both experimental results and three-dimensional finite element analysis predictions is an ongoing activity at NASA Lewis. References 4 to 6 include the details of these efforts. Illustrative results from reference 6 are shown in figures 6 and 7. The constituent material properties of SiC/Ti-6-4, i.e., silicon-carbide-fiber and titanium matrix used for these simulations are listed in table I. METCAN predictions for transverse strengths of SiC/Ti-6-4 at three different temperatures (73, 600, and 800 °F) for a fiber volume ratio of 0.34 are shown in figure 6. Difference between METCAN predictions and experimental results are minimal and the observed experimental degradation in strengths with increasing temperature is accurately predicted by METCAN. The room temperature stress-strain behavior predicted by METCAN as shown in figure 7 agrees almost exactly with experimental data. The SiC matrix property data used for simulations in figures 6 and 7 were provided by B.A. Lerch of NASA Lewis (table I).

METCAN has been verified for applied load for cyclic load behavior of HT-MMCs, as described in reference 4, where the influence of the interphase and limited comparisons with room temperature data are also described. METCAN simulation of in-situ behavior, how this can be used to interpret composite-measured behavior, and corresponding results for the development of an interphase between fiber and matrix, or weakening of the interfacial bond, are described in reference 5.

TAILORING OF HT-MMC FABRICATION PROCESS

A crucial problem limiting the use of many HT-MMCs is the high residual thermal microstresses developed during the fabrication process. These are due to the large temperature differential and the mismatch between the coefficients of thermal expansion (CTE) of the fiber and matrix. The presence of residual microstresses typically degrades the mechanical performance of the composite and is primarily responsible for the reported poor thermo-mechanical fatigue endurance of many HT-MMCs. It is desirable, therefore, to explore possible ways to reduce, or alternatively control, the development of residual microstresses. One possibility is to use a suitable fiber coating as an interphase layer between the fibers and the matrix to reduce the effects of the fiber/matrix CTE mismatch. Also, it is possible to obtain reductions in residual stresses by tailoring the combinations of temperature and consolidation pressure during fabrication (ref. 7).

More recent work along these lines has focused on a systematic development of concurrent tailoring methodology for optimal combination of the interphase layer, its properties, and the fabrication process variables. The details of this work can be found in reference 8. The computer code MMLT which includes the above mentioned methodology couples METCAN with an optimizer. MMLT simulates the thermo-mechanical response of the laminate with incremental nonlinear micromechanics and laminate mechanics theories. The structure of MMLT is shown in figure 8. MMLT is capable of concurrently tailoring the constituent materials characteristics and the fabrication process for an a priori specified HT-MMC behavior such as minimum residual stresses upon cool-down and maximum fatigue life. MMLT quantifies the strong coupling between the nonlinear thermo-mechanical response of MMCs during the fabrication process and the subsequent thermo-mechanical performance of the MMC in a typical service environment, resulting from the residual stresses and the nonlinearity of the composite. A typical thermo-mechanical life cycle of a MMC laminate from fabrication to failure at operational conditions, e.g. hot engine sections, is shown in figure 9.

Representative results from this work are reported herein to show the concept and usefulness of the methodology in achieving higher performance from HT-MMCs. A $[0/90]_s$ P100 graphite/Copper laminate is used to demonstrate the effectiveness of the MMLT code. The fabrication process is tailored for three cases: (1) tensile in-plane load; (2) compressive in-plane load; and (3) bending load, all at a constant elevated temperature. Figure 10 shows the initial and tailored processes for the three load cases. The fabrication process for the tensile load case did not change by tailoring. Whereas, the fabrication processes changed significantly for compressive and bending loads by tailoring, the consolidation pressure increased as the temperature decreased to room conditions. This led to an increase of about 40 percent for the in-service load carrying capacity of the compressive in-plane and bending load cases, as shown in figure 11. For tensile in-plane load case, the fabrication tailoring did not affect the in-service load carrying capacity because the bulk of the load is carried by the fibers. The details of these cases can be found in reference 9.

HT-MMC STRUCTURAL ANALYSIS

HITCAN is a general purpose computer code for predicting global structural and local stress-strain response of arbitrarily oriented, multilayered high temperature metal matrix composite structures both at the constituent (fiber, matrix, and interphase) and the structure scale. HITCAN combines METCAN with a noncommercial finite element code, MHOST, and a dedicated mesh generator, COBSTRAN (ref. 10). The code is stand-alone and streamlined for the thermal/structural analysis of hot metal matrix composite structures. A schematic of the code's structure is shown in figure 12. And as shown in figure 13, HITCAN is a modular code with an executive module controlling the input, analysis modules, database, nonlinear solvers, utility routines, and output. HITCAN's capabilities are summarized in table II. HITCAN is capable of simulating the behavior of all types of HT-MMC structural components (beam, plate, ring, curved panel, built-up structure) for all types of analyses (static, load stepping - multiple load steps accounting for degradation in material behavior from one load step to another, buckling, vibration) including fabrication-induced stresses, fiber degradation, and interphase. An extensive description of HITCAN including a variety of sample cases to illustrate its computational capabilities, can be found in reference 11. At this time, the capabilities shown in table II by dotted lines, are not available.

The fabrication process cool-down, static fracture, and fatigue life response for a ring subjected to internal pressure are included herein as specific examples. The ring overall geometry and cross-section are shown in figure 14. The internal diameter is 5.354 in., the external diameter is 6.676 in., and the height is 0.818 in. The ring is made of SiC fibers and Ti-5-3 matrix for a fiber volume ratio of 0.33 with $[0]_{57}$ laminate lay-up. The ring is subjected to a uniform temperature loading and its internal circumferential surface is subjected to a force via a hydraulic rig. The loading history is shown in figure 15. The simulation predicts ring failure at 27.5 lb force. The ring strains in terms of change in internal and external diameter are shown in figure 16. The failure sequence (local stress exceeds corresponding strength) of ring cross-section is depicted in figure 17. In view of the inclusiveness of the analysis, HITCAN-predicted information can be used to minimize the number of tests during the development and early design stages and provide description of information postmortem of probable initiation and propagation to fracture in the prototype. For the fatigue life simulation of the ring, the multi-factor relationship shown in figure 18 was used. The predicted fatigue life in terms of the cyclic-stress-to-static strength-ratio versus cycles to failure is shown in figure 19. As can be observed, it is a typical S/N curve. Stress level (S) to achieve a desired number of cycles (N) can be estimated from the figure. The HITCAN predictions of ring fracture were based on calibrating only the in-situ matrix behavior using a 90° tensile test room temperature stress/strain curve. This was in addition to the fiber and matrix room temperature properties in table I.

CONCLUSIONS

Three research activities pertaining to computational simulation aspects of high temperature metal matrix composites (HT-MMC) are described. These activities have resulted in computer codes which can be used to simulate the complex behavior of hot structures made from HT-MMCs. Results from each code for select sample cases are included to illustrate the capabilities of each code. The results from METCAN are for the prediction of room/high-temperature strengths/stress-strain behavior for SiC/Ti-6-4 composite. The results from the concurrent tailoring methodology are for the optimum fabrication cool-down process to achieve maximum in-service load carrying capacity. The results from HITCAN are for static fracture and fatigue life of an HT-MMC ring subjected to temperature and internal pressure.

Collectively, the results from these sample cases demonstrate that computational simulation methods can be developed to effectively simulate the complex behavior of HTMMCs. Verifications with experimental data confirm that micromechanics based hierarchical approaches (1) are fundamentally sound, (2) account for inherent attributes in the composite, (3) require few coupon characterization tests, (4) allow for early prototype design and fabrication, (5) provide an effective assessment of fabrication quality, and (6) permit postmortem identification of probable initiation and propagation to fracture in the prototype.

REFERENCES

1. Hopkins, D.A.: Nonlinear Analysis of High-Temperature Multilayered Fiber Composite Structures - Turbine Blades. NASA TM–83754, 1984.

2. Hopkins, D.A.; and Chamis, C.C.: A Unique Set of Micromechanics Equations for High Temperature Metal Matrix Composites. NASA TM–87154, 1985.

3. Chamis, C.C.; and Hopkins, D.A.: Thermoviscoplastic Nonlinear Constitutive Relationships for Structural Analysis of High Temperature Metal Matrix Composites. NASA TM–87291, 1985.

4. Chamis, C.C.; Murthy, P.L.N., and Hopkins, C.A.: Computational Simulation of High Temperature Metal Matrix Composites Cyclic Behavior. NASA TM–102115, 1988.

5. Murthy, P.L.N.; Hopkins, D.A.; and Chamis, C.C.: Metal Matrix Composite Micromechanics: In-situ Behavior Influence on Composite Properties. NASA TM–102302, 1989.

6. Chamis, C.C.; Caruso, J.J.; and Lee, H.J.: METCAN Verification Status, NASA TM–103119, 1990.

7. Saravanos, D.A.; Murthy, P.L.N.; and Morel, M.: Optimal Fabrication. Process for Unidirectional Metal Matrix Composites: A Computational Simulation. NASA TM–102559, 1990.

8. Morel, M.; and Saravanos, D.A.: Concurrent Micromechanical Tailoring and Fabrication Process Optimization for Metal-Matrix Composites. NASA TM–103670, 1990.

9. Morel, M.; Saravanos, D.A.; and Chamis, C.C.: Optimization of the Fabrication process to Improve the In Service Loading Carrying Capacity of Metal Matrix Composites. Paper presented at the Sixth Japan – U. S. Conference on Composite Materials, Orlando, Florida, June, 1992.

10. Aiello, R.A.: Composite Blade Structural Analyzer (COBSTRAN) User's Manual. NASA TM-101461, 1989.

11. Singhal, S.N., et al.: Demonstration of Capabilities of High Temperature Composite Analyzer Code HITCAN. NASA TM-102560, 1990.

TABLE I.—CONSTITUENT (FIBER/MATRIX) MATERIAL PROPERTIES USED IN METCAN

	Material properties			
	Fiber		Matrix	
	SiC[a]	SiC[b]	Ti-15-3[a]	T-6-4[b]
ρ, lb/in.^{3}	0.11	0.108	0.172	0.170
T_m, °F	4870	4500	3000	3000
E_{11}, Mpsi	62	60	12	17
E_{22}, Mpsi	62	60	12	17
G_{12}, Mpsi	26	20	5	7
ν_{12}	0.19	0.30	0.32	0.30
α_{11}, ppm/°F	2.7	2.7	4.7	5.2
α_{22}, ppm/°F	2.7	2.7	4.7	5.2
S_{11}, ksi	500	500	60	74
S_{22}, ksi	500	500	60	74
S_{12}, ksi	300	250	36	44

[a]Private communication from B.A. Lerch, NASA Lewis Research Center.
[b]Reference 6.

Notation

E elastic modulus
G shear modulus
S strength
T temperature
P density
μ Poisson's ratio
α coefficient of thermal expansion

Subscripts

m melting
11 direction 11
22 direction 22
12 direction 12

Conversion to Si Units

1 lb/in.^{3} = 2.768×10^4 Kgm/m^3
1 °F = 1.8 °C + 32
1 Mpsi = 6.895×10^9 N/m^2
1 ksi = 6.895×10^9 N/m^2

TABLE II.—HITCAN CAPABILITIES FOR HOT COMPOSITE STRUCTURES

Type of analysis	Type of structure				
	Beam	Plate	Ring	Curved panel	Built-up structure
Static	Tested	Tested	Tested	Tested	Tested
Buckling[a]	↓	↓	↓	↓	↓
Load stepping	↓	↓	↓	↓	↓
Modal (natural vibration modes)[b]	↓	↓	↓	↓	↓
Time domain	------	------	------	------	------
Loading					
Mechanical	Tested	Tested	Tested	Tested	Tested
Thermal	Tested	Tested	Tested	Tested	Tested
Cyclic	------	------	------	------	------
Impact	------	------	------	------	------
Constitutive models[c]					
$P = \text{constant}$	Tested	Tested	Tested	Tested	Tested
$P = f(T)$ (Temperature dependence)	↓	↓	↓	↓	↓
$P = f(\sigma)$ (Stress dependence)	↓	↓	↓	↓	↓
$P = f(\dot{\sigma})$ (Stress rate dependence)	↓	↓	↓	↓	↓
$P = f(t)$ (Creep)	------	------	------	------	------
$P = f(T, \sigma, \dot{\sigma})$ (Combination)	Tested	Tested	Tested	Tested	Tested
$P = f(T, \sigma, \dot{\sigma}, t)$ (Creep combination)	------	------	------	------	------
Fiber degradation	Tested	Tested	Tested	Tested	Tested
Fabrication-induced stresses	Tested	Tested	Tested	Tested	Tested
Ply orientations[d]					
Arbitrary	Tested	Tested	Tested	Tested	Tested

[a]Tested 1 buckling mode.
[b]Tested 4 vibration modes.

[c]Constitutive models: Notation
P: Material properties
T: Temperature
σ: Stress
$\dot{\sigma}$: Stress rate
t: Time

[d]Tested 3 ply orientations:
Unsymmetric: $(0/\pm45/90)$
Symmetric: $(0/45)_s$
Balanced: $(0/90)_s$

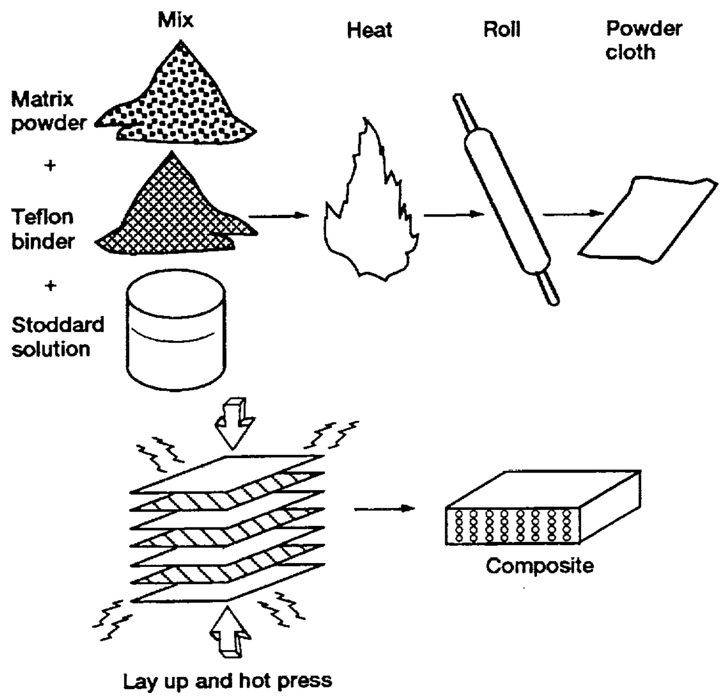


Figure 1.—Metal-matrix composite fabrication process.

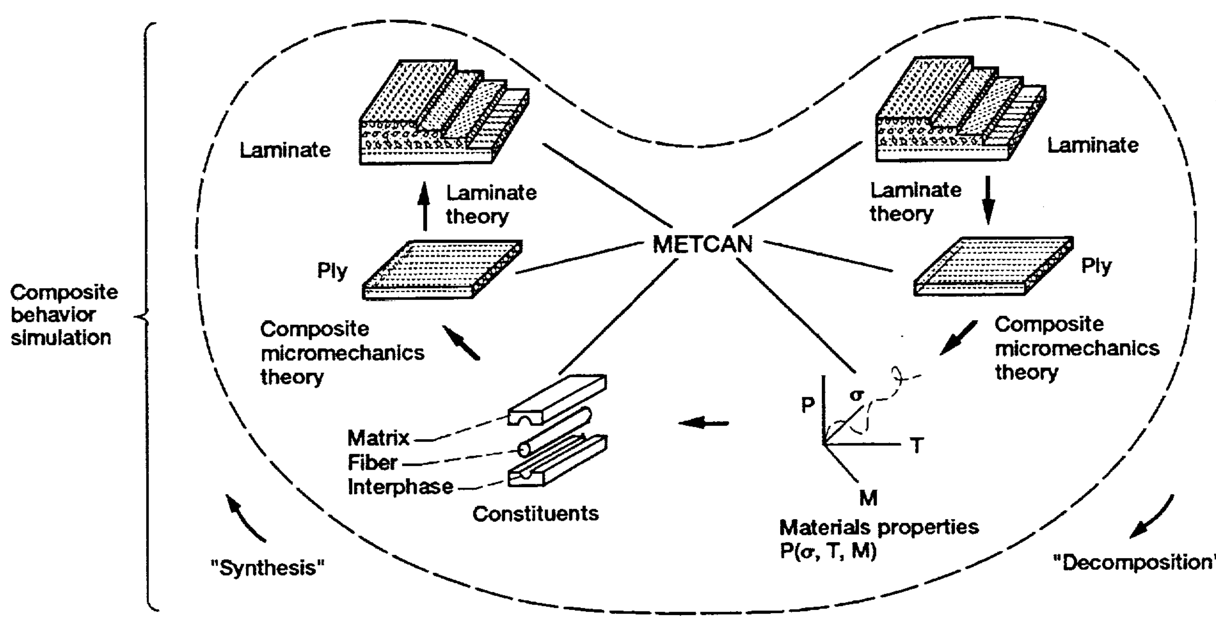
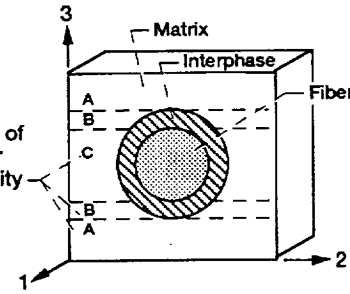


Figure 2—METCAN (Metal Matrix Composite Analyzer) for the computational simulation of high temperature metal matrix composites behavior.

$$\frac{P}{P_O} = \left[\frac{T_F - T}{T_F - T_O}\right]^{1/2} \left[\frac{S_F - \sigma}{S_F - \sigma_O}\right]^{l} \left[\frac{\dot{S}_F - \dot{\sigma}}{\dot{S}_F - \dot{\sigma}_O}\right]^{m} \left[\frac{\dot{T}_F - \dot{\sigma}}{\dot{T}_F - \dot{\sigma}_O}\right]^{n} \left[\frac{R_F - R}{R_F - R_O}\right]^{p} \ldots$$

$$\ldots \left[1 - \frac{\sigma_M N_M}{S_F N_{MF}}\right]^{r} \left[1 - \frac{\sigma_T N_T}{S_F N_{TF}}\right]^{s} \left[1 - \frac{\sigma t}{S_F t_F}\right]^{u} \ldots$$



Rationale:

- Gradual effects during most range, rapidly degrading near final stages
- Representative of the in situ behavior for fiber, matrix, interphase, coating
- Introduction of primitive variables (PV)
- Consistent in situ representation of all constituent properties in terms of PV
- Room–temperature values for reference properties
- Continuous interphase growth
- Simultaneous interaction of all primitive variables
- Adaptability to new materials
- Amenable to verification inclusive of all properties
- Readily adaptable to incremental computational simulation

Notations:

P – property; T – temperature; S – strength; σ – stress; R – metallurgical reaction; N – number of cycles: t – time; over dot – rate; subscripts: O – reference; F – final; M – mechanical; T – thermal

Figure 3.—Assumed multi-factor interaction model (MFIM) to represent the various factors which influence In Situ constituent materials behavior.

Step I Processing - Cool down from processing temperature (T_p) to room temperature (T_o)

Step II Heat up to use temperature (T_u) from room temperature

Step III Apply mechanical load to obtain stress-strain data

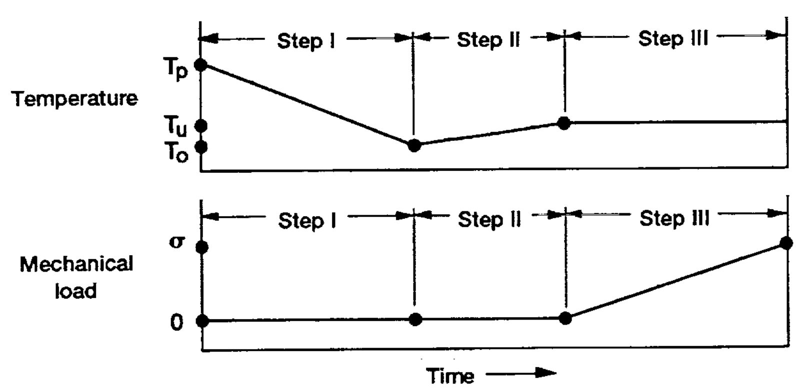


Figure 4.—METCAN computational simulation sequence.

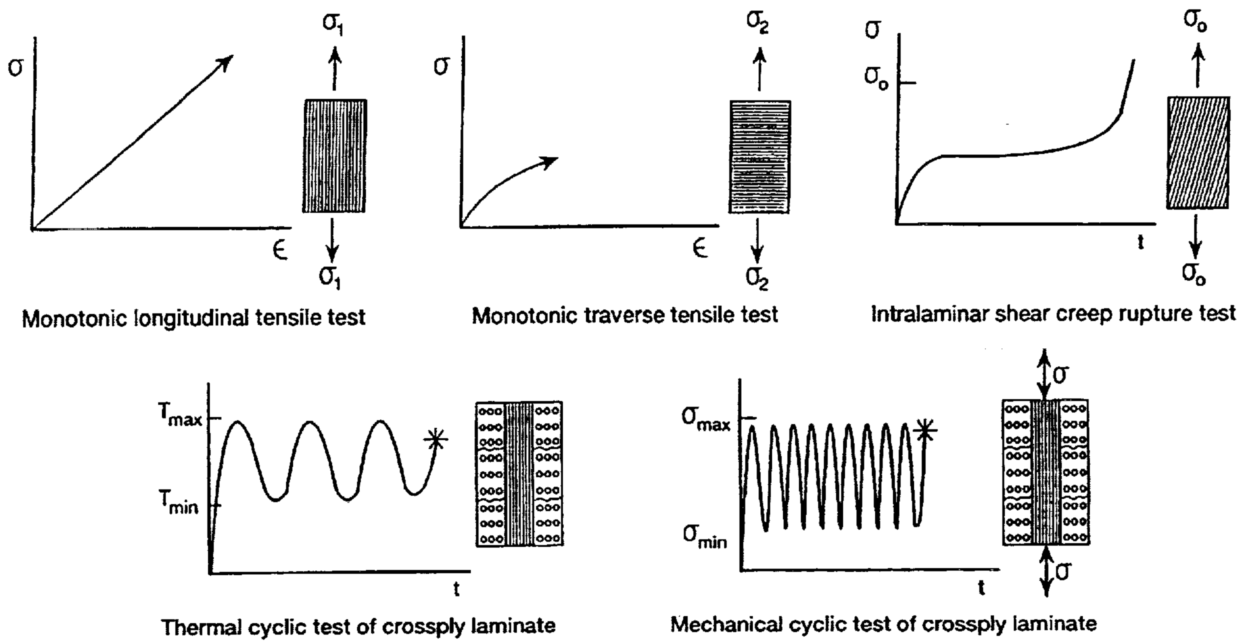


Figure 5.—Minimum number of tests for calibrating METCAN for a specific HT-MMC.

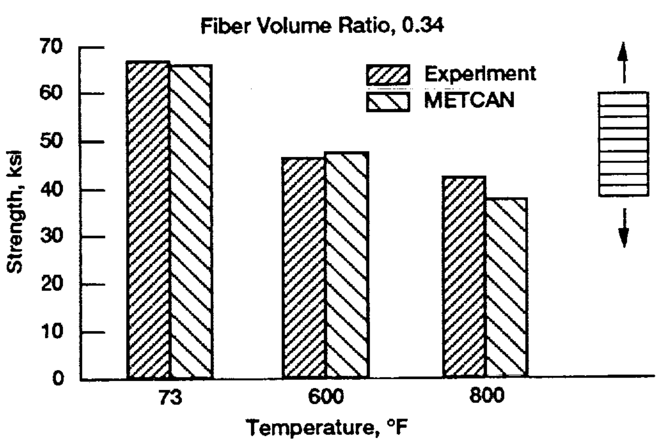


Figure 6.—METCAN accurately simulates transverse strength of SiC/Ti–6–4.

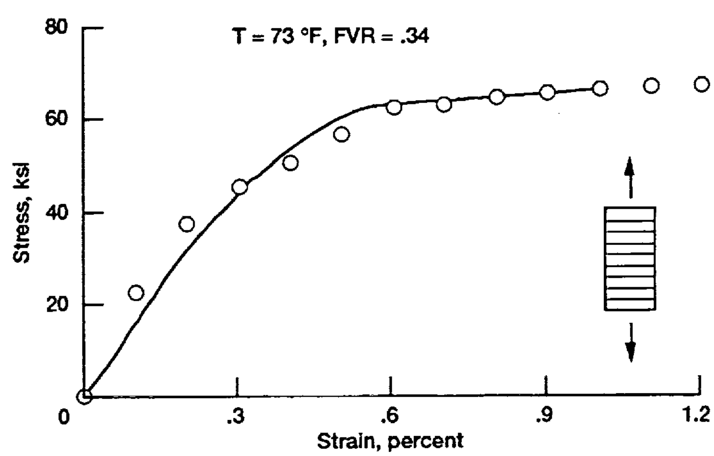


Figure 7.—METCAN accurately simulates transverse stress strain curve of SiC/Ti–6–4.

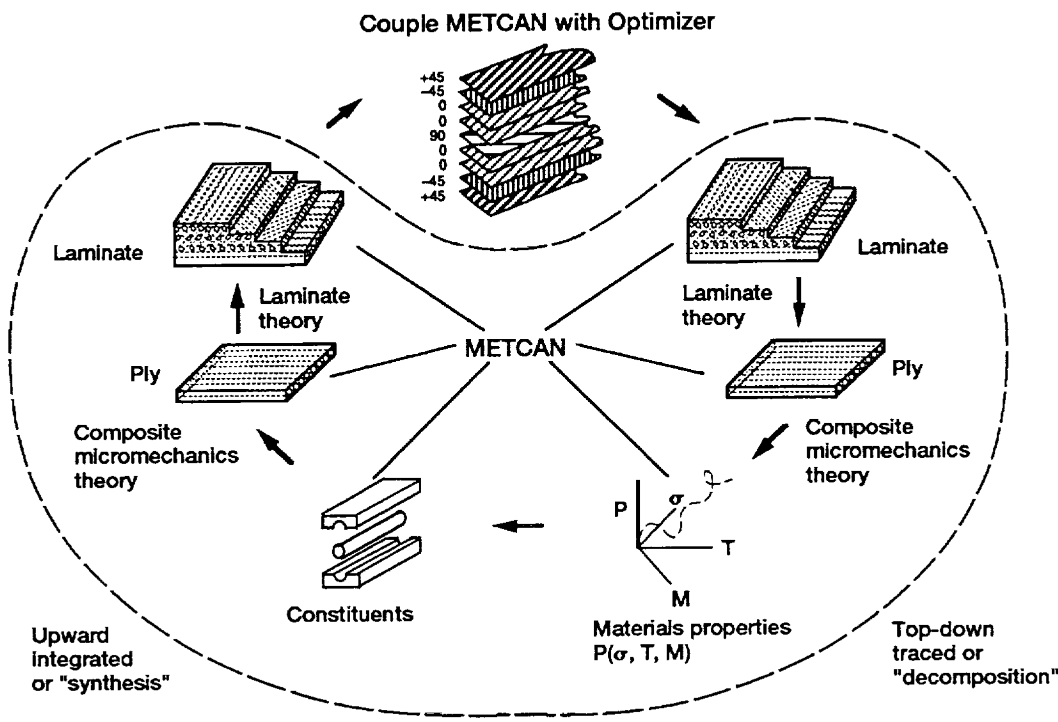


Figure 8.—Metal matrix laminate tailoring (MMLT).

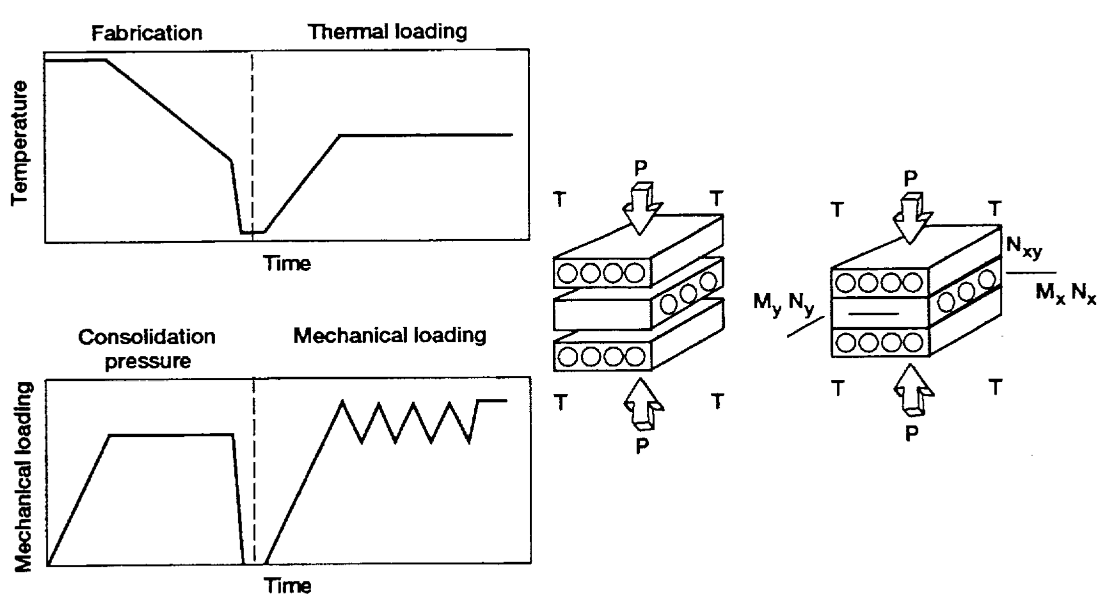


Figure 9.—Typical fabrication and thermomechanical cycle of metal matrix laminates.

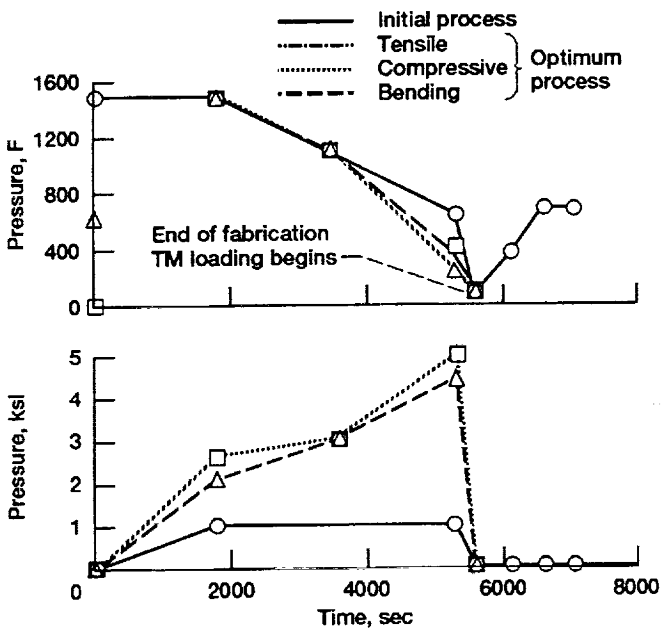


Figure 10.—Optimum and inital fabrication process for P100/ copper $[0/90]_s$ with thermomechanical (TM) loads applied.

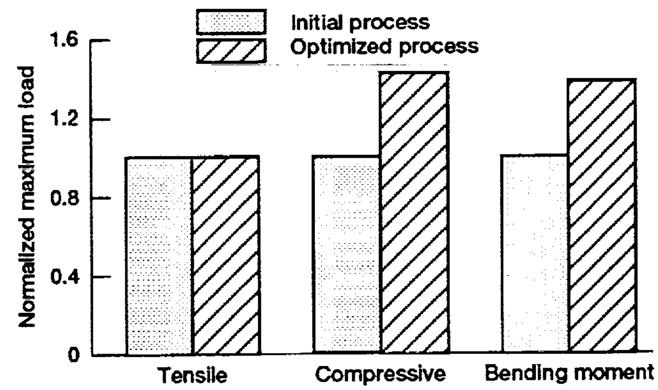


Figure 11.—Effect of fabrication optimization on the maximum in-service load for P100/ copper $[0/90]_s$ laminate.

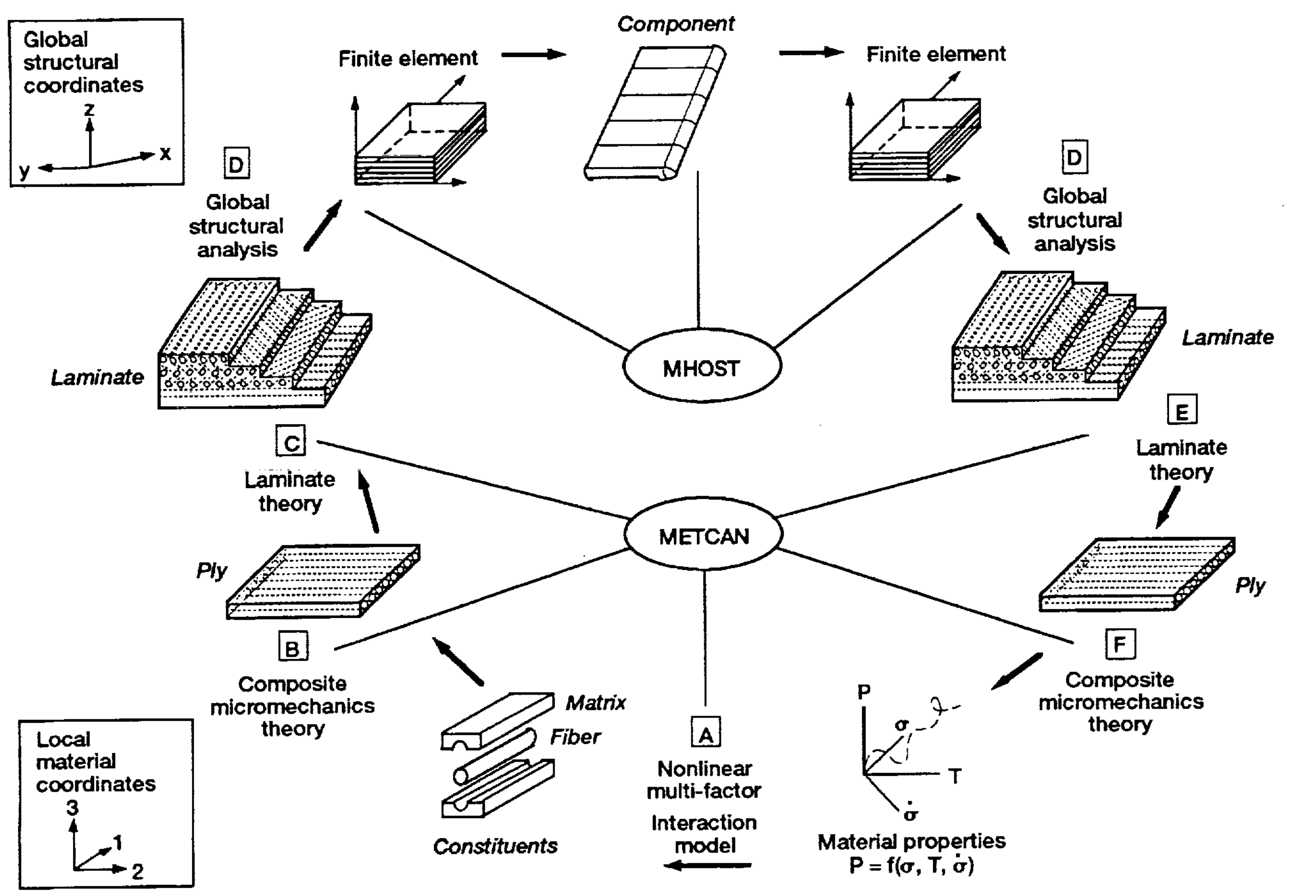


Figure 12.—HITCAN: an integrated approach for hot composite structures.

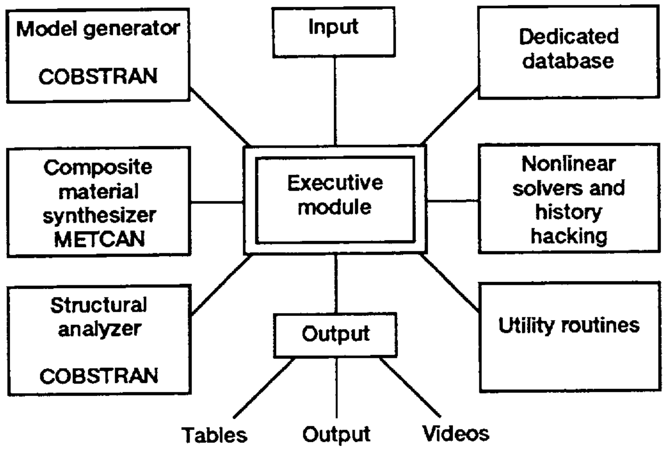


Figure 13.—HITCAN modular structures.

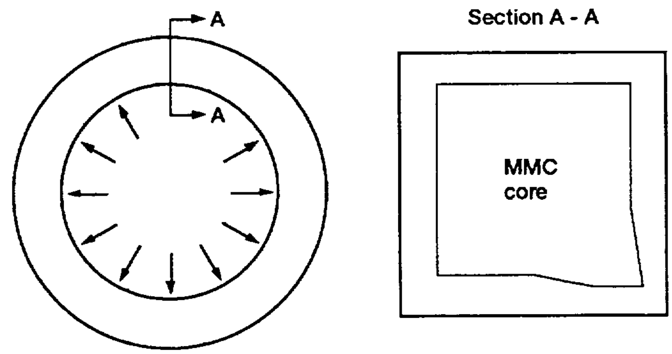


Figure 14.—HITCAN simulates thermo-structural behavior of MMC ring.

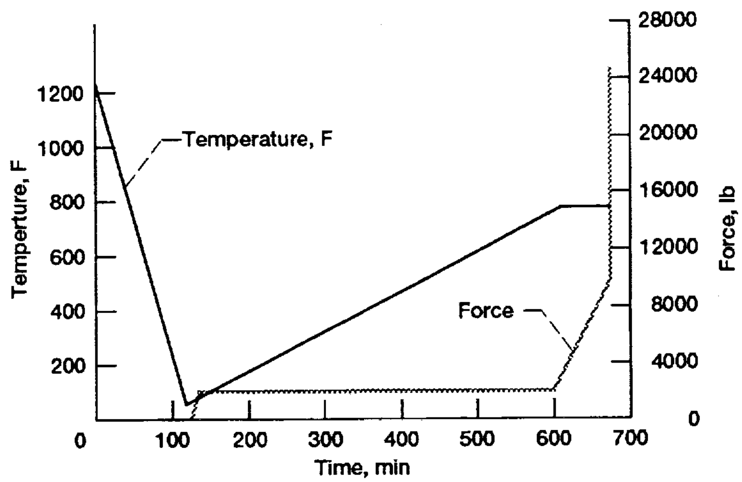


Figure 15.—Loading history of the ring.

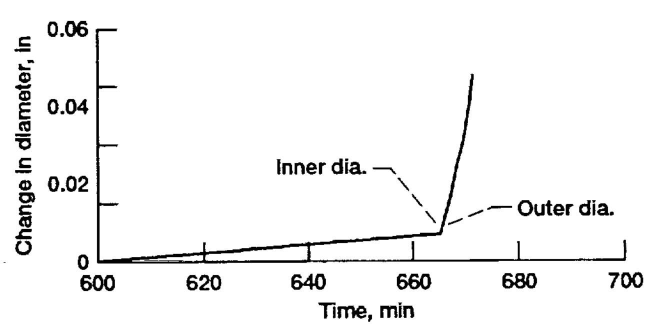


Figure 16.—Change in diameter of the ring.

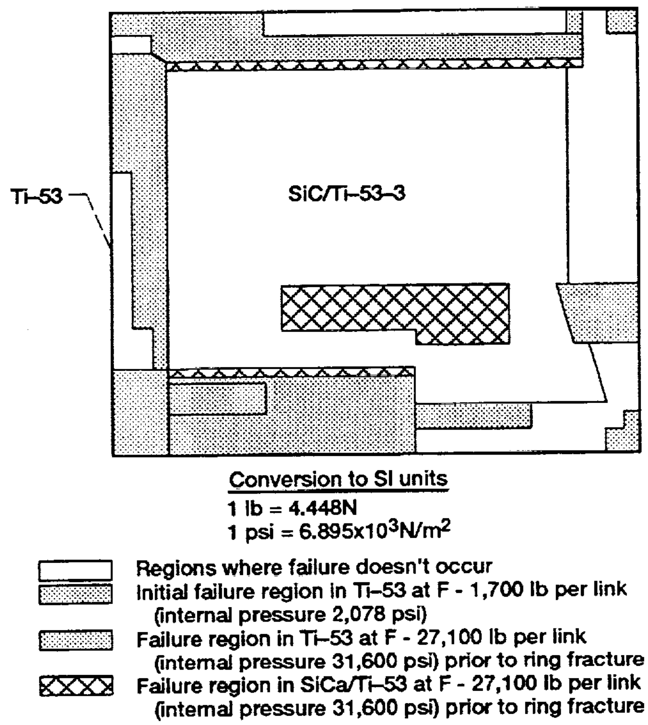
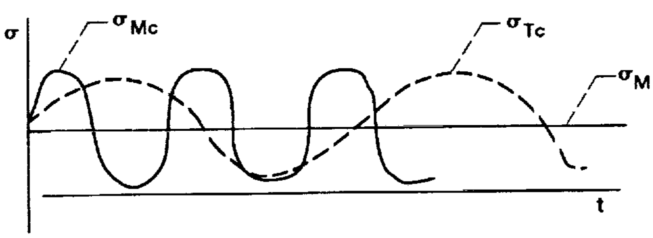


Figure 17.—Failure sequence of ring cross section.

$$\frac{S_n}{S_o} = \left[\frac{T_c - T_u}{T_c - T_o}\right]^n \left[\frac{S_F - \sigma_M}{S_F - \sigma_O}\right]^m \left[\frac{N_{MF} S_F - N_M \sigma_{Mc}}{N_{MF} S_F}\right]^p \left[\frac{N_{TF} S_F - N_T \sigma_{Tc}}{N_{TF} S_F}\right]^q$$



Notation

S: strength
T: temperature
σ: stress
N: number of cycles

Subscripts

O: reference
F: final
M: mechanical
T: thermal
c: cyclic
n: at the end of n cycles

Figure 18.—Multifactor relationship for estimating life.

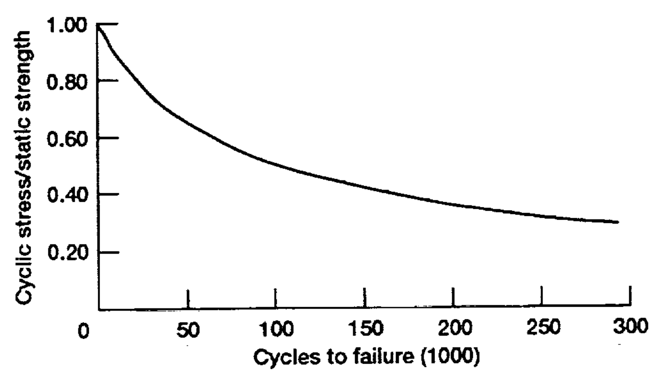


Figure 19.—Fatigue life of SiC/Ti-15-3 composite ring.

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13. ABSTRACT ***(Maximum 200 words)***

Computational procedures are described to simulate the thermal and mechanical behavior of high temperature metal matrix composites (HT-MMC) in the following three broad areas: (1) Behavior of HT-MMCs from micromechanics to laminate via Metal Matrix Composite Analyzer (METCAN), (2) tailoring of HT-MMC behavior for optimum specific performance via Metal Matrix Laminate Tailoring (MMLT), and (3) HT-MMC structural response for hot structural components via High Temperature Composite Analyzer (HITCAN). Representative results from each area are presented to illustrate the effectiveness of computational simulation procedures. The sample case results show that METCAN can be used to simulate material behavior such as strength, stress-strain response, and cyclic life in HT-MMCs; MMLT can be used to tailor the fabrication process for optimum performance such as that for in-service load carrying capacity of HT-MMCs; and HITCAN can be used to evaluate static fracture and fatigue life of hot pressurized metal matrix composite rings.

14. SUBJECT TERMS
Computational simulation; Environments; Fabrication; Fatigue; Fracture; High temperature; Interphase; Laminate theory; Material behavior; Metal matrix composites; Macromechanics; Micromechanics; Nonlinear analysis; Optimization; Residual stress; Structural response; Tailoring; Thermo-mechanical behavior

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