Scatter in Carbon/Silicon Carbide (C/SiC) Composites Quantified

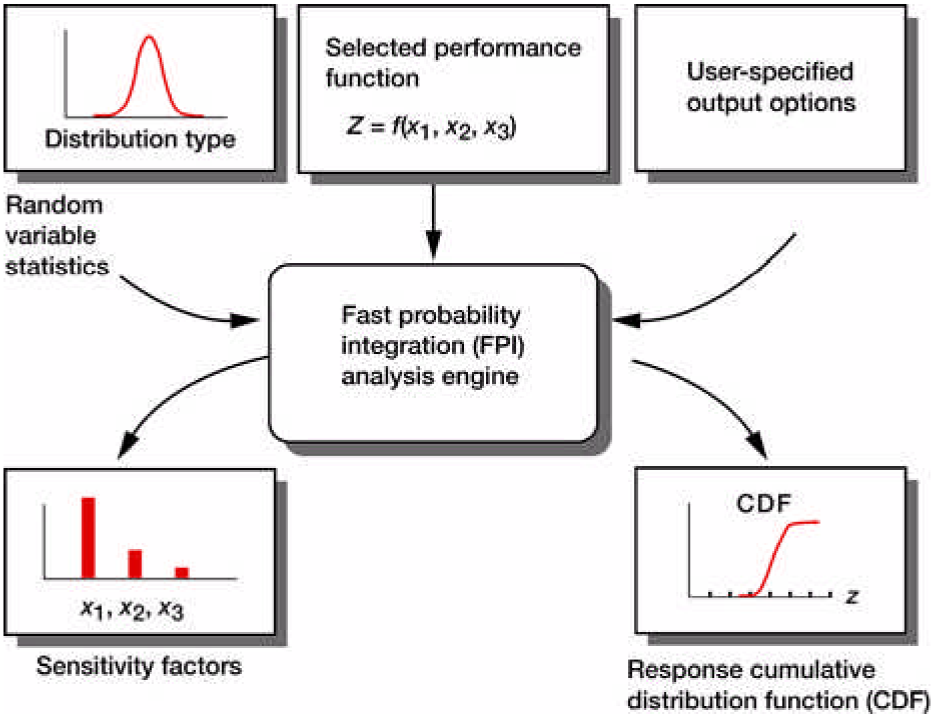
Carbon-fiber-reinforced silicon carbide matrix (C/SiC) composites processed by chemical vapor infiltration are candidate materials for aerospace thermal structures. Carbon fibers can retain properties at very high temperatures, but they are known to have poor oxidation resistance in adverse, high-temperature environments. Nevertheless, the combination of CVI-SiC matrix with higher stiffness and oxidation resistance, the interfacial coating, and additional surface-seal coating provides the necessary protection to the carbon fibers, and makes the material viable for high-temperature space applications operating under harsh environments. Furthermore, C/SiC composites, like other ceramic matrix composites (CMCs), exhibit graceful noncatastrophic failure because of various inherent energy-dissipating mechanisms. The material exhibits nonlinearity in deformation even at very low stress levels. This is the result of the severe matrix microcracking present in the as-processed composite because of large differences between the coefficients of thermal expansion of the fiber and the matrix.

Utilization of these advanced composites in next generation space vehicles will require innovative structural configurations, updated materials, and refined analyses. Structural safety issues for these vehicles are in direct competition with performance and cost. One would have to quantify the uncertainties associated with the design using formal probabilistic methods. Specifically four fundamental aspects on which analyses are based--(1) loading conditions, (2) material behavior, (3) geometrical configurations, and (4) structural connections between the composite components and baseline structure--are stochastic in nature. A direct way to formally account for uncertainties is to develop probabilistic structural analysis methods where all participating variables are described by appropriate probability density functions. The present work, however, focuses on analyzing the stochastic material behavior of these advanced composites using formal probabilistic analysis methods.

Often, some of the desirable property characteristics that allow composites to offer advantages over conventional structural materials (like tailoring of composite properties) and the complexity are in fact responsible for their greater statistical variability and the requirements for more characterization tests. Composite properties are anisotropic as well, having different properties in different directions. This means that characterization of a property such as stiffness--which will vary greatly depending on the orientation of the fiber relative to the direction of the testing--must be repeated for several different directions and loading conditions. The fabrication process for composites also introduces statistical variations in properties and geometry. A composite part is produced in a number of steps, each of which introduces statistical variability. The matrix is usually produced from a combination of raw materials; and the fiber, which has its own set of properties, is often coated or surface treated, introducing yet another source of variability. The processes are usually performed by various vendors and are not under the control of the fabricator of the composite part. Additional irregularities are introduced by the influence of temperature and moisture. Composites are usually more susceptible to environmental conditions. Changes in environmental conditions produce a significant change in properties, leading not only to a source of property variability, but also to a requirement for additional testing to characterize the effects of these variables. In general, CMCs are complex, have brittle constituents, and are potentially flaw-sensitive materials. They inherently have considerable scatter in their properties. It is important to note that because of the flaw-sensitivity of brittle materials, additional characterization is required to characterize the "volume effect." Thus, the advantages that composites bring must be weighed against increased material testing costs. Any CMC material characterization effort based solely on a large test matrix is simply impractical because of time and cost considerations.

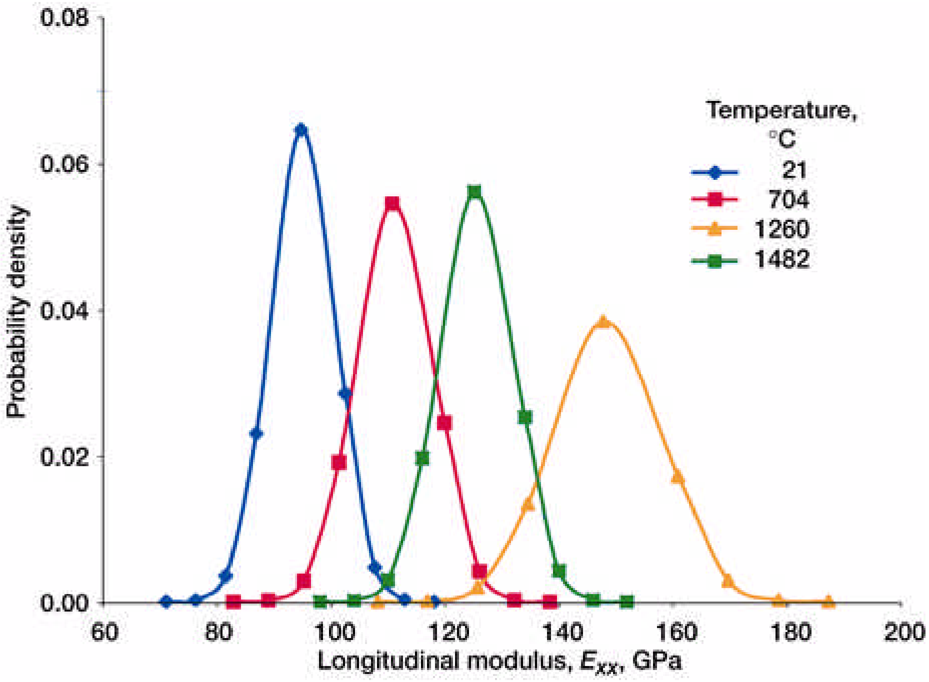
The primary objective of the present work is to develop an efficient computational design tool that could account for all the uncertainties in the constituent properties in a more rigorous manner, and predict the overall composite properties and their probabilistic distributions. Such information could then be used to design structural components to meet the necessary life requirements at an assured level of reliability. In addition to providing more rigor to the analysis than the so-called safety factor approach, such procedures would enhance the interpretation of experimentally observed data, which usually exhibit a wide range of scatter. Furthermore, the procedure would help identify the dominant variables, those that most influence scatter in a specific response, thereby providing guidelines for quality control as well as guidance for data collection resource allocation. It is important to realize that not all variability can be controlled. Thus the methodology could be applied not only in designing with these materials but in designing better CMCs as well.

The approach taken here is to combine the woven CMC analysis in the W-CEMCAN (Woven Ceramic Matrix Composites Analyzer, ref. 1) program with the Fast Probability Integration (FPI) techniques available in the NESSUS computer code (ref. 2). The W-CEMCAN computer program provides functional relationships (micromechanics and macromechanics) that tie the constituent properties and woven composite architecture to the overall composite properties. FPI performs probabilistic analyses by utilizing composite properties generated by W-CEMCAN. The results are cumulative distribution functions of the composite properties. A CDF is a relationship defined by the value of a property (response variable) with respect to its cumulative probability of occurrence. These can easily be converted to probability density functions of the response variable. As a byproduct of the probabilistic analyses, probabilistic sensitivities of response variables to the inherent scatter in the primitive variables are also obtained. As previously mentioned, an integrated approach is adopted in the present work. This approach is a synergistic combination of two methodologies developed in-house at the NASA Glenn Research Center. The first methodology is concerned with woven CMC micromechanics and macromechanics (refs. 1 and 3). The second methodology consists of an FPI technique that takes into account the uncertainties occurring at various scales in a composite material and computes the cumulative probability density functions of composite global behavior. A schematic of the integrated approach is shown in the following figure.



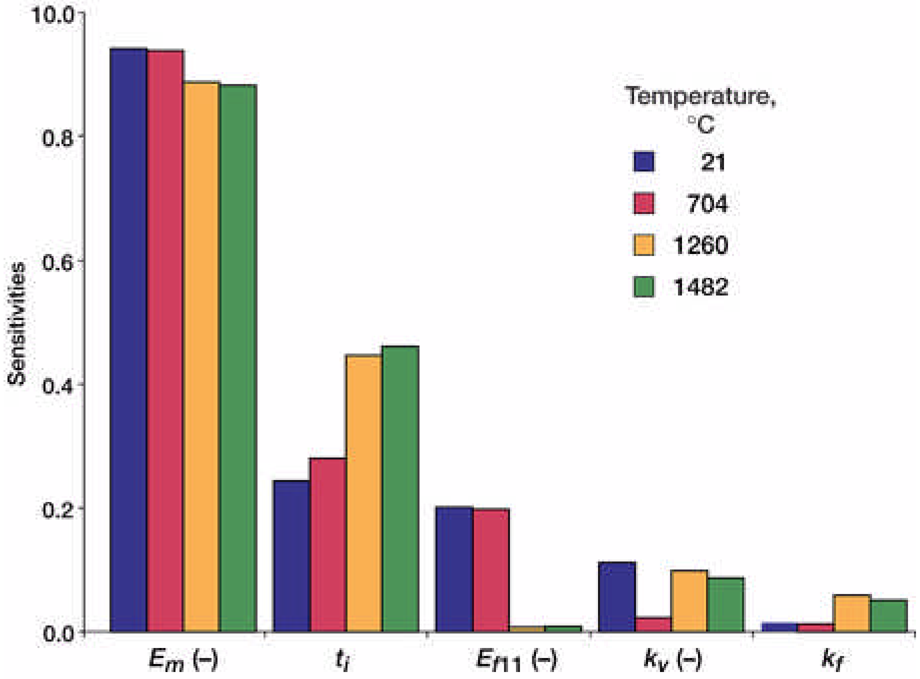
Integrated approach to computational simulation of probabilistic CMC behavior.
Long description. Diagram showing components of fast probability integration analysis engine, including distribution type, sensitivity factors (x_1,x_2, x_3), selected performance function ($Z = f(x_1,x_2, x_3)$), user-specified output options, and response cumulative distribution function.

Typical results for a carbon-fiber-reinforced silicon carbide matrix (C/SiC) woven CMC manufactured by Honeywell Advanced Composites, Inc., are shown in the following graphs (ref. 4). These show the probability density functions of the in-plane tensile modulus and their corresponding sensitivity factors to various primitive variables at a 0.001 probability level and four different use temperatures.



Probability density function of in-plane tensile modulus.

Long description. Graph of probability density versus longitudinal modulus in gigapascals for temperatures of 21, 704, 1260, and 1482 degrees Celsius.



Sensitivity factors of in-plane tensile modulus at probability level 0.001. E_m , matrix material modulus; t_i , coating thickness; E_{f11} , fiber longitudinal modulus; k_v (-), void volume ratio; k_f , fiber volume ratio.

Long description. Bar chart of sensitivities for E_m, t_i, E_{fl1}, k_v, and k_f for the same temperatures as in the preceding figure.

References

1. Mital, Subodh K.; Murthy, Pappu L.N.; and Chamis, Christos C.: Simplified Micromechanics of Plain Weave Composites. J. Adv. Mater., vol. 33, no. 3, 2001, pp. 10-17.
2. NESSUS/FEM User's Manual. Computer Code, version 6.2, Southwest Research Institute, Nov. 1995.
3. Murthy, Pappu L.N., et al.: Computational Simulation of Continuous Fiber-Reinforced Ceramic Matrix Composites Behavior. NASA TP-3602, 1996.
4. Mital, Subodh K.; and Murthy, Pappu L.N.: Characterizing the Properties of a C/SiC Composite Using Micromechanics Analysis. AIAA Paper 2001-1363, 2001.

Glenn contact: Dr. Pappu L.N. Murthy, 216-433-3332, Pappu.L.Murthy@nasa.gov
University of Toledo contact: Dr. Subodh K. Mital, 216-433-3261, Subodh.K.Mital@grc.nasa.gov
Authors: Dr. Pappu L.N. Murthy, Dr. John P. Gyekenyesi, and Dr. Subodh K. Mital

Headquarters program office: OSS
Programs/Projects: RLV