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Characterizing the Properties of a Woven SiC/SiC Composite Using W-CEMCAN Computer Code

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SUMMARY

A micromechanics based computer code to predict the thermal and mechanical properties of woven ceramic matrix composites (CMC) is developed. This computer code, W-CEMCAN (Woven CEramic Matrix Composites ANalyzer), predicts the properties of two-dimensional woven CMC at any temperature and takes into account various constituent geometries and volume fractions. This computer code is used to predict the thermal and mechanical properties of an advanced CMC composed of 0/90 five-harness (5 HS) Sylramic fiber which had been chemically vapor infiltrated (CVI) with boron nitride (BN) and SiC interphase coatings and melt-infiltrated (MI) with SiC. The predictions, based on the bulk constituent properties from the literature, are compared with measured experimental data. Based on the comparison, improved or calibrated properties for the constituent materials are then developed for use by material developers/designers. The computer code is then used to predict the properties of a composite with the same constituents but with different fiber volume fractions. The predictions are compared with measured data and a good agreement is achieved.

INTRODUCTION

The enormous potential that ceramic matrix composites hold for predominantly high temperature structural applications have led to a multitude of research activities pertaining to fabrication, testing, and modeling of these materials. The efforts directed at the development of ceramic matrix composites have focused primarily on improving the properties of the constituents as individual phases. It has, however, become increasingly clear that for CMC to be successfully employed in high temperature applications, research and development efforts should also focus on optimizing the synergistic performance of the constituent phases within the as-produced microstructure of the complex shaped CMC part. This implies development of a specific fabrication process that allows production of complex parts with minimum technical/cost risk. Furthermore, design/analysis tools that allow selection and optimization of the key properties of interest within the physical and chemical constraints of the chosen CMC process would be a requirement as well. Most technically viable CMC methods have focused on a generic approach in which a woven fiber fabric is assembled into a fiber preform of the CMC part which is then infiltrated with the desired interphase and matrix material. For convenience, this CMC fabrication approach will be called WPI for its fundamental use of Woven fiber Preform construction and interphase/matrix Infiltration. These processes usually lead to complex CMC microstructures. Limited thermo-mechanical data on advance SiC/SiC CMC fabricated by WPI processes have shown good behavior both at low and high temperatures. However, because of their complex microstructures, very little effort has been initiated in the second important area of mechanistic modeling for design

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and performance optimization of the total WPI CMC system. There is certainly a need for sound engineering data as well as verified and efficient analytical/design methodologies to evaluate different constituent parameters for use of these advanced CMC's in structural components with assured reliability. The present paper addresses this specific issue.

The need to analyze woven composites has been addressed by many researchers (refs. 1 to 7). A review of various approaches can be found in reference 2. Reference 1 addresses an approach based on micromechanics for plain weave composites consisting of fiber, matrix and coating or interphase as three distinct constituents. An approach based on classical laminate theory to predict the laminate level properties is presented in reference 3. It should be noted that in such approaches, details regarding local response within fiber tows, interphase and matrix rich areas are lost due to the smearing involved in considering the ply level properties as a starting point. Numerical methods based on three-dimensional finite element formulations overcome such difficulties and do address the local detailed response. However, because of the complex microstructure, model generation itself can be quite time consuming in the case of three-dimensional finite element analyses. For this reason, such analysis techniques are not practical for routine trade-off studies for optimizing the constituent geometries or volume fractions to obtain a desired response characteristic (ref. 4). Others have addressed the computational aspects by adopting a judicious combination of micromechanics and three-dimensional finite element formulations that overcome the above shortcomings to some extent (ref. 7). However, they have not addressed the issue of multiple constituent phases typically present in an advanced WPI CMC. In summary, a completely micromechanics based formulation accounting for the various constituent phases specific to advanced woven CMC's that are being considered for some of the high temperature engine applications is currently not available. Development of such an approach is desirable as it provides an efficient tool to quickly analyze woven CMC's made of different fiber architectures as well as multiple constituents. They also enable the designer to account for constituent level material nonlinearity, environmental effects, and constituent geometry.

The authors have developed a micromechanics based technique to predict the properties of advanced WPI ceramic matrix composites. Details regarding that technique were presented earlier (ref. 8). The properties of a five-harness SiC/SiC composite at various temperatures were predicted. This composite was made of 0/90 Sylramic weave with boron nitride interfacial coating and multiple matrix phases, using a manufacturing process described in the next section. However, the constituent properties at elevated temperature are not readily available. The constituents properties used were based on the best initial estimates and judgement along with properties available in the literature and any measured data obtained from the HSR (High-Speed Research) program of NASA. It was realized that there were some issues regarding the constituent properties and the confidence that can be put in these properties, particularly those of BN coating and MI (melt-infiltrated) silicon carbide matrix material. When the predictions were compared with the measured data obtained from the HSR program, the comparison was reasonable for some properties and poor for certain other properties. It was decided that a calibrated set of constituent properties needs to be established by comparing the predictions with the measured data. The material developers/design engineers will be able to use this calibrated set of properties to carry out trade-off studies to optimize key composite properties and generate a set of properties needed by the design engineers, difficult to measure experimentally.

The objective of the present work is to develop a set of calibrated constituent properties that can be used for WPI SiC/SiC composites based on BN interphase and MI SiC material. The first section briefly describes the WPI process and the following section describes computer code that incorporates the technique developed by the authors previously to analyze the WPI composites. It makes use of the capabilities of the CEMCAN (Ceramic Matrix Composite Analyzer) developed previously by the authors (refs. 9 and 10). An overall schematic of the approach embedded in CEMCAN computer code is shown in figure 1. The properties of an advanced SiC/SiC composite with a five-harness satin weave are then predicted and compared with measured data. Based on this comparison, a set of calibrated constituent properties was created as a function of temperature. This set of constituent properties was then used to predict the properties of a composite with a different volume fraction. The capabilities and potential uses of such an analytical tool are then briefly outlined.

WPI PROCESSES AND CONSTITUENT GEOMETRIES

In general, the objective of the WPI fabrication approach is to produce complex-shape CMC components with processes that will allow (1) full retention of the as-produced fiber strength, (2) fiber architectures with high fiber volume fractions in the principal stress directions, (3) fiber interfacial coatings with uniform thickness and desirable interaction with the matrix phase, and (4) matrix phases that inhibit fiber and coating attack by the component environment while providing other important CMC properties such as high thermal conductivity and interlaminar strength.

Typically in the WPI approach, a three-dimensional fiber preform is formed by weaving continuous-length fiber tows in a desirable three-dimensional pattern or architecture or by stacking two-dimensional woven fiber fabric into multiple layers or plies. For this study, only two-dimensional fiber architecture will be considered. In the case of two-dimensional woven fabric composites, two mutually orthogonal sets of yarns of the same material (nonhybrid) or different material (hybrid) are interlaced with each other. Various types of weaves can be formed depending upon how the pattern in the interlaced region is repeated. Plain weave, 5-harness and 8-harness satin weaves are some of the variations of two-dimensional orthogonal weaves. For example, in the case of 5-harness satin weave, a “warp” or longitudinal fiber tow is interlaced with every fifth “fill” or width fiber tow. A typical cross-section of the repeating unit cell is shown in figure 2(a). If one takes a section where the fiber tow is straight, the construction is like a [0/90] laminate. There are wavy portions of the fiber tow and there are matrix rich areas whose volume fraction depend upon the geometry and can be a substantial fraction of the overall volume. The fiber tow or fiber yarn is usually composed of several hundred or even thousands of filaments. Fiber tow cross-sectional dimensions, in the as-fabricated composites, depend upon the fiber type as well as the weaving conditions. Another important parameter is ends per inch (epi), i.e., the number of fiber tows in a linear inch. The epi with the ply height determines the overall fiber volume fraction in the composite.

Once the fiber perform is made, an interfacial coating is deposited on all the fiber surfaces typically by a chemical vapor infiltration (CVI) process. The volume fraction of this interfacial coating is determined from the weight gain of the fiber preform. Following this, the component is infiltrated with matrix constituents, usually by gas, slurry or liquid processes or a combination these processes. Ideally, the matrix phase first fills up the area within the tow (intratow) and then forms a thin coating around the fiber tow. The intertow region can then be filled by using the same or different infiltration processes. Again, the volume fraction of the different matrix phases is estimated by measured weight gains and knowing the densities of those phases. There is, generally, a small residual porosity both in the intratow and intertow regions. Efforts are underway to minimize the porosity in both areas since it is known that porosity reduces CMC performance. Many advanced CMC’s are employing a final high temperature matrix infiltration step in which a matrix precursor is added in liquid or molten stage. This step known as melt infiltration (MI) typically results in very low porosity composites.

WOVEN COMPOSITE MODELING: W-CEMCAN COMPUTER CODE

The computer code W-CEMCAN (Ceramic Matrix Composite Analyzer for Woven Ceramic Matrix Composites) is an out growth of CEMCAN (ref. 10), which was originally developed for continuous filament reinforced laminated ceramic matrix composites. The code is based upon micromechanics and employs a unique fiber sub-structuring concept. This code was further enhanced to analyze composite materials consisting of stacked two-dimensional woven fabric. Application of the plain weave composite code to graphite/epoxy and SiC/SiC composites is presented in reference 1. The approach used is quite generic and in fact can be applied to any type of satin weave architecture. The present research effort focuses on automating the process so that a user can routinely analyze different woven architectures with minimal input. Table I provides details of the input needed by the code and a summary of resulting output.

The modeling details will be explained briefly in this report with respect to a 5-harness satin weave. Figure 2(a) shows a cross section of the unit cell of a 5 HS weave and 2(b) shows a vertical slice taken from the cross section showing details of different constituents namely, the 0° fibers, 90° fibers and matrix rich area. The geometry of these regions depends upon the particular weave architecture. Also shown are the details of a typical unit cell from the interior of fiber tow with three distinct constituents: fiber, matrix, and BN coating (interphase). For modeling purposes, the parts where the fiber tow is straight, the construction is assumed to be like a [0/90] laminate. In other parts, where the fiber tow is wavy or has a “crimp,” the undulated shape of the fiber tow is assumed to be same as was assumed before by the authors (ref. 1). It matches closely with the geometry observed in photomicrographs. Furthermore, it is assumed here that laminate theory is applicable at each section of the model along the x-axis. One such section is shown in figure 2(b). For a slice in the straight region, the equivalent properties of the slice can be obtained by running a [0/90] laminate analysis. For slices where the fiber is undulated, the following technique is used–a typical slice in the undulated region looks like the one shown in figure 2(b). In general, it will have four regions –0° fiber region, 90° warp fiber region, a thin layer of matrix phase around the fiber tow region and a matrix rich area. The off-axis angle of the warp yarn in any slice is known because of the assumed geometrical shape of the warp yarn. In-plane stiffness of this particular slice can be obtained using a laminate analysis of a [90/θ/0] laminate. From these one can obtain the longitudinal modulus at this section E_{xx}. The 90 “ply” in this “laminate” represents a fill yarn, θ “ply” represents the warp yarn and the 0 “ply” represents the matrix rich area. The thickness of each “ply” is properly accounted for depending upon the location of a particular slice in the section. Equivalent through-the-thickness modulus E_{zz} can be obtained as the E_{yy} of the [0/θ/0] laminate. In a regular laminate analysis, the ply is oriented in the X-Y plane. In this situation, the 0° fiber tow has an inclination in X-Z plane. To account for that properly, the existing laminate analysis codes have to be used judiciously taking into account proper orientations.

Once the equivalent properties of a vertical slice are established, the procedure is repeated for all other slices along the length of the representative volume element. In the next step these slices are stacked up as plies in a laminate and CEMCAN’s laminate analysis capability is once again utilized to arrive at equivalent properties for the section shown in figure 2(a). This now represents equivalent properties of a 5-harness [0/90] woven CMC material. The details of this technique are provided in reference 1. The process is equally applicable to a N-harness [0/90] woven CMC in general. The number of vertical slices is a user input parameter and in the present study 40 vertical slices are used which was arrived at after performing several sample runs to test convergence of properties. Since this technique is based on micromechanics, it is computationally more efficient compared to a full three-dimensional finite element analysis approach. Any level of detail can be modeled routinely. The incorporation of processing, effects of voids and environmental degradation etc., can be easily incorporated in the analysis as well.

RESULTS/DISCUSSION

In order to illustrate the capabilities of W-CEMCAN computer code, a specific CMC system made of Sylramic (SiC fiber) 0/90 5-harness woven preform coated with BN and CVI-SiC and subsequently melt infiltrated with SiC matrix was chosen. This material system has been fabricated and tested under the NASA EPM (Enabling Propulsion Materials) program as a part of the HSR (High-Speed Research) initiative at NASA. Two specific 5-harness satin weave composite systems; one with 18 and one with 22 epi fiber tow spacing were fabricated and tested (ref. 12). The experimental data from the 22 epi material was utilized to calibrate constituent properties, necessary to run W-CEMCAN as well as to predict composite mechanical and thermal properties of 18 epi material. The calibration of constituent properties was necessary due to the fact that the in-situ and the bulk properties often differ and many times bulk properties, as a function of temperature, are simply not available. In the present approach the following procedure is followed. The constituent properties are obtained from literature, handbooks or from measured data under NASA’s EPM program and are used as such to predict the overall composite properties. Some of these properties are calibrated using the experimental data for 22 epi CMC. With the calibrated constituent properties, the 18 epi CMC properties are predicted and compared with experimental results.

The fiber tow is made of Sylramic fibers with a tow count of 800. For 22 epi CMC, microstructural observations indicate an average tow height of 115 μm (4.5 mils), and an average tow width of 985 μm (38.5 mils). The cross-sectional shape of the fiber tow is approximated as an elongated ellipse, which results from the fiber weaving process and the compression process during preform lay-up. The tow-width (A) depends upon fiber tow count (N) and fiber diameter (d). From figure 2(a), the unit cell width (X’) depends only on the epi by the relation X’ = 1/epi. The intertow spacing B is simply given by B = X' – A.

The laminate preform contains 8 plies of 5 HS fabric in 0/90 architecture. Each ply has a 0/90 woven preform and has a nominal thickness of 254 μm (10 mils) for a total average observed laminate thickness of 2032 μm (80 mils). Fiber preforms are coated with boron nitride (BN) using a CVI process, followed by a thin coating of SiC material again using a CVI process. The CVI-SiC material goes inside the fiber tow region, depending upon the BN volume fraction and also forms a thin coating around the fiber tow region. The rest of the laminate is then filled with a SiC matrix using a melt infiltration (MI) process. The overall fiber volume ratio is ~42 percent for 22 epi composite and the void volume fraction is ~7 percent, while the fiber volume ratio is ~34 percent and void volume ration is ~4 percent for the 18 epi material. The fiber volume ratio in the fiber tow itself is generally much higher than the overall fiber volume ratio because of denser packing within the tow.

The initial constituent material properties based on literature properties of the constituents in the bulk form were obtained from reference 13 and are shown in table II. The numbers within the parentheses are the calibrated constituent properties using the experimental results for the 22 epi composite system. Table III shows the average volume fractions obtained from corresponding weight gains of different constituents or obtained from the photo micrographs for both 18 (F-34 for 34 percent fiber volume fraction) and 22 epi (F-42 for 42 percent fiber volume fraction) CMC materials whose thermal and mechanical properties have been measured. The variation of constituent properties due to temperature is modeled through the following functional relationship (ref. 9):

$$\frac{P}{P_o} = \left[\frac{T_f - T}{T_f - T_o} \right]^n \tag{1}$$

where P is the constituent property at temperature T, and P_o is the reference property at the reference temperature T_o, usually the room temperature. T_f is the final temperature where the property is nearly zero and n is an exponent. Based on the constituent properties data provided in table I as a function of temperature, the T_f and n were computed for each of the constituent.

5-Harness 22 Ends/Inch Weave

The predictions based on estimated constituent properties, experimental data as well as predictions based on calibrated constituent properties are shown in figures 3 to 7. The in-plane tensile modulus predictions are compared to experimental data in figure 3 at various temperatures. The predictions based on original constituent properties show higher moduli and steeper degradation compared to the experimentally observed behavior. It should be noted that the BN moduli, based upon the values reported in the literature (ref. 11) shows a steep degradation (table I). Since the interface conditions are generally not precisely known, it was decided to calibrate this property using the average measured value of in-plane tensile modulus. Accordingly, BN modulus was calibrated and is shown within the parenthesis in table I. The predicted in-plane modulus with the calibrated properties is shown with a dashed line in figure 3 as well. With the aid of these calibrated properties for the constituents as well as the original constituent properties, the through-the-thickness modulus is predicted and compared with values that are 80 percent of the corresponding in-plane value at that temperature, a practice commonly used by design engineers, and shown in figure 4. The predictions show a much steeper degradation of the property due to temperature than the assumed values of the MI CMC. This assumption of a flat 80 percent reduction of the longitudinal modulus may not provide a conservative estimate of the through-the-thickness modulus. One certainly needs to correlate this with data or infer through-the-thickness modulus with a related experimental result. A micromechanics based analysis tool that predicts a consistent set of properties for design/analysis components made of these materials is useful.

The predictions for the thermal conductivities along with the experimental data are shown figures 5 to 6. The predicted values based on the original constituent properties for in-plane as well as through the thickness thermal conductivities are much higher than the measured values, especially at room temperature. The thermal conductivity of MI matrix is adjusted accordingly to produce a closer match the room temperature predictions and the measured data. The original conductivity value of MI matrix appears to be too high. Due to the thermal expansion coefficient mismatch between free silicon and the surrounding medium, fine gaps could form in the MI matrix such that its in-situ thermal conductivity could be considerably lower than the bulk values. Therefore, it was decided to calibrate this property based on the measured data. The calibrated predictions shown by the dashed curve in figures 5 to 6 agree closely with the measured data.

The experimental and predicted values of coefficients of thermal expansion as a function of temperature are shown in figure 7. The predictions agree well with measured data after calibration of constituent thermal expansion coefficient values. It should be noted that the expansion coefficients for CVI-SiC and Sylramic fiber are assumed to be the same and the MI matrix expansion coefficient is different. Both needed to be adjusted in order to achieve agreement with the measure data as indicated in table I. The computer code also predicts shear moduli and Poisson’s ratio as functions of use temperature. These are not explicitly shown, as the constituent property data as a function of temperature is not readily available. It should be noted that a consistent set of all the properties are required to perform design/analysis and the present code provides such properties, some of which are difficult to measure.

5-Harness 18 Ends/Inch Weave

With the aid of the calibrated constituent properties, a similar set of results is generated for 18-epi 5-harness satin woven composite properties. These are shown in figures 8 to 12. The selected constituent volume ratios, computed from the weight gains are also shown in table II and identified as constituents F-34 (for 34 percent fiber volume fraction). The agreement between the predictions using the calibrated constituent properties and the measured data is excellent. The trends shown for the various properties are similar to those for 5-harness 22-epi satin weave composite. The results show that changes in the tow count and thus, the fiber volume fraction effect the composite thermal conductivities and moduli only slightly. It has very minimal effect on the composite thermal expansion coefficients. The results confirm that the computer code is able to predict the behavior of woven CMC. For any material system, one needs to calibrate the material properties of the constituents using similar procedures described above.

CONCLUSIONS

A micromechanics based computer code W-CEMCAN was utilized to predict the thermal and mechanical properties as a function of temperature of a 5-harness satin weave CMC material. The material is composed of Sylramic fiber with CVI-BN and CVI-SiC coatings and MI-SiC matrix. Two different materials, one with a count of 22 epi and one with 18 epi, were considered for this work, as measured data are available for these materials. The measured data for 22 epi CMC were utilized to calibrate some of the in-situ constituent properties. Once calibrated, the same properties were used to predict the properties of 18 epi CMC material. The predictions of the code are found to be very good when compared with the available test data. Some general observations can be made:

1. The computer code provides an excellent tool for trade-off studies that will allow the optimization of a key composite property, calibration of in-situ constituent properties through back calculations and generation of a complete and consistent set of properties for design/analysis studies. It is important to note that many of the properties needed for analysis are often difficult to establish through measurements and usually only a handful of properties can be measured and are available to analyst.
2. Through-the-thickness modulus and conductivity are anywhere from 50 to 80 percent of the corresponding in-plane value at that temperature. Assumption of a flat reduction of 20 percent throughout the range of temperature for the through-the-thickness modulus and conductivity for design data therefore could lead to nonconservative estimates. These properties should be inferred from a test to validate the predictions.
3. Increasing the tow count from 18 to 22, i.e., increasing the overall fiber volume ratio from 35 to 42 percent or equivalently decreasing the fiber tow spacing, decreases the composite thermal conductivities and moduli only slightly. It has practically no effect on the composite thermal expansion coefficient at all temperatures.

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TABLE I.—W-CEMCAN INPUT-OUTPUT

Input	Output
Ends per inch, epi Filament count in fiber tows Ply thickness Constituent properties (fiber, matrix, coating, secondary matrix)–Resident databank Coating thickness Volume fractions (fiber, voids) Number of plies Use temperature Weave parameter (2,5,8 etc.)	Composite mechanical properties-normal and shear moduli, Poisson's ratios Composite thermal properties-thermal conductivities, expansion coefficients, heat capacity etc. Composite three-dimensional stress/strain relations Material properties for FE analysis Force/displacement relations for the composite

TABLE II.—CONSTITUENT PROPERTIES

	20 °C	600 °C	1200 °C
Sylramic fiber			
Density, gm/cc	3.1	– – – – –	– – – – –
Modulus, GPa	380	368	356
Poisson's ratio	0.17	– – – – –	– – – – –
Thermal conductivity, W/m-K	43.0	34.5	20.4
Coefficient of thermal expansion, 10^{-6}/C	2.62 (2.2)	4.8 (4.0)	6.0 (4.6)
CVI-SiC matrix			
Density, gm/cc	3.2	– – – – –	– – – – –
Modulus, GPa	425	413	401
Poisson's ratio	0.17	– – – – –	– – – – –
Thermal conductivity, W/m-K	65	46	27
Coefficient of thermal expansion, 10^{-6}/C	2.62 (2.2)	4.8 (4.0)	6.0 (4.6)
MI-SiC matrix (a two-phase material, ~50 percent SiC particulate and ~50 percent silicon)			
Density, gm/cc	2.86	– – – – –	– – – – –
Modulus, GPa	345	333	321
Poisson's ratio	0.17	– – – – –	– – – – –
Thermal conductivity, W/m-K	120 (70)	49.3 (49)	29.2 (30)
Coefficient of thermal expansion, 10^{-6}/C	2.7 (2.3)	4.9 (4.1)	6.2 (4.7)
CVI-BN coating			
Density, gm/cc	1.4	– – – – –	– – – – –
Modulus, GPa	62	[a]29 (41)	[a]7 (18)
Poisson's ratio	0.17	– – – – –	– – – – –
Thermal conductivity, W/m-K	6.9	[a]5.2	[a]3.5
Coefficient of thermal expansion, 10^{-6}/C	6.3	[a]5.2	[a]3.7

[a]Estimated.

Note: The numbers in parentheses show calibrated properties.

TABLE III.—CMC CONSTITUENT VOLUME RATIOS

[800 count fiber tow; fiber density 3.1 gm/cc; fiber diameter = 9.4 μm

Constituent	Total volume fraction	
	22-epi; 5-HS composite Constituents: F-42, percent	18-epi; 5-H/S composite Constituents: F-34, percent
Fiber (Sylramic)	42	34.5
CVI-BN coating	17	13.6
Porosity	7	4
CVI-SiC[a]	21	25.6
MI-SiC[b]	13	22.3

[a]Includes any CVI-SiC inside the fiber-tow region as well as a layer of CVI-SiC around fiber tow.

[b]Includes both SiC particulate and free silicon, treated as one material in this work.

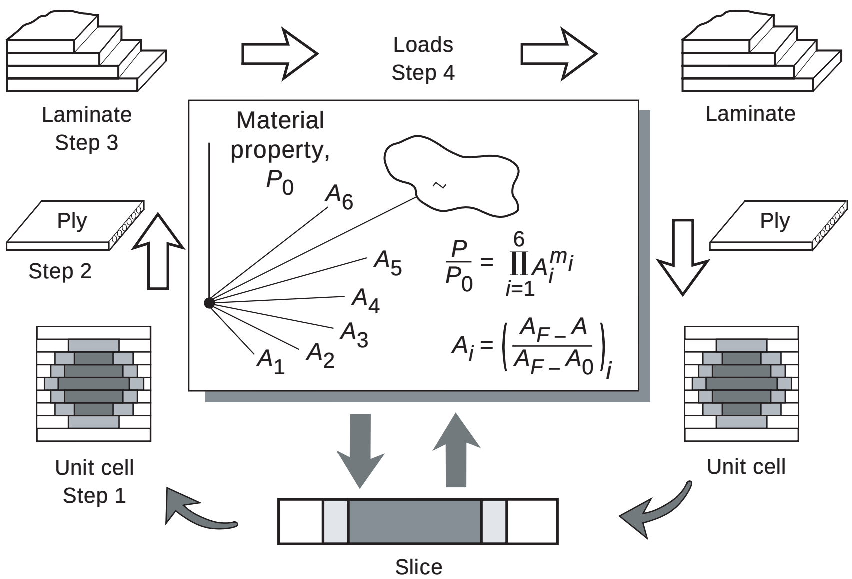

Figure 1.—Integrated analysis approach embedded in CEMCAN computer code.

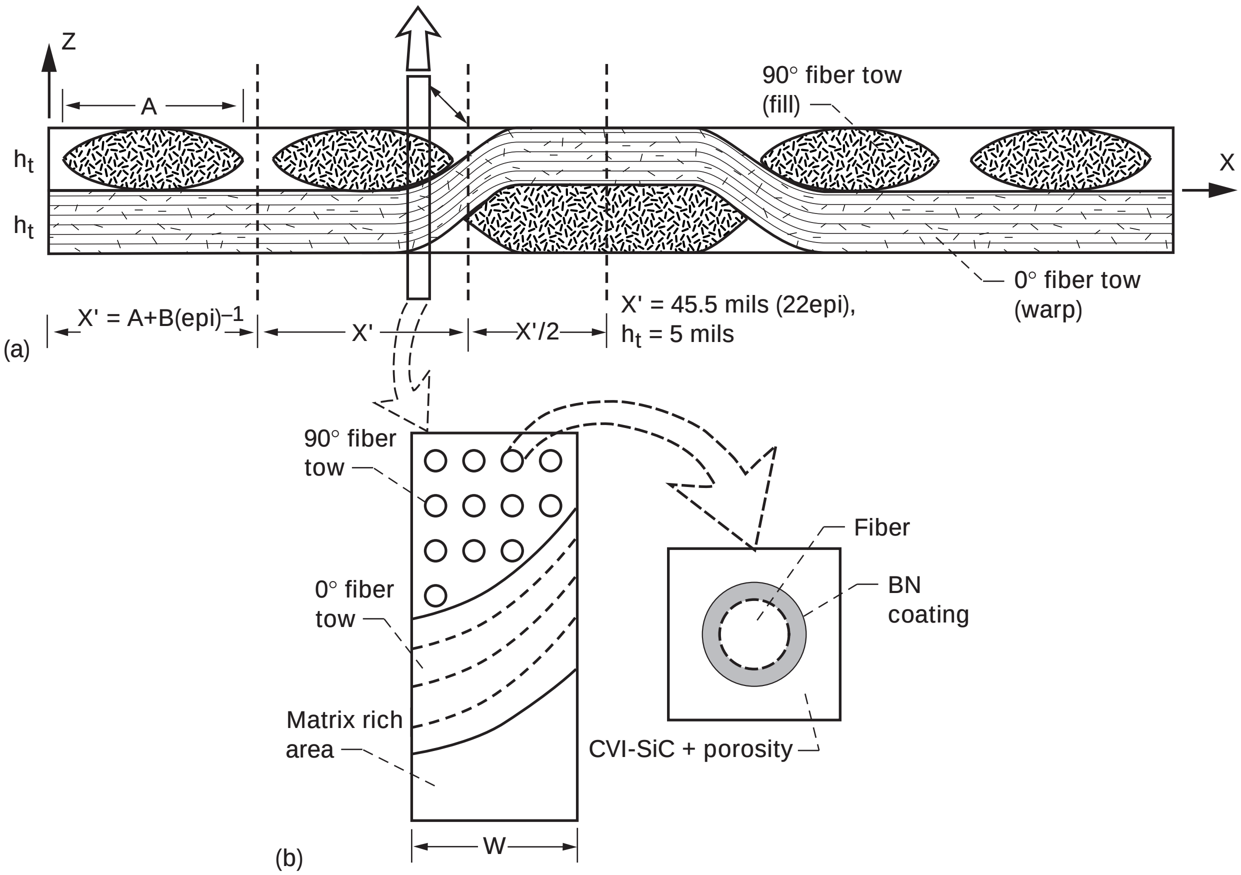

Figure 2.—Woven composite analysis modeling details.

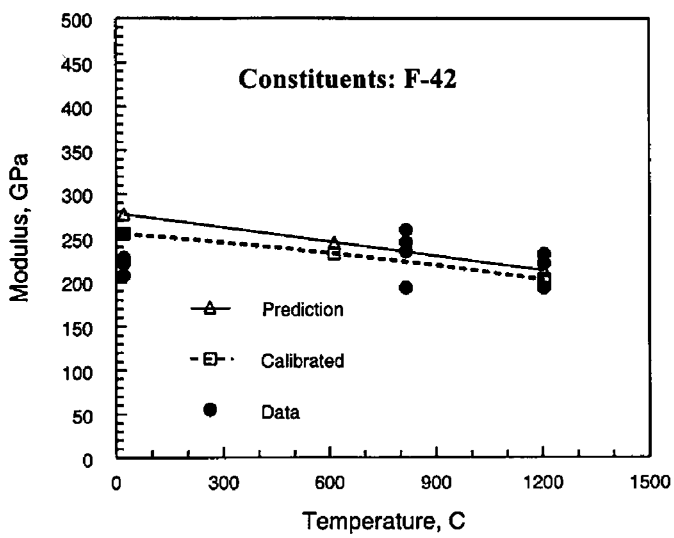

Figure 3.—In-plane tensile modulus. Constituents: F-42.

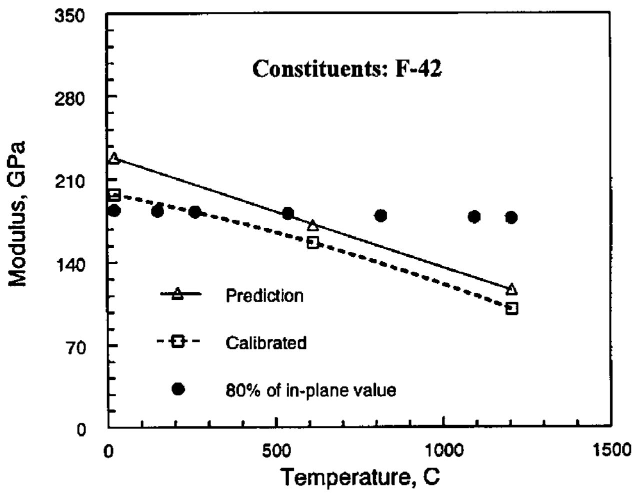

Figure 4.—Through-the thickness tensile modulus. Constituents: F-42.

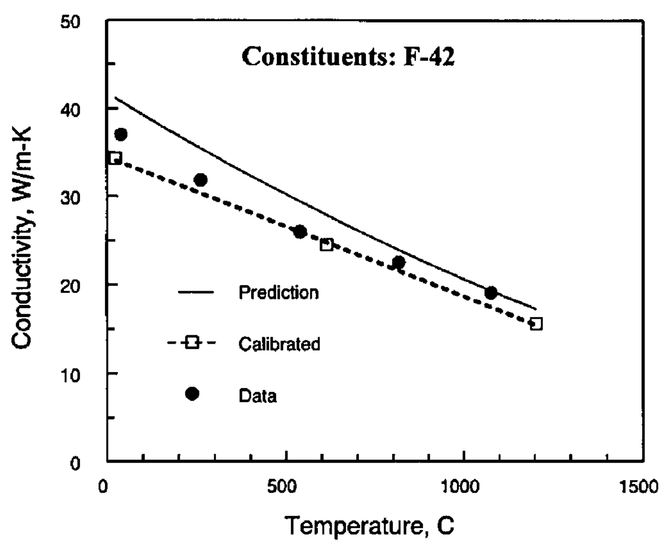

Figure 5.—In-plane thermal conductivity. Constituents: F-42.

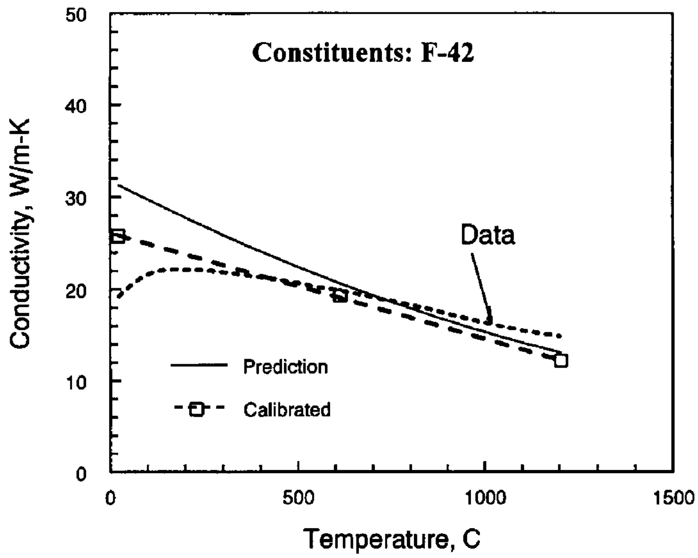

Figure 6.—Through the thickness thermal conductivity. Constituents: F-42.

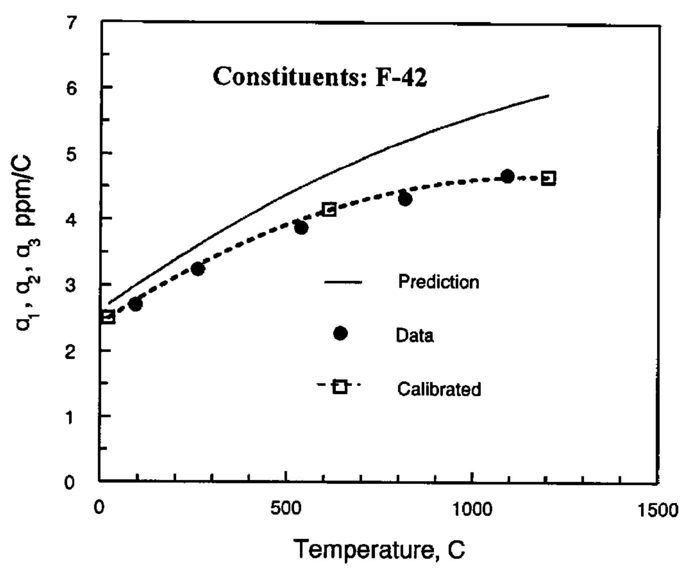

Figure 7.—Coefficient of thermal expansion. Constituents: F-42.

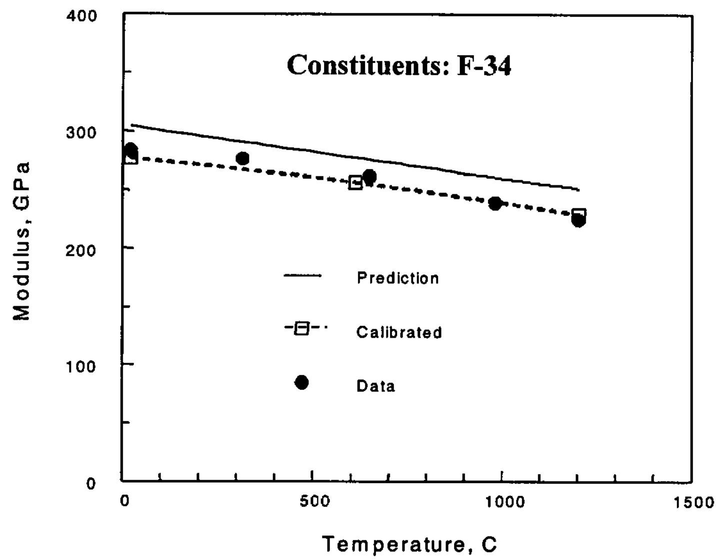

Figure 8.—In-plane tensile modulus. Constituents: F-34.

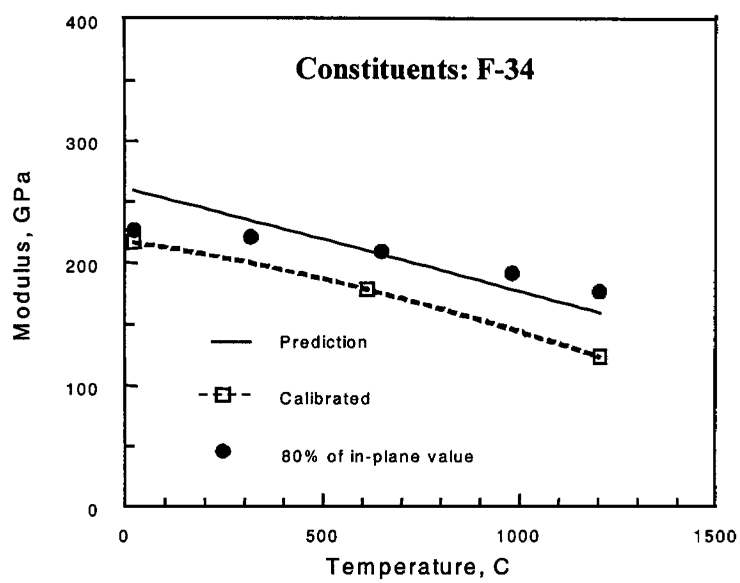

Figure 9.—Through the thickness tensile modulus. Constituents: F-34.

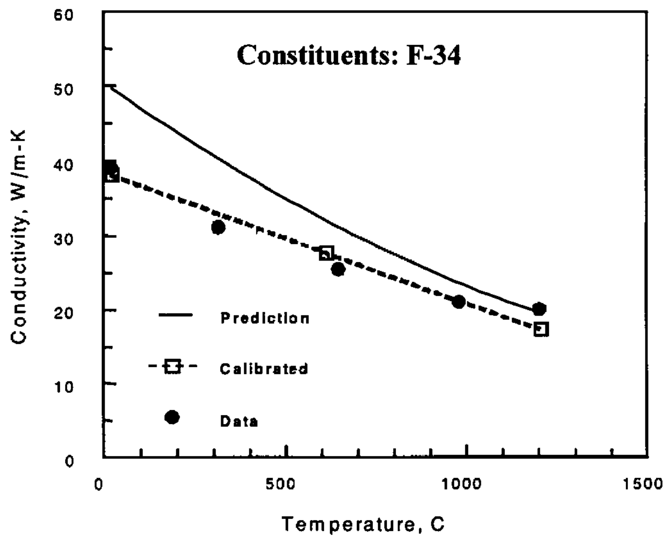

Figure 10.—In-plane thermal conductivity. Constituents: F-34.

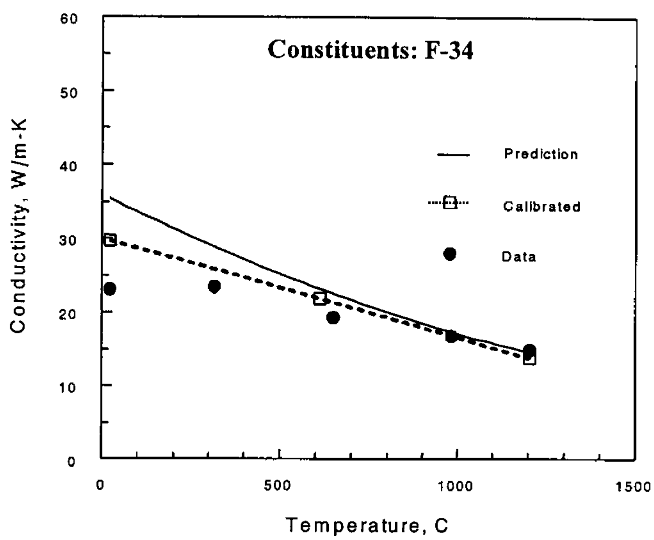

Figure 11.—Through the thickness thermal conductivity. Constituents: F-34.

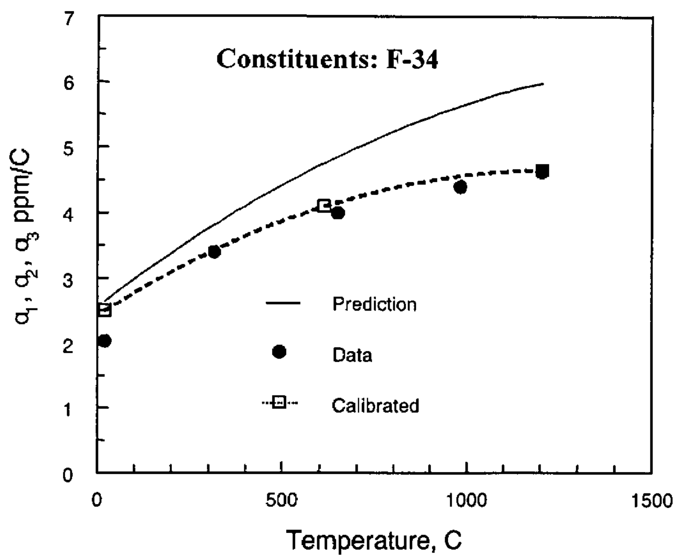

Figure 12.—Coefficient of thermal expansion coefficient. Constituents: F-34.

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

A micromechanics based computer code to predict the thermal and mechanical properties of woven ceramic matrix composites (CMC) is developed. This computer code, W-CEMCAN (Woven CEramic Matrix Composites ANalyzer), predicts the properties of two-dimensional woven CMC at any temperature and takes into account various constituent geometries and volume fractions. This computer code is used to predict the thermal and mechanical properties of an advanced CMC composed of 0/90 five-harness (5 HS) Sylramic fiber which had been chemically vapor infiltrated (CVI) with boron nitride (BN) and SiC interphase coatings and melt-infiltrated (MI) with SiC. The predictions, based on the bulk constituent properties from the literature, are compared with measured experimental data. Based on the comparison, improved or calibrated properties for the constituent materials are then developed for use by material developers/designers. The computer code is then used to predict the properties of a composite with the same constituents but with different fiber volume fractions. The predictions are compared with measured data and a good agreement is achieved.

14. SUBJECT TERMS
Woven composite; Melt-infiltrated; Porosity; Sylramic fiber; Boron nitride coating; Chemical vapor infiltration; SiC composite; Five-harness

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