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Probabilistic Simulation of Multi-Scale Composite Behavior

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September 2012

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Probabilistic Simulation of Multi-Scale Composite Behavior

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Abstract

A methodology is developed to computationally assess the non-deterministic composite response at all composite scales (from micro to structural) due to the uncertainties in the constituent (fiber and matrix) properties, in the fabrication process and in structural variables (primitive variables). The methodology is computationally efficient for simulating the probability distributions of composite behavior, such as material properties, laminate and structural responses. Bi-products of the methodology are probabilistic sensitivities of the composite primitive variables. The methodology has been implemented into the computer codes PICAN (Probabilistic Integrated Composite ANalyzer) and IPACS (Integrated Probabilistic Assessment of Composite Structures). The accuracy and efficiency of this methodology are demonstrated by simulating the uncertainties in composite typical laminates and comparing the results with the Monte Carlo simulation method. Available experimental data of composite laminate behavior at all scales fall within the scatters predicted by PICAN. Multi-scaling is extended to simulate probabilistic thermo-mechanical fatigue and to simulate the probabilistic design of a composite redome in order to illustrate its versatility. Results show that probabilistic fatigue can be simulated for different temperature amplitudes and for different cyclic stress magnitudes. Results also show that laminate configurations can be selected to increase the redome reliability by several orders of magnitude without increasing the laminate thickness—a unique feature of structural composites. The old reference denotes that nothing fundamental has been done since that time.

1.0 Introduction

Polymer matrix composites (PMC) form an important class of engineering materials in structural applications. Their outstanding mechanical properties, such as durability and corrosion-resistance characteristics combined with low density, are very attractive to the aerospace industry. The mechanical properties of composite materials depend on a wide variety of composite structures shows a scatter from its average value. Traditionally, an ad-hoc "safety factor" is used in the design to account for the difficulty in predicting the structural behavior. However, this approach may result in either an ultraconservative or an unsafe design.

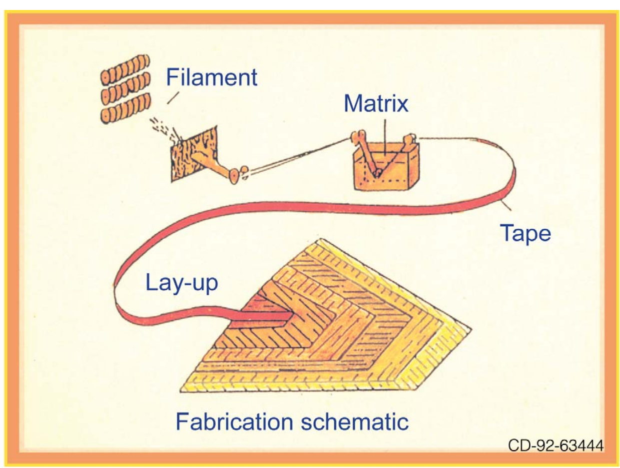
In order to non-deterministically/probabilistically assess the behavior of composite structures, a methodology was developed at the NASA Glenn Research Center for simulating the probabilistic material properties in all composite scales (Ref. 1 to 3). The methodology requires the identification of uncertainties of primitive variables at constituent levels including material properties and fabrication process variables, ply, laminate and structural scales which are then filtered through PICAN and IPACS to computationally simulate the probabilistic laminate and structural responses. Although the uncertainties in primitive variables on laminate and structural responses can be computed by the Monte Carlo simulation (MCS) method, it is inefficient and expensive. In order to save computational time, a newly developed methodology uses the Fast Probability Integration (FPI) algorithm, instead of the traditional Monte Carlo simulation. This provides an efficient and affordable way for computationally simulating the uncertainties in composite structural responses. As mentioned previously, the methodology was implemented in the computer code PICAN (Probabilistic Integrated Composite ANalyzer) and in

IPACS (Integrated Probabilistic Assessment of Composite structures (Ref. 4), which are described in the present paper. The uncertainties of composite material properties at ply and laminate levels were simulated via PICAN. Extension to laminate thermomechanical fatigue and to composite redome design are described to illustrate multi-scaling versatility in probabilistic simulation of complex composite behavior and structures. Simulation of probabilistic multi-scaling for composite laminate behavior (laminate scale) is described first, followed by probabilistic multi-scaling of laminate thermomechanical fatigue (loading scale) and then probabilistic multi-scaling of composite structural design (structural scale).

2.0 Non-Deterministic/Probabilistic Simulation of Composite Response

Composite materials are made of fiber and matrix through an appropriate fabrication process. Since the mechanical properties of the constituent material vary statistically, the uncertainties in composite material properties are produced from the uncertainties in the constituent material properties, also from the uncertainties in the fabrication parameters. The probabilistic simulation of composite material properties requires identification of uncertainties at all composite scales as described below. Also note the non-deterministic and probabilistic are synonyms.

Many thermoset laminated fiber-reinforced composite materials are manufactured by three basic steps: tape, layup and curing (see Fig. 1). The uncertainties incurred during the layup process are due to the misalignment of ply orientation. Typical uncertainties incurred from the curing process are intralaminate voids, incomplete curing of resin, excess resin between plies, excess matrix voids and porosity, and variation in ply thickness. Uncertainties incurred in the constituent material properties include all the fiber and matrix material properties. These uncertainties are referred to as uncertainties in the composite primitive variables (as enumerated in Fig. 1) which will be processed computationally through composite mechanics and probability methods as depicted in Figure 2. The details of the computer code PICAN for the computational simulation of uncertainties in composite material properties are described next.



- Constituents (fiber and matrix properties)
- Fiber misalignment
- Fiber volume ratio
- Void volume ratio
- Ply misalignment
- Ply thickness

Figure 1.—Primitive variables in the typical fabrication process.

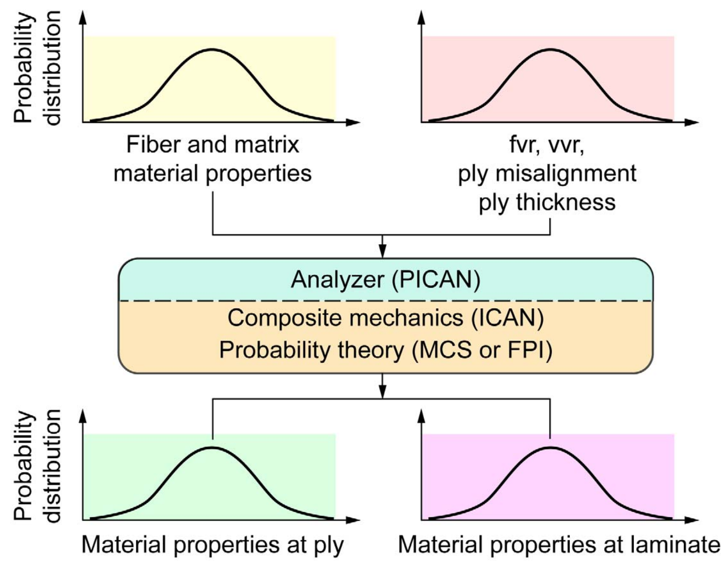


Figure 2.—Probabilistic simulation of composite behavior; fvr, fiber volume ratio; vvr, void volume ratio.

3.0 Probabilistic Integrated Composite Analyzer: PICAN

PICAN (Probabilistic Integrated Composite ANalyzer) is a computer code for the probabilistic simulation of composite behavior (material properties). It integrates two NASA in-house computer programs, ICAN (Integrated Composite ANalyzer) (Ref. 5) and FPI (Fast Probability Integrator) (Ref. 6). ICAN was developed based upon composite mechanics to simulate the composite material behavior at all composite scales including many effects of environment and fabrication. FPI, developed using structural reliability algorithms, probabilistically processes the material property information generated by ICAN and efficiently computes the cumulative distribution functions (cdf) of composite material properties at all composite scales. Further details of ICAN and FPI are explained in the following

4.0 ICAN Module

The ICAN module (Ref. 5) performs a comprehensive analysis of composite material properties at all scales by selectively perturbing the primitive variables at the constituent level (fiber and matrix material properties, fiber volume ratio and void volume ratio), and the ply level (ply misalignment and ply thickness). Perturbed material properties at all composite scales corresponding to all the perturbed primitive variables are computed and stored in a database.

5.0 FPI Module

The FPI module (Ref. 6) performs the probability evaluations. It takes the relationship between the composite material property and the primitive variables as well as the probability distributions of the primitive variables to compute the probability distribution of that material property. The relationship is expressed as

$$M_p = a_0 + \sum_{i=1}^{N} a_i V_i + \sum_{i=1}^{N} b_i V_i^2 \quad (1)$$

where M_p is any material property; N is the number of primitive variables considered; V_i are the primitive variables; a_0, a_i, b_i are calculated constants to satisfy equation equilibrium. More theoretical details concerning FPI can be found in Reference 6.

6.0 PICAN Simulation

The primitive variables at the constituent and the ply levels are first identified and their respective distribution type and corresponding parameters are rarely known but most often are assumed. These variables are then selectively perturbed in order to create a database to determine the constants a_0, a_i, and b_i in the approximate relationship given by Equation (1) between the composite material property and the primitive variables. For each set of perturbed values of primitive variables, composite micro-mechanics is used to determine the corresponding mechanical properties at the ply level. Laminate theory is then used to determine the corresponding mechanical properties at the laminate level. The process is repeated until enough data sets are generated by the ICAN module that the functional relationship between material properties and primitive variables can be numerically determined through a least square curve fitting procedure in FPI module. For example, if each primitive variable is perturbed four times, a quadratic functional relationship can be obtained through the calculated values of a_0, a_i, and b_i. With the known probabilistic distributions of the primitive variables and the numerically determined relationships between the composite material properties and the primitive variables, the fast probability integration is applied. For every discrete response value, a corresponding cumulative probability is computed by FPI. This process is repeated until the cumulative distribution function is represented with sufficient accuracy. The output information from FPI for a given material property includes its discretized cdf values, the coefficients for a special type of probability distribution function, and the sensitivities of the composite material property to the primitive variables.

7.0 Numerical Results and Discussions—Laminate Scale

The methodology described previously was applied to a 16-ply $(0_2/\pm45/0_2/90/0)_S$ graphite/epoxy (AS/3501-5) composite with 1.8 percent moisture at room temperature. The experimental data for the longitudinal modulus, transverse modulus, in-plane shear modulus, major Poisson's ratio, longitudinal and transverse tensile strengths, longitudinal and transverse compressive strengths, and in-plane shear strength of the graphite/epoxy unidirectional single ply and 16-ply composite laminate can be found in Reference 7 as listed in Table 1. Based upon these experimental data (mean values) for the ply and laminate properties, the mean values of constituent material properties (fiber and matrix) were estimated. The assumed statistical properties (mean value, coefficient of variation (cov) or standard deviation (stdv), and distribution type) of each random variable are also listed in Table 1.

Typical probabilistic material properties for ply and laminate moduli and strengths were simulated. The sensitivities of the ply and laminate properties to the most sensitive random variables were also computed at two cumulative probability levels, 0.001 and 0.999. All the cumulative distribution functions of the material properties at ply and laminate levels were compared with the results predicted by a Monte Carlo simulation with 1000 samples. Good agreement was observed. The cumulative distribution functions (cdf) of the ply moduli and the sensitivity information are shown in Figures 3 to 5. In each Figure, the experimental datum (mean value) is indicated by an arrow. In Figure 3, it is seen in the sensitivities that the ply modulus in the fiber direction ($E_{\ell11}$) is most sensitive to the fiber modulus and fiber volume ratio. This means that the reduction of the uncertainty in the ply longitudinal modulus can be achieved mostly by the reduction of the uncertainties in the fiber modulus and fiber volume ratio. In Figure 4, it is seen that the shear modulus of matrix and fiber volume ratio have the most contribution in the uncertainty of the ply in-plane shear modulus ($G_{\ell12}$). The uncertainty in the ply major Poisson's ratio

TABLE 1.—STATISTICAL PROPERTIES OF RANDOM VARIABLES

Random variables	Reference 4	Mean value	Coefficient of variation (cov) or standard deviation (stdv), percent	Distribution type
Fiber				
Normal modulus E_{f11}	32 mpsi	32 mpsi	8	Normal
Normal modulus E_{f22}	2 mpsi	3 mpsi	8	Normal
Poisson's ratio ν_{12}	0.2	0.23	8	Normal
Poisson's ratio ν_{23}	0.2	0.25	8	Normal
Shear modulus G_{f12}	2 mpsi	2.5 mpsi	8	Normal
Shear modulus G_{f23}	2 mpsi	2.5 mpsi	8	Normal
Tensile strength S_{fT}	400 ksi	400 ksi	8	Weibull
Compressive strength S_{fC}	400 ksi	400 ksi	8	Weibull
Matrix				
Normal modulus E_m	0.4 mpsi	0.45 mpsi	8	Normal
Poisson's ratio ν_m	0.4	0.41	8	Normal
Tensile strength S_{mT}	7 ksi	6.7 ksi	8	Weibull
Compressive strength S_{mC}	36.3 ksi	39 ksi	8	Weibull
Shear strength S_{mS}	7 ksi	8.9 ksi	8	Weibull
Fabrication variables				
Fiber volume ratio (fvr)	60 percent	60 percent	8	Normal
Void volume ratio (vvr)	0.01 percent	0.01 percent	8	Normal
Ply thickness	0.0055 in.	0.0055 in.	5	Normal
Ply misalignment	0	0	0.9° stdv	Normal

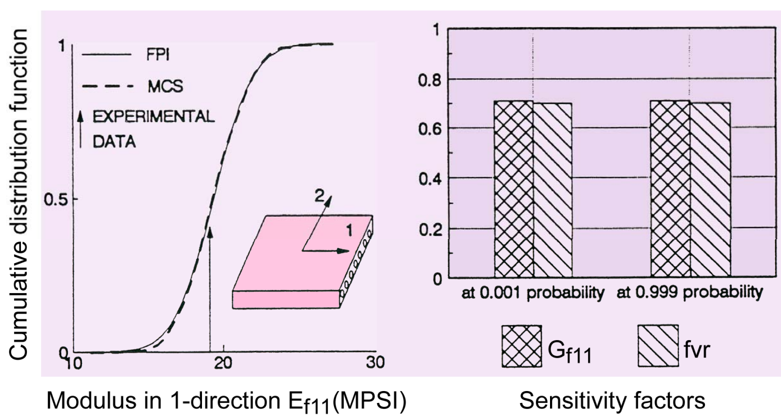


Figure 3.—CDF's and sensitivity factors of ply modulus in X-direction.

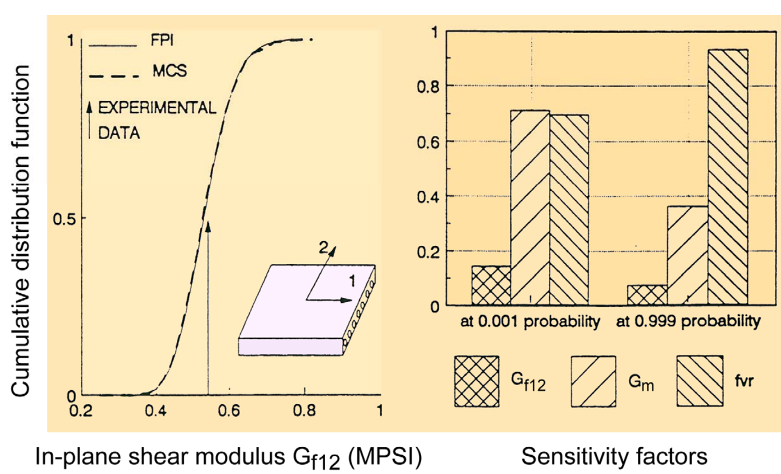


Figure 4.—CDF's and sensitivity factors of ply in-plane shear modulus.

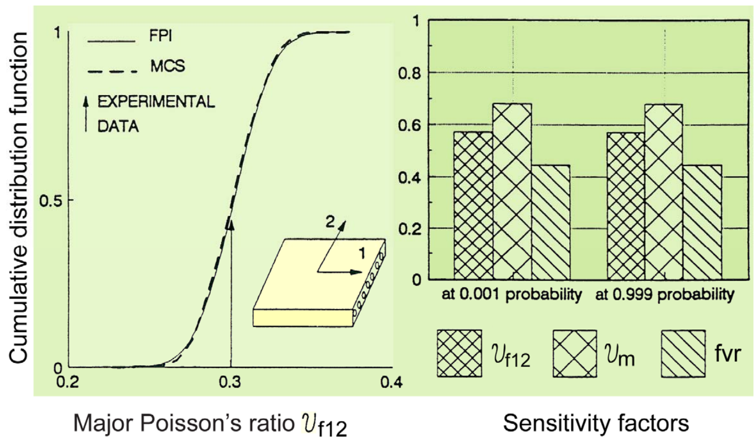


Figure 5.—CDF's and sensitivity factors of ply major Poisson's ratio.

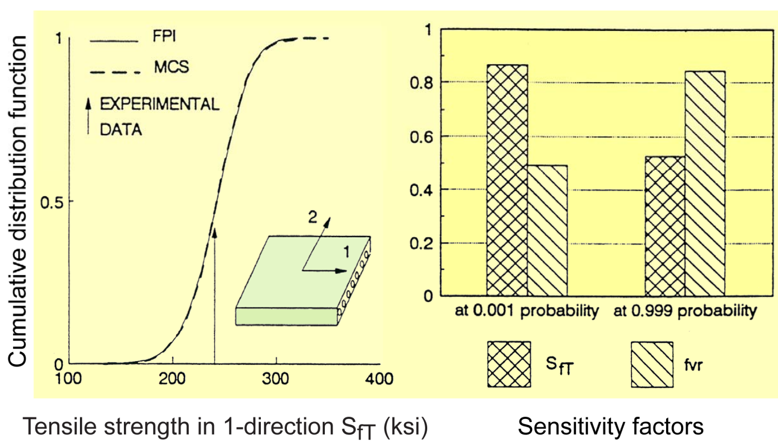


Figure 6.—CDF's and sensitivity factors of ply tensile strength in X-direction.

(ν_{l12}) results mainly from the uncertainties in the fiber and matrix Poisson's ratios and the fiber volume ratio as shown in Figure 5. The results for the probabilistic tensile strength in the fiber direction (S_{l11T}) are shown in Figure 6. It is observed that the probabilistic tensile strength is most sensitive to the uncertainties in the fiber tensile strength and fiber volume ratio. The cumulative distribution functions (cdf) of the equivalent laminate moduli and their sensitivities to their respective primitive variables are shown in Figures 7 to 9. It is seen that both the modulus in the X-direction (E_{cxx}) and the in-plane shear modulus (G_{cxy}) are sensitive to the uncertain fiber modulus and fiber volume ratio as shown in Figures 7 and 8.

In Figure 9, the uncertainty in the laminate major Poisson's ratio (ν_{cxy}) results from the uncertainties in fiber modulus, fiber volume ratio, fiber and matrix Poisson ratios, matrix shear modulus and ply misalignment. Using strengths calculated at the ply level, the laminate tensile strength in the X-direction (S_{cxxT}) was simulated by assuming both first ply failure and fiber fracture failure modes as shown in Figure 10. It is shown that neither scatter predicted by these two criteria covers the experimental scatter. However, the experimental scatter is bounded by the probabilistic scatter of both failure criteria. Indeed, the assumed failure modes represent extreme "failure" scenarios in a composite specimen. Consequently, the predicted cdf's describe upper and lower bounds of the laminate strength. From the sensitivity analysis, the tensile strength predicted by first ply failure mode is most sensitive to the fiber modulus and matrix tensile strength. On the other hand, the tensile strength predicted by fiber fracture mode is most sensitive to fiber tensile strength and fiber volume ratio.

The six ply stress components are along the material axes.

$$S_{L11C} < \sigma_{L11} < S_{L11T}$$

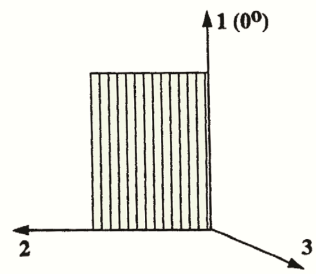
$$S_{L22C} < \sigma_{L22} < S_{L22T}$$

$$S_{L33C} < \sigma_{L33} < S_{L33T}$$

$$S_{L12(-)} < \sigma_{L12} < S_{L12(+)}$$

$$S_{L23(-)} < \sigma_{L23} < S_{L23(+)}$$

$$S_{L13(-)} < \sigma_{L13} < S_{L13(+)}$$



MDE combined stress failure criterion.

$$F = 1 - [\, (\sigma_{L11a}/S_{L11a})^2 + (\sigma_{L22b}/S_{L22b})^2 - K_{L12ab}(\sigma_{L11a}/S_{L11a})(\sigma_{L22b}/S_{L22b}) + (\sigma_{L12S}/S_{L12S})^2 \,].$$

Where if	$1 > F > 0$	No ply failure
	$F = 0$	Ply failure imminent
	$1 < F$	Ply failure has occurred

Figure 6.—Play failure criteria, maximum stress failure citerion.

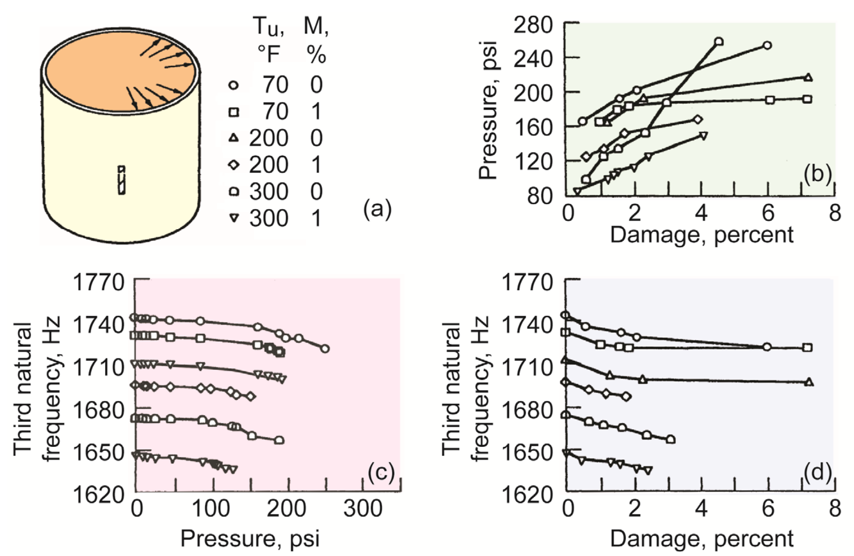


Figure 7.—Hygrothermal effects—T300/epoxy [90 ±15]s shell with fiber volume ratio 0.6. (a) Geometry and environment. (b) Pressure. (c) Vibration frequency. (d) Buckling load (1 psi = 6.9 Pa).

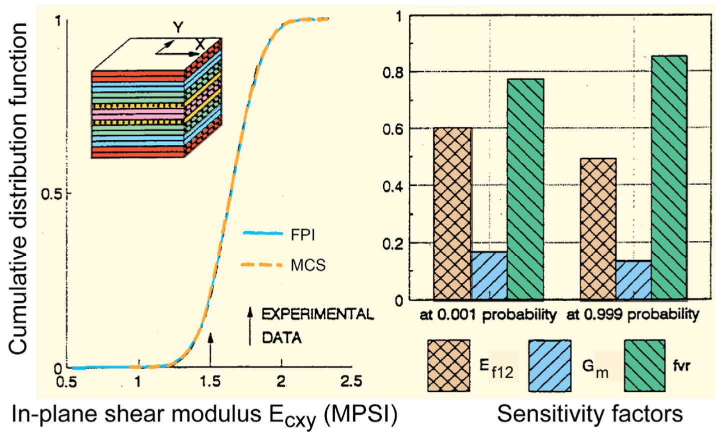


Figure 8.—CDF's and sensitivity factors of laminate in-plane shear modulus.

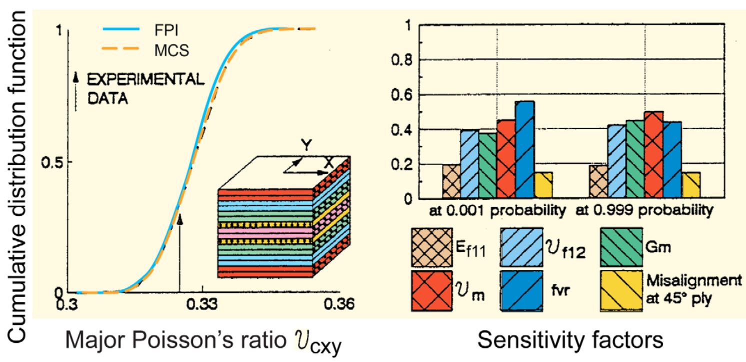


Figure 9.—CDF's and sensitivity factors of laminate major Poisson's ratio.

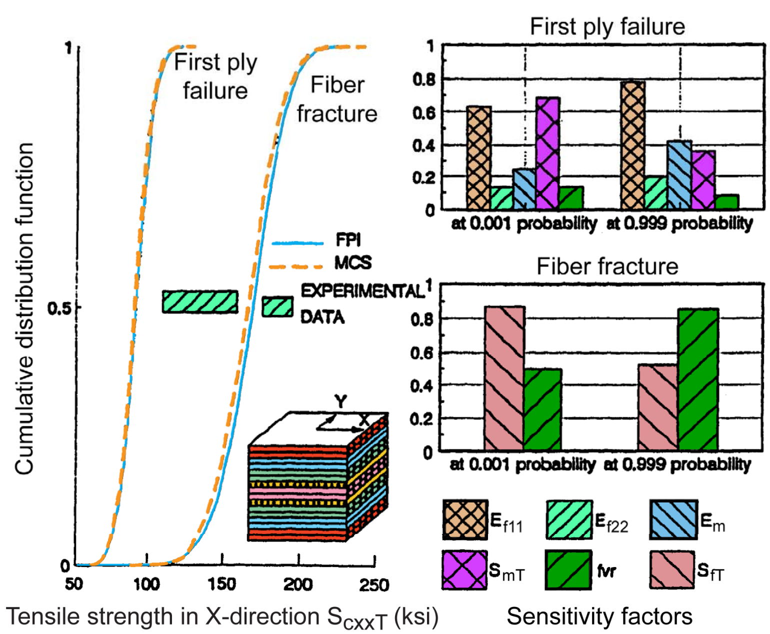


Figure 10.—CDF's and sensitivity factors of laminate tensile strength in X-direction.

8.0 Probabilistic Laminate Thermomechanical Fatigue

Probabilistic simulation of thermomechanical fatigue is an interesting multi-scale representation because of multi-factor effects in material behavior in addition to laminate geometry multi-scale. The multi-factor material effect is represented by the following Equation (8)

$$\frac{M_p}{M_{po}} = \left(\frac{T_{gw} - T}{T_{gd} - T_o}\right)^l \left(1 - \frac{\sigma}{S_f}\right)^m \left(1 - \frac{\sigma_T}{S_f t_f}\right)^n \left(1 - \frac{\sigma_M N_M}{S_f N_{Mf}}\right)^p \left(1 - \frac{\sigma_T N_T}{S_f N_{Tf}}\right)^q \qquad (2)$$

Each term in parenthesis accounts for a specific physical effect. Any number of effects can be included in one single equation as seen by the nature of the equation. The exponents are determined from the available experimental data or estimated from the anticipated material behavior due to a particular primitive variable. Each primitive variable equation can be random with a statistical distribution. The insufficiency of a set of experimental data can be taken into account by means of uncertainties in the exponent. An important part of the previous model is the fact that only one equation can include all the effects with any nonlinearity in the material behavior and follow the physics of behavior. It can describe all the interacting effects of different variables (thermal, metallurgical, mechanical, chemical, and load). Since the variables used are at a primitive level, the equation simulates the in situ degradation in the constituents caused by applied cyclic and environmental effects. It is important to note that the σ's, evaluated as described previously, are obtained from PICAN for specified T, N_m and N_T. The S's are obtained from PICAN for specified constituent material properties, etc. as listed in Table 1. Application of using Equation (2) for fatigue is illustrated on a panel subjected to loading conditions, as depicted in Figure 11. Results obtained from that simulation for mechanical fatigue are shown in Figure 12(a) in terms of cumulative distributions and in Figure 12(b) in terms of probabilistic sensitivity factors. Note that the cumulative distributions and the sensitivities are for three load ratios. The cycles are expressed as ratios of the current cyclic stress to the total number of cycles for panel fracture. As would be expected, increase in the load decreases the cycle survival. The sensitivities, Figure 12(b), show the composite laminate mechanical fatigue is influenced primarily by fiber modulus, matrix tensile strength, and ply thickness. It is noted that matrix tensile strength indicates substantial transply cracking during

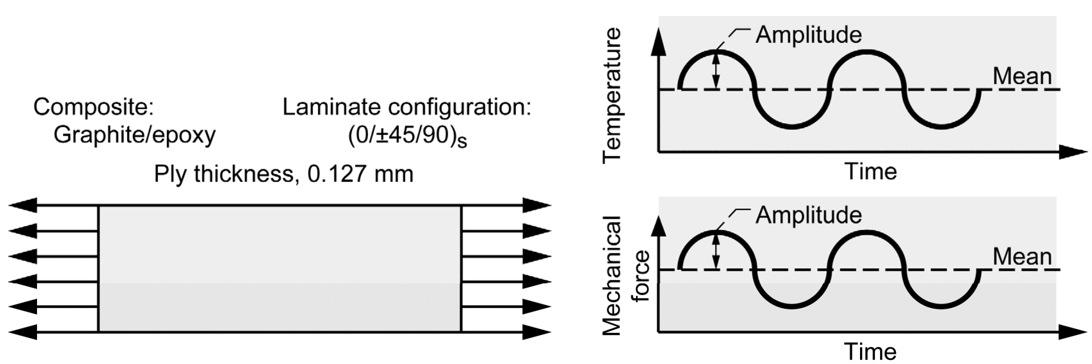


Figure 11.—Description of thermomechanical cyclic load.

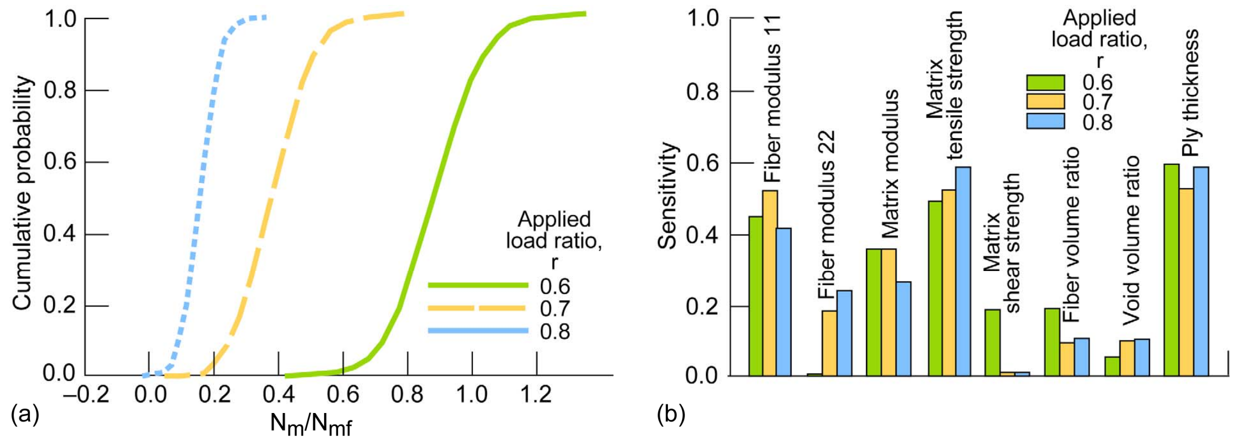


Figure 12.—Cumulative distribution function for and sensitivity of fatigue life for 0.999 reliability of $(0/\pm45/90)_s$ graphite/epoxy laminate. Ply thickness, 0.127 mm under mechanical cyclic load; mean mechanical load = 0.5 × static strength. (a) Cumulative distribution function. (b) Sensitivity of fatigue life for 0.999 reliability.

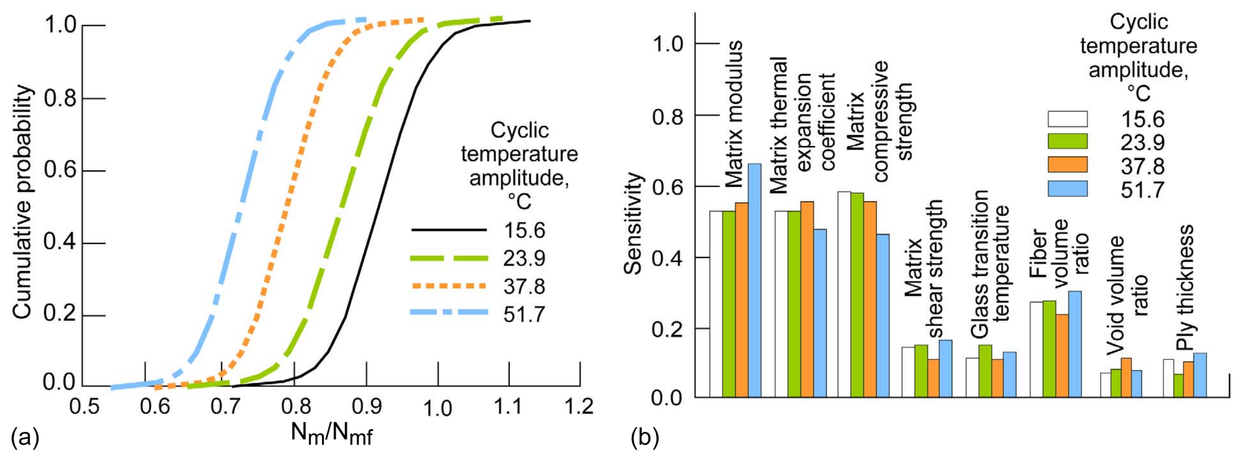


Figure 13.—Cumulative distribution function for and sensitivity of fatigue life for 0.999 reliability of $(0/\pm45/90)_s$ graphite/epoxy laminate. Ply thickness, 0.127 mm under thermal cyclic load; mean mechanical load = 0.5 × static strength. (a) Cumulative distribution function. (b) Sensitivity of fatigue life for 0.999 reliability.

mechanical fatigue. Comparable results for thermal fatigue are shown in Figures 13(a) and 13(b). As would be expected, an increase in the amplitude of the temperature decreases the survival thermal cycles for the same probability. The sensitivities are not as much dependent on the thermal amplitude. The sensitivities, Figure 13(b), indicate that composite laminate thermal fatigue is controlled primarily by matrix modulus, matrix thermal expansion coefficient and matrix compressive strength. The afore discussion demonstrates that multi-scaling is also applicable to factor influencing material behavior.

9.0 Probabilistic Composite Design—Structural Scale

The reliability assessment at the structural scale level, Figure 14, is performed from the strength criterion consideration only (Ref. 9). All he strengths namely; tensile, compressive and shear are computed using micromechanics theory (Ref. 3). The compressive strength in the longitudinal fiber

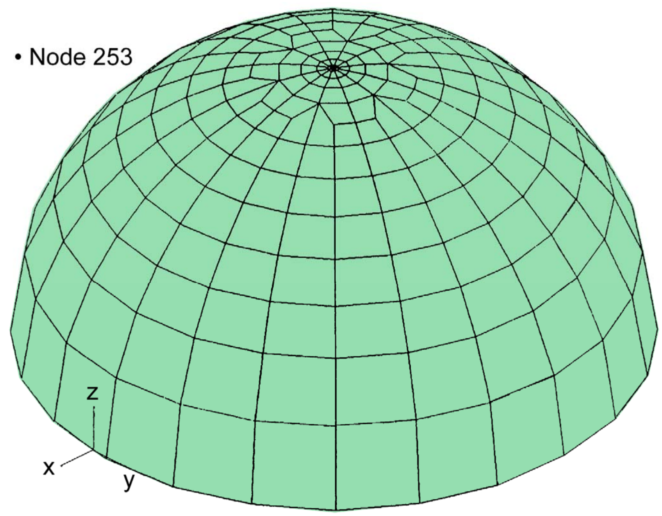
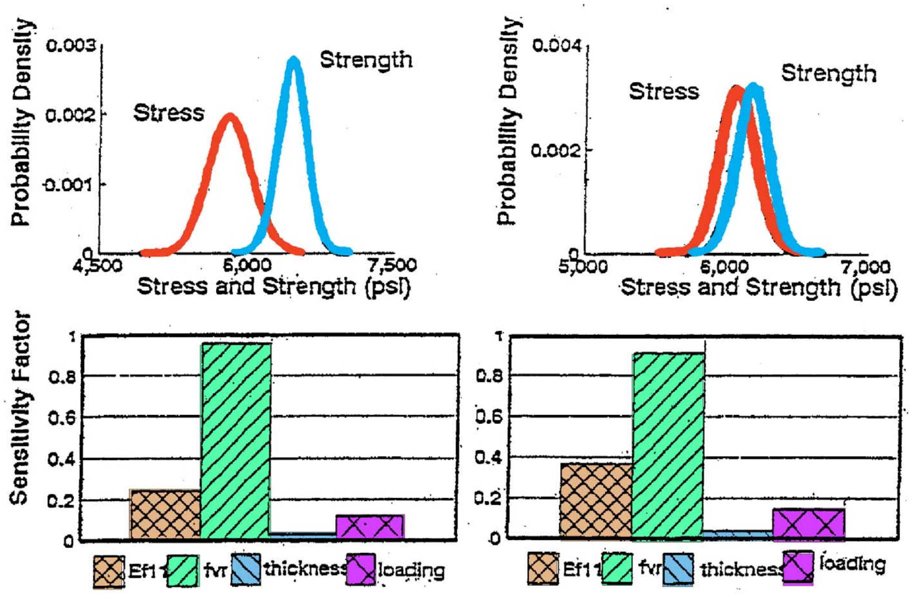


Figure 14.—Redome structure—finite element model.

direction is the minimum of the strengths determined from fiber crushing, delamination or fiber micro-buckling criteria. The following equation is used to compute the reliability

$$R = 1 - P_f = 1 - \int f_0(X) F_S(X) dX \tag{3}$$

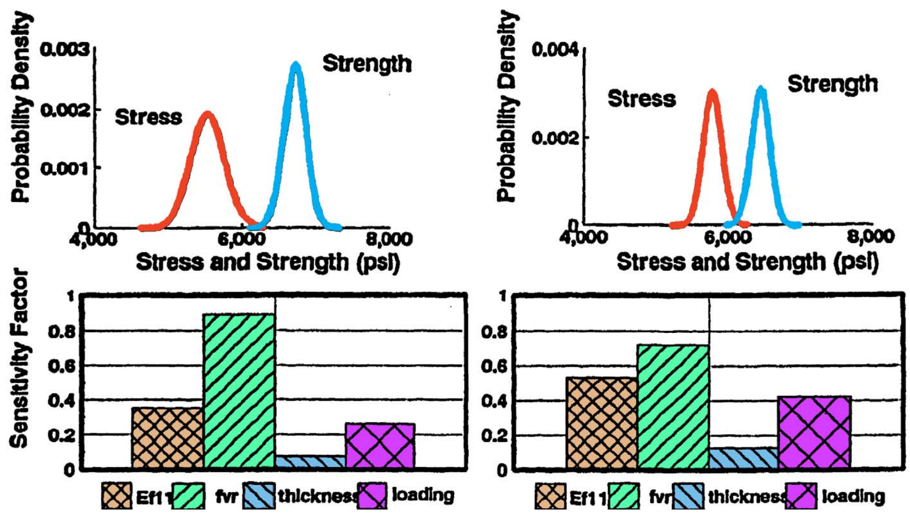
Where R is the reliability, P_f is the probability of failure, ($f_o(X)$ denotes the probability density function of stress and $F_s(X)$ denotes the cumulative probability distribution function of strength. Reliability evaluated together with the respective sensitivity of primitive variables. Based on this study and considering the realistic situation a best design with the highest reliability (lowest probability of failure) is selected. Numerical results of each case are discussed below. Probability density functions (PDF) of the stress and strength in the transverse fiber direction are computed and plotted for ply configuration $(90/\pm45/0/90)_s$ and FVR of 0.6 and 0.5 in Figure 15. The sensitivity of primitive variables to the ply stress and strength at selected probability levels are also plotted in Figure 15. It is seen from Figure 15 that for the same ply configuration, the reliability against strength in the transverse direction is less when mean FVR is smaller. The plot for sensitivity of primitive variables (Fig. 15) shows that the uncertainties in the FVR govern the reliability in both. However, the sensitivity of FVR decreases when its mean value reduces. In that situation, the sensitivities of the uncertainties in other primitive variables become high. PDFs of stress and strength and sensitivity of primitive variables to the reliability for ply configuration $(0/\pm45/90/0)_s$ and FVR 0.6 and 0.5 are plotted in Figure 16. The sensitivity of primitive variables to the stress and strength are shown in Figure 16. Conclusions for this case are also similar to those of the first cases (Fig. 15). However, the reliability for this ply configuration is higher than that of the previous case. It can be seen from Figures 15 and 16 that the fiber volume ratio (FVR) and the fiber modules in longitudinal direction control the scatter of stress and strength. Therefore, it is obvious that the reliability will also be controlled by these variables which are verified by results plotted in Figures 15 and 16. As can be observed from Figures 15 and 16 that larger the intersection between the PDFs of stress and strength, the lower the reliability. Hence, to achieve higher reliability, the PDFs of stress and strength should be as far apart as possible. It is important to judge in a situation like this to pick the best design. Looking at the sensitivity factors against reliability (Figs. 15 and 16), it is obvious that the sensitivity of the pressure load is the lowest. Using this important information it can be inferred that the case in



Case 1 FVR = 0.6
Reliability = 0.987249319

Case 2 FVR = 0.5
Reliability = 0.718075461

Figure 15.—Case 1 and 2 reliability analysis of the node at the crown for ply configuration $(90/\pm45/0/90)_S$ and sensitivity of random variables to the reliability.



Case 5 FVR = 0.6
Reliability = 0.999999369

Case 6 FVR = 0.5
Reliability = 0.999989808

Figure 16.—Case 5 and 6 reliability analysis of the node at the crown for ply configuration $(0/\pm45/90/0)_S$ and sensitivity of random variables to the reliability.

Figure 16 is the best design, since controlling the uncertainties of air pressure (being the applied load) is impossible. Uncertainties in the FVR and fiber modules can be easier controlled than those of the loads. Thus, the ply configuration is equally important in determining the best reliable design. It is noted that the design of the entire structure would involve computing the reliability at every ply of every node against each different design criteria. However, the methodology described herein for multi-scaling composite mechanics can be accomplished effectively using IPACS to design composite structures (Ref. 4).

10.0 Concluding Remarks

A multi-scaling methodology has been developed to accurately and efficiently simulate the uncertainties in composite material properties at all scales of the composite considering the uncertainties in all variables describing the composite material behavior (constituent material properties and fabrication variables). This methodology, integrating the probabilistic concepts in conjunction with composite mechanics, has been implemented into the computer code PICAN. The accuracy and efficiency of the multi-scaling methodology in composites were demonstrated by comparison with the Monte Carlo simulation method for uncertainties in ply and laminate properties. The experimental data of the composite ply and laminate material properties at all scales fall within the scatters predicted by PICAN. The sensitivity of the material property to each primitive variable at the constituent and ply levels was computed. This information can be used as a guide to increase the structural reliability or to reduce the cost. The most sensitive primitive variables for the laminate strengths predicted by different failure modes are different. Composite probabilistic thermo-mechanical fatigue is adequately described by respective cumulative distribution functions and sensitivities. Probabilistic structural analysis and risk assessment can be performed once the uncertain ply and laminate properties are computationally simulated. Laminate configurations can be selected for increased structural reliability (about 3-orders) without increasing the laminate thickness.

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14. ABSTRACT A methodology is developed to computationally assess the non-deterministic composite response at all composite scales (from micro to structural) due to the uncertainties in the constituent (fiber and matrix) properties, in the fabrication process and in structural variables (primitive variables). The methodology is computationally efficient for simulating the probability distributions of composite behavior, such as material properties, laminate and structural responses. Bi-products of the methodology are probabilistic sensitivities of the composite primitive variables. The methodology has been implemented into the computer codes PICAN (Probabilistic Integrated Composite ANalyzer) and IPACS (Integrated Probabilistic Assessment of Composite Structures). The accuracy and efficiency of this methodology are demonstrated by simulating the uncertainties in composite typical laminates and comparing the results with the Monte Carlo simulation method. Available experimental data of composite laminate behavior at all scales fall within the scatters predicted by PICAN. Multi-scaling is extended to simulate probabilistic thermo-mechanical fatigue and to simulate the probabilistic design of a composite redome in order to illustrate its versatility. Results show that probabilistic fatigue can be simulated for different temperature amplitudes and for different cyclic stress magnitudes. Results also show that laminate configurations can be selected to increase the redome reliability by several orders of magnitude without increasing the laminate thickness--a unique feature of structural composites. The old reference denotes that nothing fundamental has been done since that time					
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