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Probabilistic Assessment of Composite Structures

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SUMMARY

A methodology and attendant computer code have been developed and are described to computationally simulate the uncertain behavior of composite structures. The uncertain behavior includes buckling loads, stress concentration factors, displacements, stress/strain, etc., which are the consequences of the inherent uncertainties (scatter) in the primitive (independent random) variables (constituent, ply, laminate, and structural) that describe the composite structures. The computer code is IPACS (Integrated Probabilistic Assessment of Composite Structures). IPACS simulates both composite mechanics and composite structural behavior. Application to probabilistic composite mechanics is illustrated by its use to evaluate the uncertainties in the major Poisson's ratio and in laminate stiffness and strength. IPACS application to probabilistic structural analysis is illustrated by its use to evaluate the uncertainties in the buckling of a composite plate, stress concentration factor in a composite panel, and the vertical displacement and ply stress in a composite aircraft wing segment. IPACS application to probabilistic design is illustrated by its use to assess the thin composite shell (pipe).

INTRODUCTION

Probabilistic composite mechanics and probabilistic composite structural analysis are formal methods which are used to quantify the scatter that is observed in composite material properties and structural response. The observed scatter in composite material properties is the range of measured values in modulus, strength, thermal expansion coefficient, etc., while that in structural response is the range of measured values for displacement, frequency, buckling load, etc. The formal methods relate the scatter and respective probability of occurrence in the observed values to the corresponding scatter in the physical parameters which make up the composite and/or the composite structure. For example, these parameters include constituent material properties, fabrication process variables, structural component geometry, and any other variables which contribute to the composite behavior and/or structural response.

The development of these types of formal methods has been the subject of considerable research at NASA Lewis Research Center. This research has led to computational simulation methods and attendant computer codes for relating the scatter (uncertainties) in the composite properties or composite structural response to the corresponding uncertainties in the respective parameters (primitive variables) which are used to describe the composite in all its inherent scales: micro, macro, laminate, and structural. A more recent continuing development is the computer code IPACS (Integrated Probabilistic Assessment of Composite Structures). The objective of this paper is to summarize the status of IPACS and to present results of select examples to illustrate its application to evaluate the uncertainties in composites and in composite structures. The fundamental concepts driving the methodology are briefly described for completeness. The significance and/or relevance of the results obtained to actual design problems are noted.

FUNDAMENTAL CONCEPTS

The fundamental concepts/assumptions in the probabilistic composite mechanics described herein are (1) the scatter in all the primitive variables, which describe the composite behavior, can be represented by well known probabilistic distribution, (2) the values for the primitive variables can be randomly selected from the known distributions for a specific composite, (3) these values can be used in composite mechanics to predict composite behavior, and (4) the whole process can be repeated many times to obtain sufficient information to develop the distribution in order to quantify the probability of occurrence for the ply properties, laminate properties, or structural responses. This process is analogous to making and testing composites. The probabilistic distributions represent properties of available materials that the composite can be made from. The composite mechanics represent the physical experiment and the process repetition represents several experiments. Subsequent statistical analysis of the data is the same for both approaches. The primitive variables which describe the composite are identified by examining the fabrication process. A schematic depicting the fabrication process for an aircraft wing top cover is shown in figure 1.

PROBABILISTIC COMPOSITE MECHANICS

Probabilistic composite mechanics is key to probabilistic structural analysis. Probabilistic composite mechanics from micromechanics to laminate theory is described in reference 1. Briefly it is a combination of composite mechanics and probability concepts. Respective schematics of the computational simulation of the physics are shown in figures 2 and 3. Representative results from composite micromechanics (ref. 2) are shown in figure 4 for the ply longitudinal compressive strength. These results show that the data point lies in the 80 percent probability of occurrence. Of course several other data points will be required to determine the distribution of the test data. It is interesting to observe from the sensitivity factors that: (1) the fiber volume ratio (FVR), the matrix compressive strength (SMC), the matrix shear modulus (GM), and the fiber misalignment (THETA 15) affect the ply longitudinal compressive strength in that order of sensitivity; (2) the fiber shear modulus and the matrix shear strength have comparatively negligible effect; (3) the single experimental point is near the 80 percent probability; and (4) the level of probability does not affect the magnitude of the sensitivities (0.0001 versus 0.5).

Representative results of probabilistic laminate behavior simulation are summarized in table I for three different laminates. Scanning the ranges in this table, it can be observed that the mean values of the (scatter not known) experimental data is within the simulated scatter for all the values except one Poisson's ratio and two shear moduli. Both of which are sensitive to the boundary and loading conditions. The simulation scatter can be modified to include these data points by modeling the specimen in its entirety. Laminate thermal expansion coefficient results are shown in figure 5. Just about every primitive variable affects this laminate property except the fiber volume ratio. These sensitivity factors are not affected by probability levels.

PROBABILISTIC STRUCTURAL ANALYSIS

Probabilistic structural analysis is performed by using IPACS (Integrated Probabilistic Assessment of Composite Structures). A schematic of the physics integrated into IPACS is shown in figure 6 while a block diagram of its constituent modules is shown in figure 7. As can be seen in figure 6, IPACS consists of a combination of two major modules. (1) NESSUS (ref. 3) for probabilistic structural analysis and PICAN (ref. 2) for probabilistic composite mechanics. IPACS is used to evaluate the scatter in several structures as is described below.

Composite Plate Buckling

Representative results from applying IPACS to simulate buckling of composite plates are shown in figure 8. The most significant point to observe in this figure is that the plates with the asterisk required probabilistic simulation of the support fixity as will be discussed later to increase the simulated results upper bound in order to include the experimental values. The fixity of the supports was simulated by assuming a 10 percent end-moment and a 5 percent scatter about this 10 percent fixity. The conclusion is that experimental results can be bounded by including uncertainties in all the primitive variables that describe the composite structure.

Stress Concentration Factor

An interesting problem in composite structures is stress concentration factors in open holes. IPACS was used to evaluate the scatter in the Stress Concentration Factor (SCF) in a composite panel with a center hole as shown in figure 9. Results obtained for the SCF are shown in figure 10. These results were obtained by assuming 2 and 5 percent scatter in the participating (primitive) variables that describe the physics of the problem. In figure 10, results are also shown for comparison with experimental data, an independent source simulation (independent source simulation same as experimental data (ref. 5)) and from a closed form solution. It is worthy of note that the IPACS results with 2 percent scatter in the primitive-variables bound the data and that the results from the closed form solution over-predict the stress concentration factor. It is not known what scatter was used to obtain the independent source results.

The important point to be made is that the IPACS results are obtained by using the whole panel while those for the closed form solution are only at a point. In a limited way these results underline the importance of modeling the whole structure to properly account for boundary conditions rather than evaluating responses by considering only a local region which is the traditional approach. Cumulative distribution function comparisons are shown in figure 11 for 1.5 percent scatter. The comparisons are excellent and lend credence to the simulation capability in IPACS. The corresponding sensitivity factors for the 2 percent scatter are shown in figure 12. Only four of the forty factors used have significant effect on the stress concentration factor. All four of these contribute to the stiffness of the panel. The important observation is that IPACS can handle composite scatter with numerous primitive variables inherent in fiber composites.

Another interesting stress concentration problem is that depicted in figure 13. What is important in this case is that it became necessary to include uncertainties in the out-of-plane axial load eccentricity in order to shift the distribution to the right to match the data. The sensitivity factors are shown in figure 14. The eccentricity is dominant.

Composite Wing Section

Aircraft wings are current candidates for composites application. The uncertainties in an assumed wing segment shown in figure 15, are simulated by using IPACS. This section consisted of composite skins with three-internal spars and three-internal frames as shown by the interrupted lines in the plan view. The composite system, wing geometry, loading conditions and uncertainties assumed are summarized in figure 15. The IPACS finite element model consisted of 840 nodes and 908 quadrilateral elements.

The range of uncertainty predicted by IPACS for the transverse (vertical) displacement is shown in figure 16, where a computer plot of the finite element model is also shown. As can be seen, 3 times out of 10 000 the displacement will be less than 4 in. while 3 times out of 10 000 it will be greater than 7 in. The bounded range is very useful for the following important reasons: (1) static tests for qualifying the wing segment will produce results in this range and will be consistent with the uncertainties in the primitive variables which are used to describe the wing and (2) the 7-in. dimension is critical in sizing actuators to prevent displacements from growing beyond this range.

The sensitivity factors for the transverse displacement are shown in figure 17. Several factors influence the lower bound of the displacement while the pressure is the most dominant factor for the upper bound. This is a very interesting and perhaps an expected result: "The upper bounds of the scatter are mainly influenced by uncertainties in the loading conditions."

Corresponding results for the highest longitudinal ply stress are shown in figure 18 for the range of the scatter in terms of cumulative distribution function. Only about 3 times out of 10 000 the stress will be less than about 30 ksi or greater than about 55 ksi. The sensitivity factors for the ply longitudinal stress are shown in figure 19. The stringer misalignment influences the lower bound of the stress scatter. This factor did not influence the displacement. Only the pressure influences the upper bound of the stress scatter. It is doubtful that this would be intuitively expected. It demonstrates the wealth of information provided by the probabilistic structural analysis or, more generally, the computational simulation of probabilistic structural behavior.

Composite Thin Shells

A composite stiffened thin shell (pipe) is probabilistically assessed against probabilistic design criteria. The diameter of the cylindrical shell is 2 ft and it is 20 ft long as shown in figure 20. The structure is modeled by 588 4-node shell elements and 600 active nodes (6 dof per node). The pipe consists of composite skin, three composite horizontal circumferential frames, and four composite vertical stringers. The laminate configuration for skin, frames, and stringers are $[\pm 45/0_2/\pm 45/0_2/\pm 45/0/90]_s$, $[0_{24}]$, and $[0_{24}]$, respectively. The pipe is assumed to be supported at one end by a set of translational and torsional spring constants and free at another end. This type of structure is representative of off-shore risers. When the spring constant approaches infinity, a completely fixed boundary condition is simulated. If the spring constants are set to be zero, it represents a free boundary condition. For a given set of spring constants, partially fixed boundary condition is modeled. The pipe is subjected to axial, lateral, and torsional loads at its free end as shown in figure 21.

The uncertain variables are identified at constituent, ply and structural levels. At constituent, 17 material properties for graphite fiber and 12 material properties for epoxy matrix of skin, frames and stringers are modeled as uncertain variables. Their respective probability distribution type and associated parameters are listed in table II. At ply level, the fabrication variables (fiber volume ratio, void volume ratio, ply orientation, ply thickness) are treated as random variables. Their statistics are shown in table III. At structural level, spring constants, which simulates a partially fixed boundary condition, are assigned by a probability distribution to reflect respective uncertainties. Their statistics are shown in table IV.

In the following, the composite pipe is assessed/checked against two design criteria namely clearance and delamination. The results and discussions are described.

(1) Clearance Assessment - A failure (violation of design criterion) occurs when the displacement at the free end in the lateral direction is greater than the allowable value. In this assessment, acceptable failure probability is chosen to be 10^{-3}. From the static analysis, the probabilistic displacement at the free end in the lateral direction was simulated as shown in figure 22. The critical displacement corresponding to 10^{-3} failure probability is 5.2 in. If the allowable displacement is 6 in., then the critical displacement falls in the safe region. It means the clearance criterion is satisfied. If the allowable displacement is 5 in., then critical displacement falls in the failure region. The clearance design is violated and the pipe needs to be redesigned. In the IPACS sensitivity analysis, it is found that the fiber modulus, fiber volume ratio, ply thickness of the skin, as well as the random loads in lateral direction have the most contribution to the failure probability as shown in figure 23.

(2) Delamination Assessment - Delamination buckling (refs. 2 and 6) interlaminar occurs when the ply stress is greater than the ply delamination strength. From IPACS analysis, the relationship between the ply interlaminar shear stress S and the independent random variables X is obtained as shown in equation (1).

$$S = a_o + \sum_{i=1}^{N} a_i X_i + \sum_{i=1}^{N} b_i X_i^2 \tag{1}$$

where a_o, a_i, b_i are constants; N is number of independent random variables. The ply delamination strength S_{DL11C} is shown in equation (2).

$$S_{DL11C} = 10 S_{1_{12s}} + 2.5 S_{mT} a \tag{2}$$

where

$$S_{1_{12s}} = \left[1 - \left(\sqrt{K_f} - K_f\right)\left(1 - \frac{G_m}{G_{f12}}\right)\right] S_{mS}\ a \tag{3}$$

and

$$a = 1 - \sqrt{\frac{4K_v}{\pi(1 - K_f)}} \tag{4}$$

where K_f and K_v are fiber volume ratio and void volume ratio respectively; G_{f12} and G_m are fiber and matrix shear modulus; S_{mT} and S_{ms} are the matrix tensile and shear strength. Defining a limit state function G as

$$G = S_{DL11C} - S \tag{5}$$

If G is less than 0, it indicates that laminate stress is greater than the delamination buckling strength. Therefore, laminate buckling by delamination will occur. The probability of $G \leq 0$, computed by FPI (Fast Probability Integrator), is 0.012 which is greater than the acceptable failure probability (10^{-3}). From sensitivity analysis, eight most influential random variables which have the major contribution to the failure probability are identified as shown in figure 24. It shows that matrix shear strength is the most important one (about 60 percent) followed by the ply thickness (about 40 percent). By controlling, adjusting the mean and standard deviation of those important independent random variables, redesign can be achieved most efficiently. For example, if the coefficient of variation (scatter) of the intra ply shear strength can be reduced from 5 to 2.5 percent, the failure probability is reduced to 0.005 which is more than 50 percent reduction improvement by reliability. A safe design can be accomplished through this (controlling of important variables) procedure.

The four different and important structural examples previously described demonstrate the breadth and depth of the IPACS computer code to probabilistically assess inherent uncertainties in composite structures. The results from these three examples are evidence of the maturity of the methodology, the status of the IPACS computer code and in a limited way, the effectiveness of IPACS for: (1) application to the design of composite structures and (2) assessment of their reliability.

CONCLUSIONS

Formal methods and a computer code IPACS for integrated probabilistic assessment of composite structures were described. Select examples for probabilistic composite mechanics and probabilistic structural analysis were presented to demonstrate the status of the development of the code and its applications. Results from these examples (composite plate buckling, stress concentration factors, structural response of an aircraft/segment wing, and probabilistic design assessment of a thin composite pipe) illustrate that IPACS can be used to quantify the uncertainties in composite structural behavior from the inherent uncertainties in the various parameters that define the composite structure. In addition, the methodology can be used to evaluate sensitivity factors which influence composite structural response. Boundary conditions are important in composite plates with certain laminate configurations. Parameters contributing to stiffness are important in stress concentration factors. While several factors influence the lower bounds of the vertical displacement and ply stress of an aircraft wing segment, only the pressure dominates the upper bounds of the scatter. Delamination buckling in thin composite shells is controlled mainly by matrix shear strength and ply thickness. Collectively, the results demonstrate that the IPACS computer code has matured to the point that it can be very useful for the design and reliability assessment of composite structures.

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TABLE I.—PICAN VERIFICATION FOR LAMINATE STIFFNESS

Laminate	Lower bound (95% confidence)	Mean	Experimental value[a]	Upper bound (95% confidence)
$[0/\pm45_2/0/\pm45]_s$				
Long. modulus (Msi)	5.48	6.31	6.30	7.12
Trans. modulus (Msi)	2.76	3.16	3.08	3.54
Shear modulus (Msi)	3.34	3.85	3.21	4.38
Major Poisson's ratio	.771	.792	.803	.813
$[0_2/\pm45/0_2/90/0]_s$				
Long. modulus (Msi)	11.49	13.27	13.00	15.08
Trans. modulus (Msi)	3.85	4.40	4.20	4.93
Shear modulus (Msi)	1.42	1.63	1.50	1.84
Major Poisson's ratio	.305	.312	.325	.318
$[(0/\pm45/90)_2]_s$				
Long. modulus (Msi)	6.27	7.22	6.68	8.16
Trans. modulus (Msi)	6.27	7.22	6.62	8.16
Shear modulus (Msi)	2.38	2.74	2.34	3.10
Major Poisson's ratio	.310	.315	.350	.320

[a]Reference 7.

TABLE II.—MATERIAL PROPERTIES AT CONSTITUENT LEVEL FOR BOTH SKIN AND STRINGERS

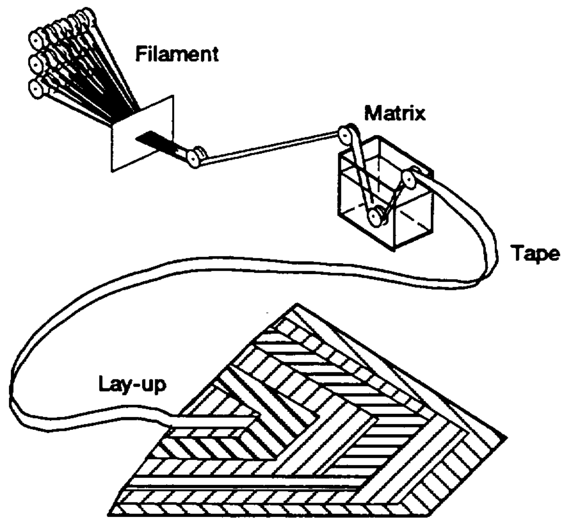
	Unit	Distribution type	Mean	Coefficient of variation
E_{f11}	Msi	Normal	31.0	0.05
E_{f22}	Msi	Normal	2.0	↓
G_{f12}	Msi	Normal	2.0	
G_{f23}	Msi	Normal	1.0	
ν_{f12}	---	Normal	0.2	
ν_{f23}	---	Normal	0.25	
α_{f11}	ppm/°F	Normal	-0.55	
α_{f22}	ppm/°F	Normal	5.6	
ρ_f	lb/in.^{3}	Normal	0.063	
N_f	---	Constant	10 000	
d_f	in.	Normal	0.0003	
C_f	Btu in./°F	Normal	0.17	
K_{f11}	Btu in./hr/in.^{2}/°F	Normal	580	
K_{f22}	Btu in./hr/in.^{2}/°F	Normal	58	
K_{f33}	Btu in./hr/in.^{2}/°F	Normal	58	
S_{fT}	Ksi	Weibull	400	
S_{fC}	Ksi	Weibull	400	
E_m	Msi	Normal	0.5	
G_m	Msi	Normal	0.185	
ν_m	----	Normal	0.35	
α_m	ppm/°F	Normal	42.8	
ρ_m	lb/in.^{3}	Normal	0.0443	
C_m	Btu/in./°F	Normal	0.25	
K_m	Btu in./hr/in.^{2}/°F	Normal	1.25	
S_{mT}	Ksi	Weibull	15	
S_{mC}	Ksi	Weibull	35	
S_{mS}	Ksi	Weibull	13	
β_m	in./in./1% moist	Normal	0.004	
D_m	in.^{3}/sec	Normal	0.002	↓

TABLE III.—FABRICATION VARIABLES AT PLY LEVEL

	Unit	Distribution type	Mean	Coefficent of variation
fvr	----	Normal	0.60	0.05
vvr	----	↓	.02	.05
θ_p	deg		.00	.9 (stdv)
t_{psk}	in.		.005	.05
t_{pst}	in.		.02	.05

TABLE IV.—UNCERTAINTIES IN THE STRUCTURAL LEVEL

	Unit	Distribution type	Mean	Coefficient of variation
K_{cTR}	lb/in.	Normal	30E+06	0.20
K_{cTO}	lb-in./rad.	↓	12E+02	.20
Fx	kips		288	.05
Fy	kips		5.76	.05
Mxx	kips-ft		576	.05



Fabrication schematic of
a aircraft wing top cover

- Constituents
- Fiber misalignment
- Fiber volume ratio
- Void volume ratio
- Ply orientation angle
- Ply thickness

Figure 1.—Sources of scatter - fabrication process.

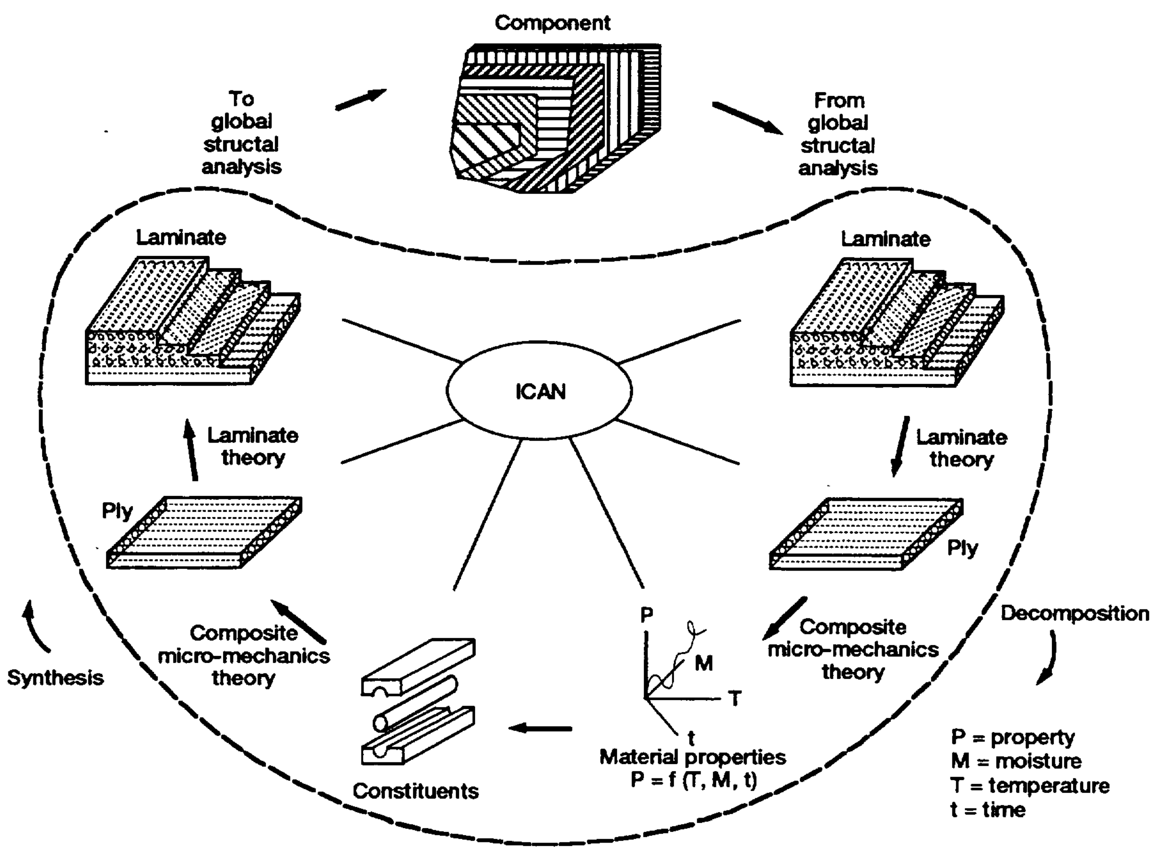
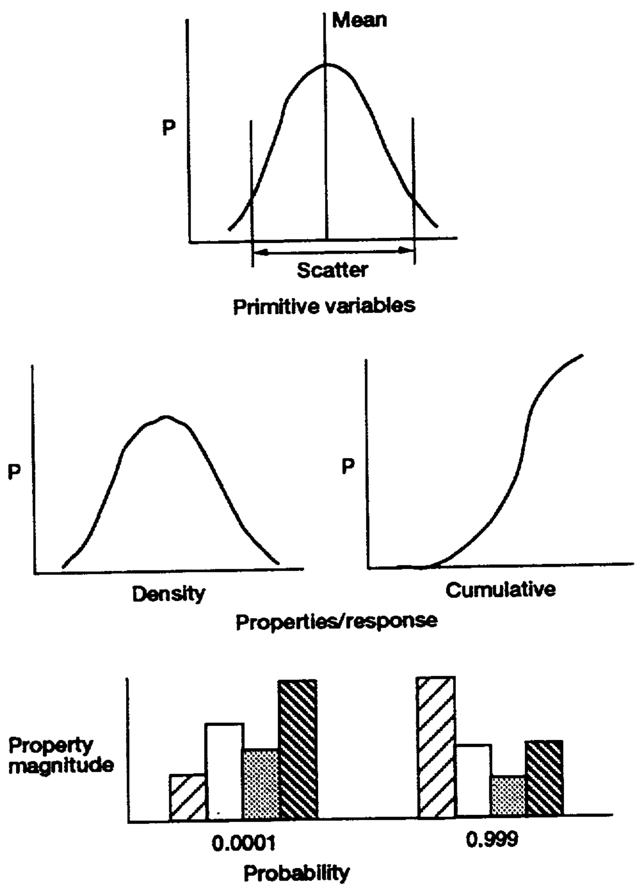


Figure 2.—Composite behavior simulation - ICAN.



- Assume statistical distributions of scatter in all primitive variables
- Probabilistically select values from these distributions
- Enter these values in ICAN to calculate composite properties
- Repeat process until sufficient values have been obtained to develop statistical distributions for the desired composite properties/structural response
- Evaluate sensitivities

Figure 3.—Probabilistic simulation of composite behavior.

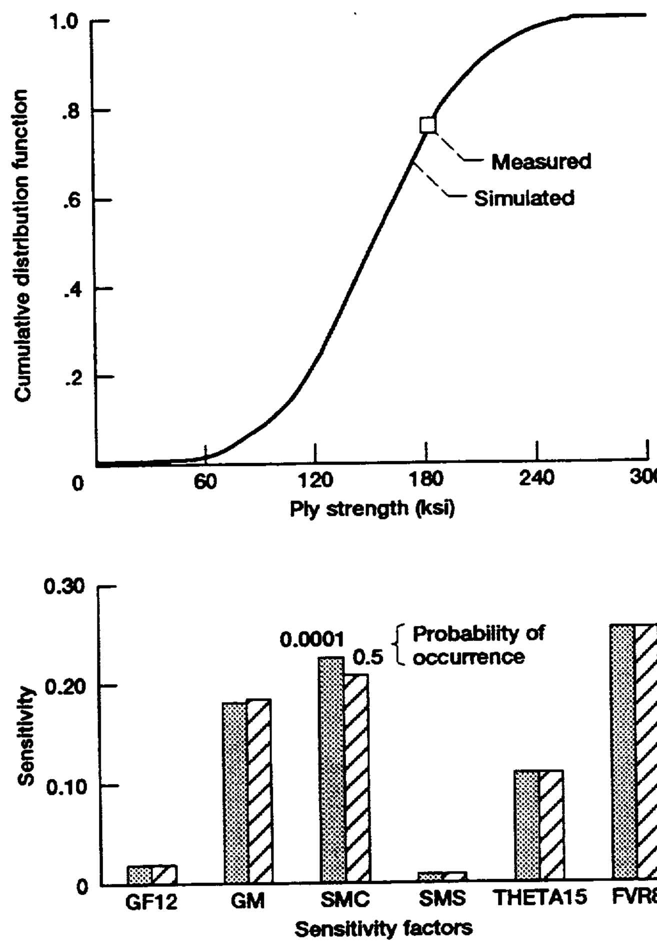


Figure 4.—Probabilistic ply longitudinal compressive strength (AS4/3501-6 graphite/epoxy at 0.6 FVR).

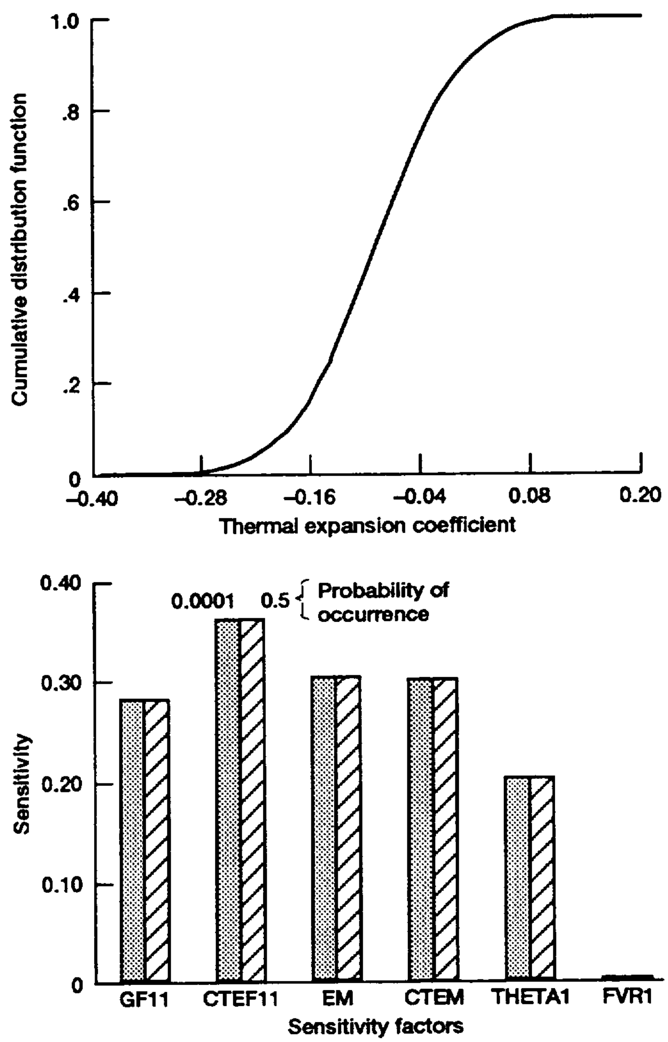


Figure 5.—Probabilistic laminate thermal expansion coefficient along the 0° plies ([0/±45/0±45]$_s$ AS4/3501-6 graphite/epoxy composite).

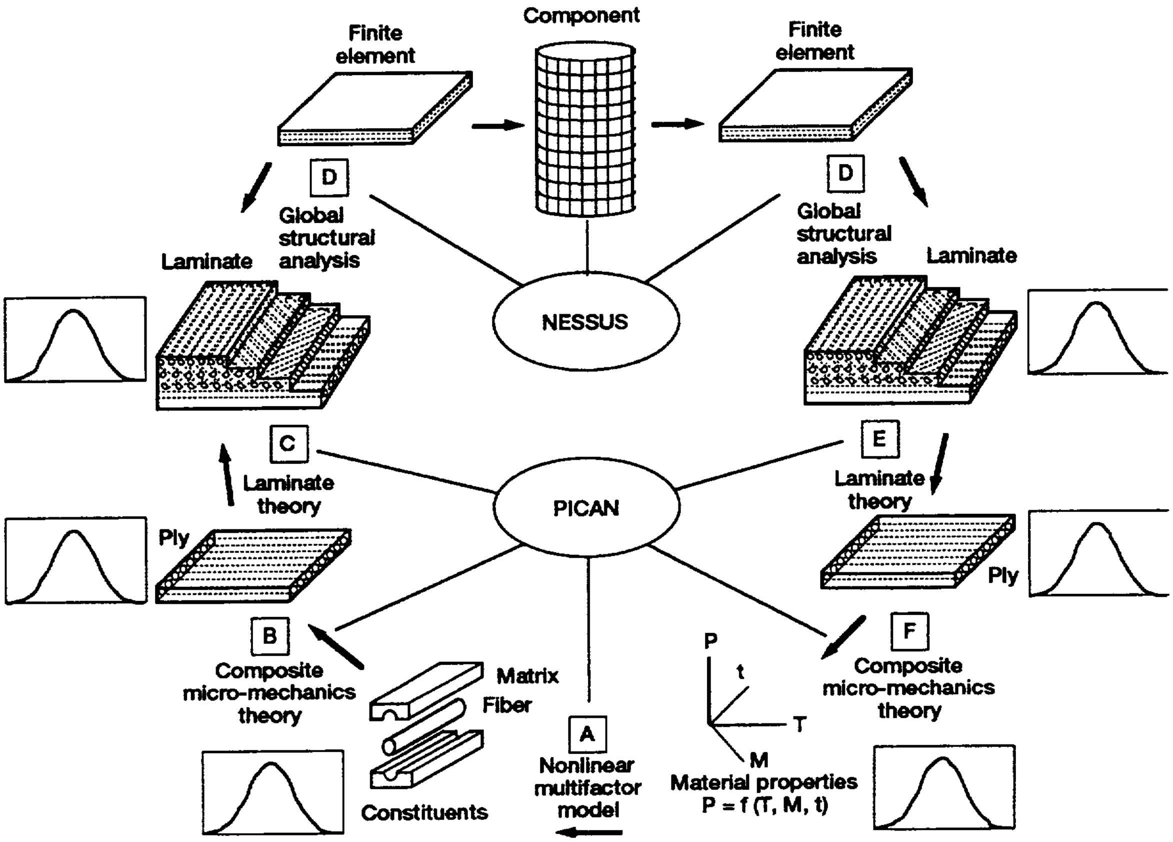


Figure 6.—IPACS: Integrated Probabilistic Assessment of Composite Structures

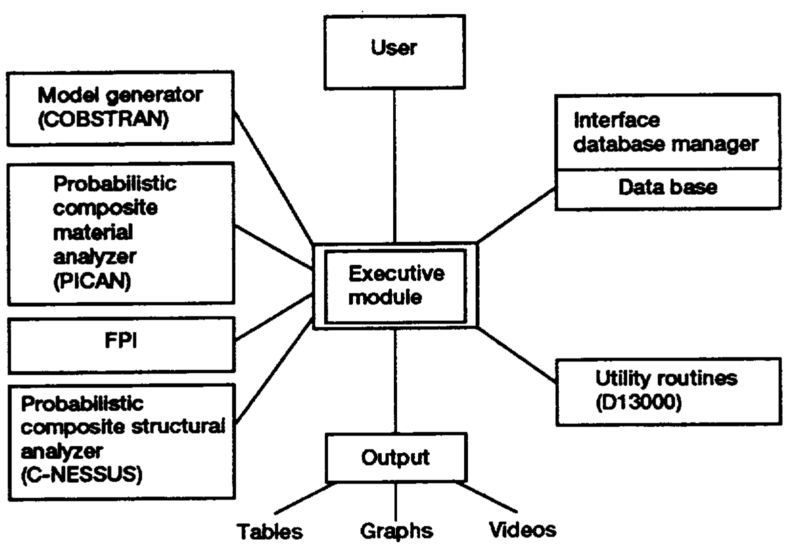


Figure 7.—Integrated Probabilistic Assessment of Composite Structures (IPACS); architecture of software system.

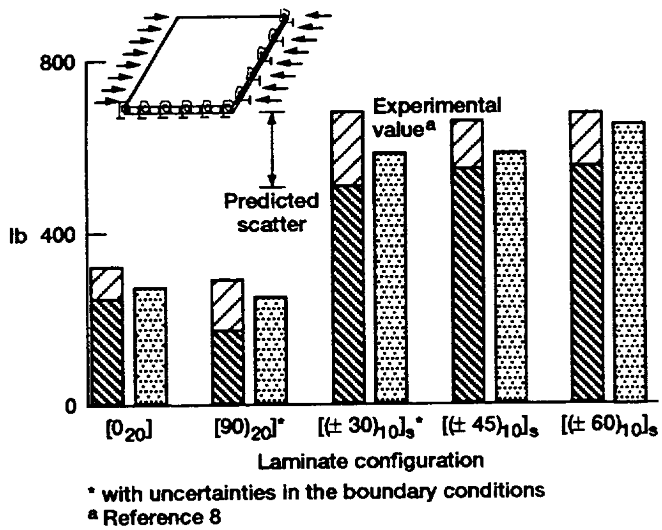


Figure 8.—Probabilistically simulated buckling loads of boron/ epoxy composite plates.

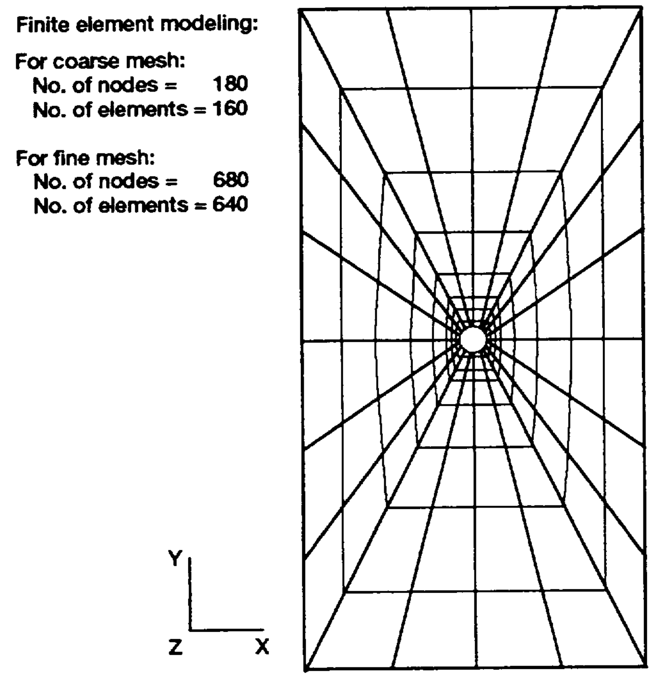


Figure 9.—Composite panel with center hole.

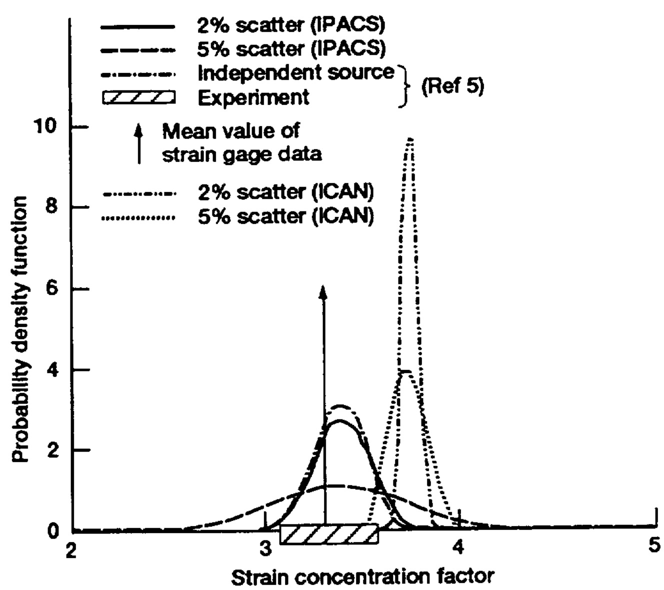


Figure 10.—Probabilistic strain concentration factor of a (0/45/-45/0/90)s laminated plate (boron/epoxy).

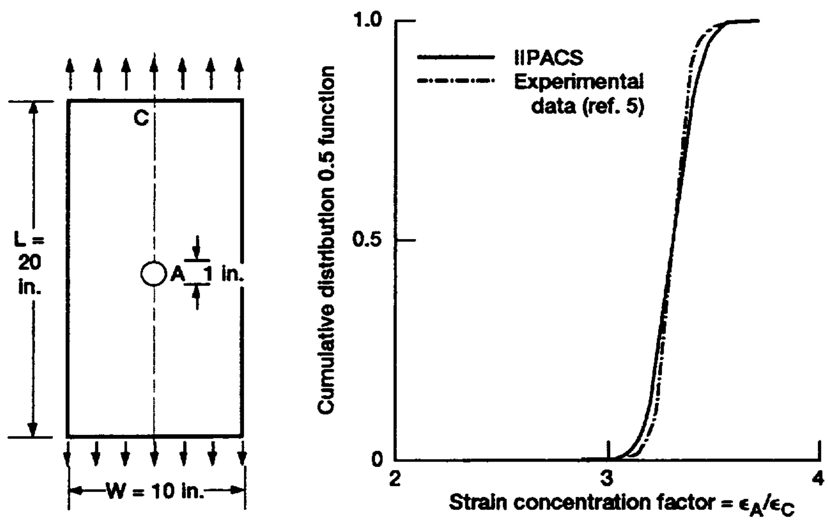


Figure 11.—Probabilistic strain concentration factor of a (0/45/-45/0/90)s laminated plate (boron/epoxy with 1.5% scatter)

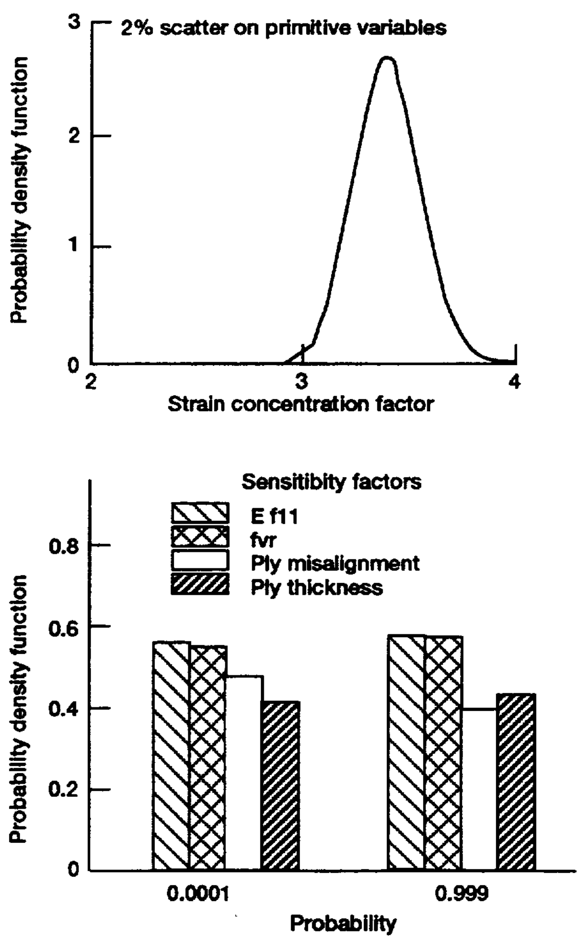


Figure 12.—Probability density function of the Strain Concentration Factor (SCF) and the sensitivity of each primitive variable to the probabilistic SCF of boron/ epoxy laminated plate is simulated by IPACS.

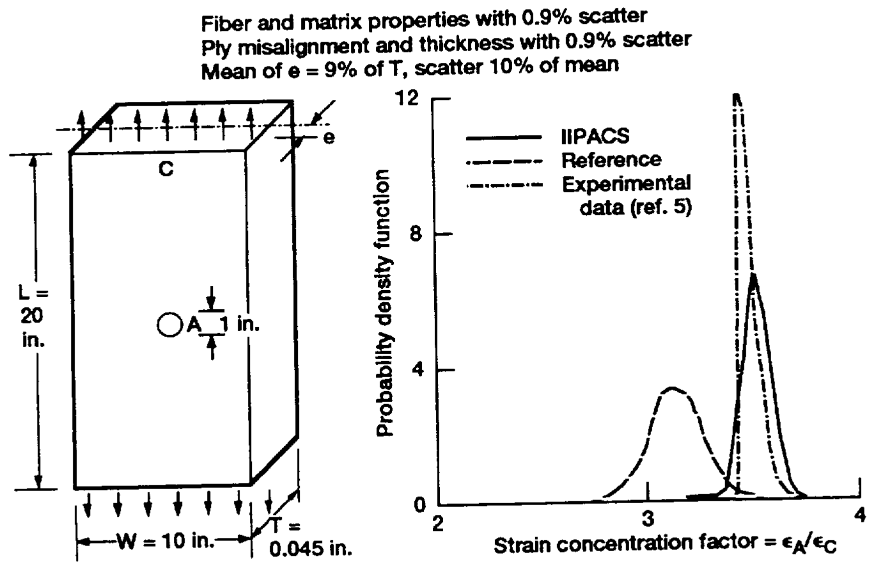


Figure 13.—Probabilistic strain concentration factor of a (0/45/-45/0/90)s glass/epoxy laminated plate.

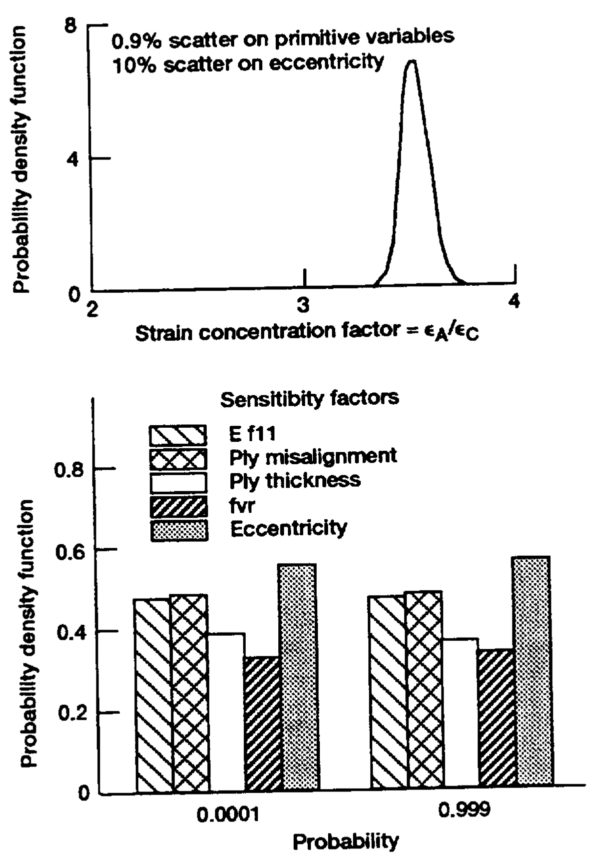


Figure 14.—Probability density function and sensitivity factors for the Strain Concentration Factor (SCF) of a $[0/45/-45/0/90]_s$ glass/epoxy laminated plate, (with out-of-plane eccentricity).

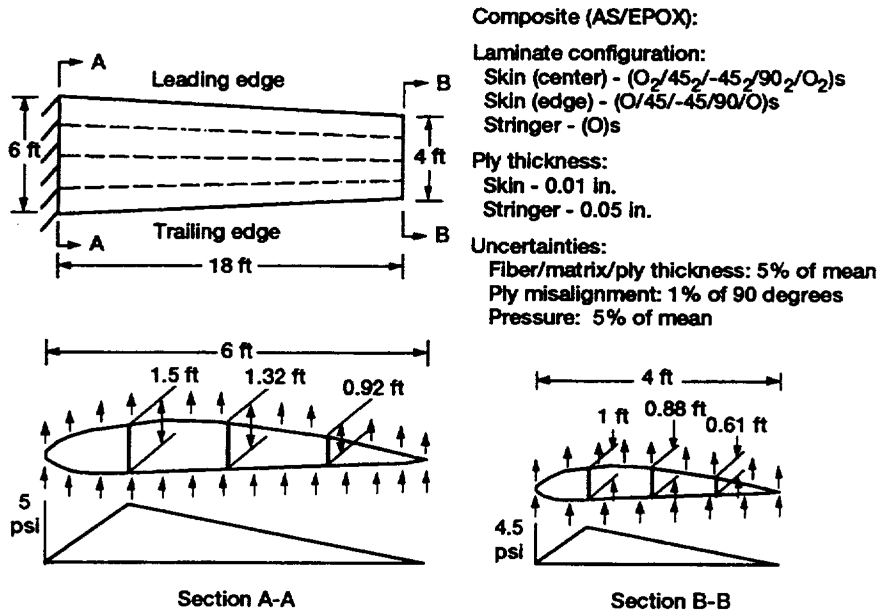


Figure 15.—Geometry and loading of a composite wing.

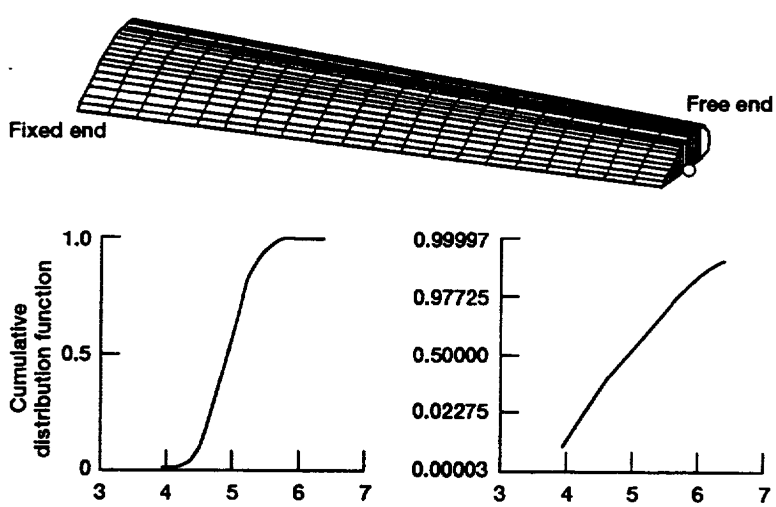


Figure 16.—Probabilistic transverse displacement of the composite wing.

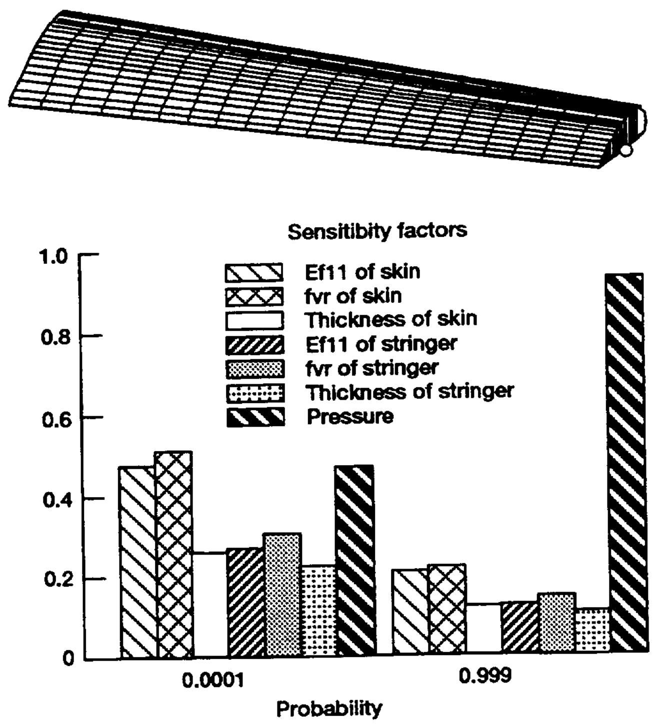


Figure 17.—Sensitivity analysis of probabilistic transverse displacement of the composite wing.

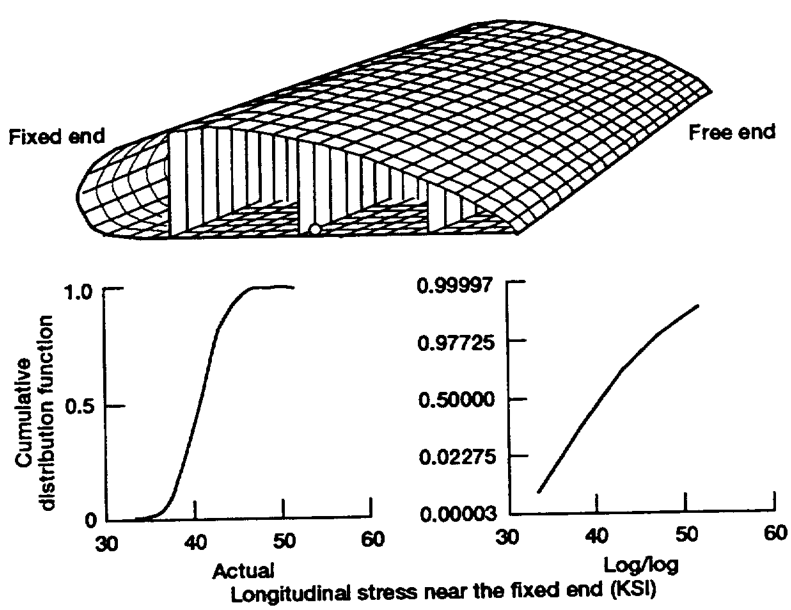


Figure 18.—Probabilistic longitudinal stress of the composite wing.

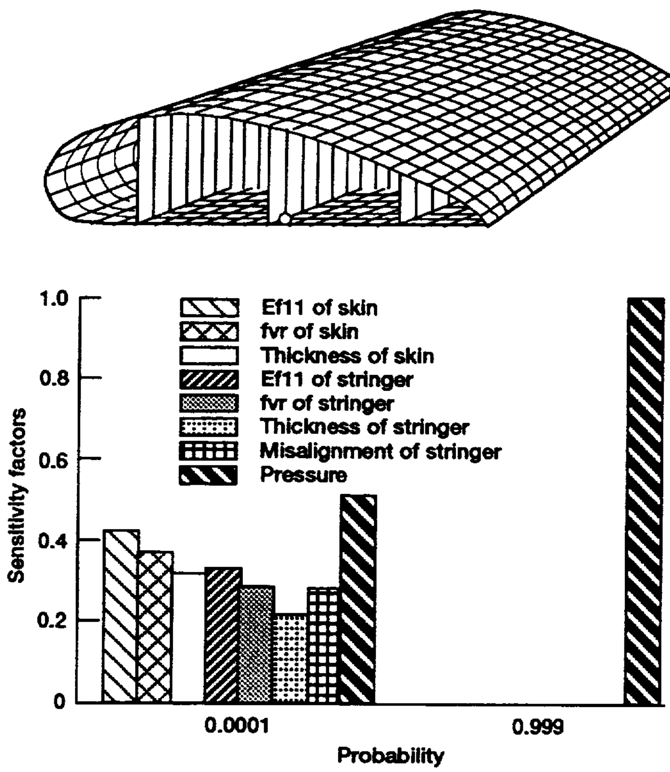


Figure 19.—Sensitivity analysis of probabilistic longitudinal stress of the composite wing.

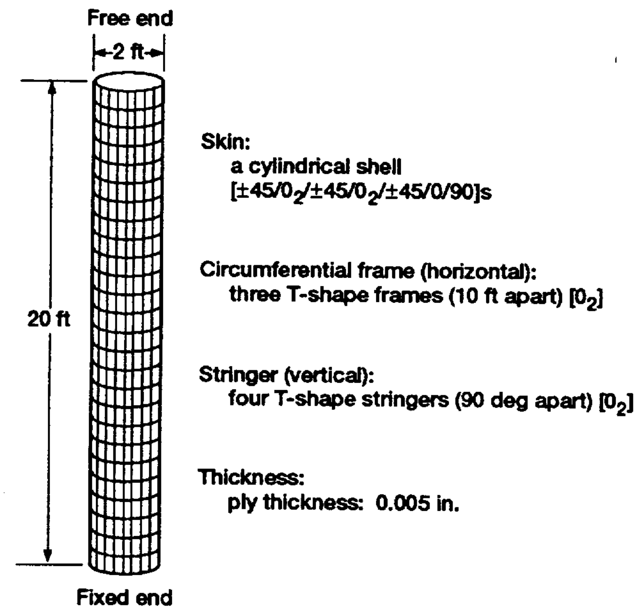


Figure 20.—Geometry and composite configuration of a stiffened composite pipe.

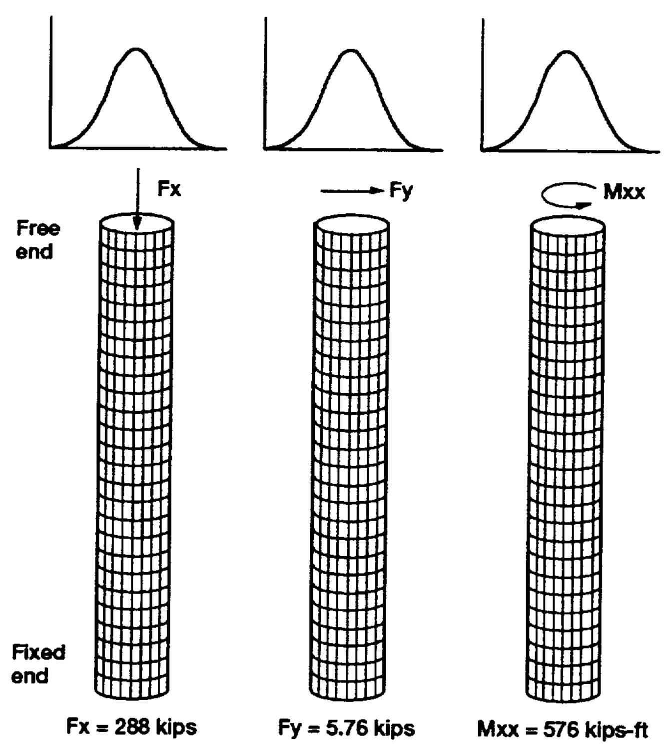


Figure 21.—Assumed loading conditions of the composite pipe.

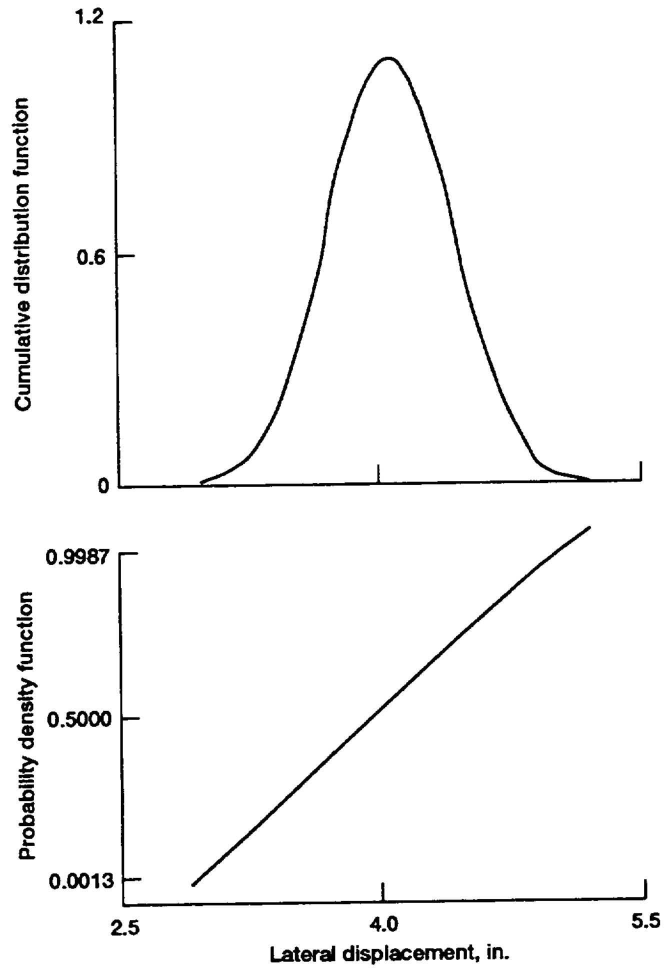


Figure 22.—Cumulative Distribution (CDF) and Probability Density Function (PDF) of the lateral displacement at free end.

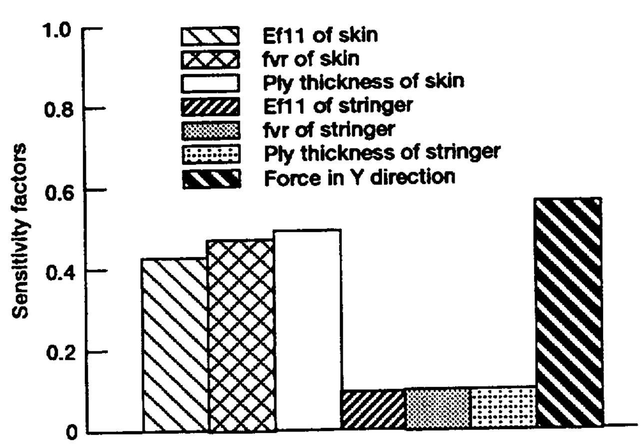


Figure 23.—Sensitivity factors of the lateral displacement at free end at 0.999 cumulative probability (0.001 failure probability).

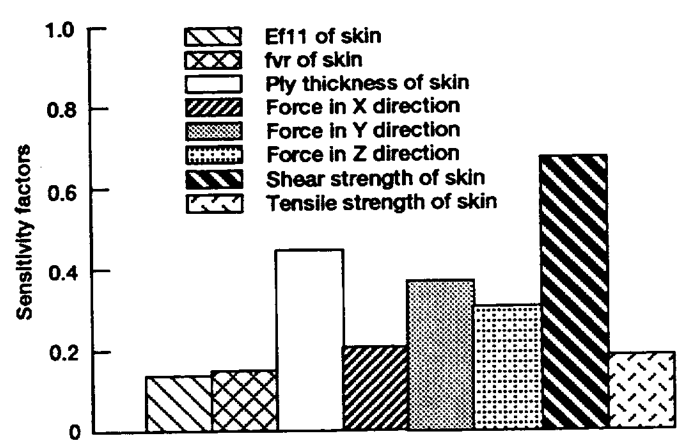


Figure 24.—Sensitivity factors of the delamination probability equal to 0.012.

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

A methodology and attendant computer code have been developed and are described to computationally simulate the uncertain behavior of composite structures. The uncertain behavior includes buckling loads, stress concentration factors, displacements, stress/strain, etc., which are the consequences of the inherent uncertainties (scatter) in the primitive (independent random) variables (constituent, ply, laminate, and structural) that describe the composite structures. The computer code is IPACS (Integrated Probabilistic Assessment of Composite Structures). IPACS simulate both composite mechanics and composite structural behavior. Application to probabilistic composite mechanics is illustrated by its use to evaluate the uncertainties in the major Poisson's ratio and in laminate stiffness and strength. IPACS application to probabilistic structural analysis is illustrated by its use to evaluate the uncertainties in the buckling of a composite plate, stress concentration factor in a composite panel, and the vertical displacement and ply stress in a composite aircraft wing segment. IPACS application to probabilistic design is illustrated by its use to assess the thin composite shell (pipe).

14. SUBJECT TERMS
Uncertainties; Composites, Fibers; Matrices; Stress concentrations; Buckling; Wing section; Thin shells, Sensitivity factors; Composite properties; Computer programs; Stiffness; Strength

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