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IPACS - INTEGRATED PROBABILISTIC ASSESSMENT OF COMPOSITE STRUCTURES: CODE DEVELOPMENT AND APPLICATIONS

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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 can handle both composite mechanics and composite structures. Application to probabilistic composite mechanics is illustrated by its uses 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, in the stress concentration factor in a composite panel and in the vertical displacement and ply stress in a composite aircraft wing segment.

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 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.

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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 the 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, 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 of the ply properties, composite properties, or structural responses. These concepts are analogous to making and testing composites. The probabilistic distributions represent 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. The formal procedure is summarized in the schematic in Figure 2.

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. Representative results from ref. 2 for composite micromechanics are shown in Figure 3 for the major ply Poisson's ratio. It is interesting to observe from the sensitivity analysis results that: (1) the fiber misalignment (THETA 1) has the greatest effect on the Poisson's ratio followed by the in situ matrix Poisson's ratio and then by the fiber Poisson's ratio; (2) the fiber volume ratio has comparatively negligible effect; (3) the single experimental point is near the mean (50 percent probability); and (4) the level of probability does not affect the magnitude of the sensitivities.

Representative results of probabilistic laminate behavior simulation are summarized in Table 1 for three different laminates. Scanning the ranges in this table, it can be observed that the experimental data is within the simulated scatter for all the values except one Poisson's ratio and two shear models, 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.

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 4 while a block diagram of its constituent modules is shown in Figure 5. As can be seen in Figure 4, IPACS consists of a combination of two major modules: (1) NESSUS for probabilistic structural analysis and (2) PICAN for probabilistic composite mechanics. IPACS is used to evaluate the scatter in several structures as is described below. Additional discussions on IPACS are found in Reference 3.

Composite Plate Buckling

Representative results from applying IPACS to simulate buckling of composite plates are shown in Figure 6. The most significant point to observe in this Figure is that the plates with the asterisk required probabilistic simulation of the support fixity to increase the simulated results upper bound in order to include the experimental values. The fixity of the supports was simulated by assuming a ten percent moment and a five percent scatter about this ten percent fixity. The conclusion is that experimental results can be bounded by including uncertainties in all the 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 hold, shown in Figure 7. Results obtained for the SCF are shown in Figure 8. These results were obtained by assuming two and five percent scatter in the participating (primitive) variables that describe the physics of the problem (Fig. 4). In Figure 8, results are also shown for comparison with experimental data, an independent source (independent source same as experimental data) and from a close form solution. It is worthy of note that the IPACS results with two percent scatter in the primitive-variables bound the data and that the results from the close form solution over-predict the stress concentration factor. It is not know 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 close form solution are only at a point. In a limited way these results underline the importance of modeling the whole structure rather than evaluating responses by considering only a local region which is the traditional approach. Cumulative distribution function comparisons are shown in Figure 9 for 1.5 percent scatter. The comparisons are very good, if not excellent, and lend credence to the simulation capability in IPACS.

The corresponding sensitivity factors for the two percent scatter are shown in Figure 10. 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 such as fiber composites.

COMPOSITE WING SECTION

Aircraft wings are current candidates for composites application. The uncertainties in an assumed wing segment shown in Figure 11 were simulated by using IPACS. This section consisted of composite skins with 3-internal spars and 3-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 11. The IPACS finite element model consisted of 840 nodes and 908 quadrilateral elements.

The range of uncertainty predicted by IPACS is shown in Figure 12, for the transverse (vertical) displacement where a computer plot of the finite element model is also shown. As can be seen, three times out of 10,000 the displacement will be less than four inches while three times out of l0,000 it will be greater than seven inches. 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 and, (2) the seven inch 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 13. 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 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 14 for the range of the scatter in terms of cumulative distribution function. Only about three times out of 10,000 will the stress be less than about 30 ksi or greater than about 55 ksi. The sensitivity factors for the ply longitudinal stress are shown in Figure 15. The stringer misalignment influences the lower bound of the stress scatter. This factor did <u>not</u> influence the displacement. Only the pressure influences the upper bound of the stress scatter. It is doubtful that this would be an expected result. It demonstrates the wealth of information provided by the probabilistic structural analysis or, more generally, the computational simulation of probabilistic structural behavior.

The three 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 and structural response of an aircraft/segment wing) 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. 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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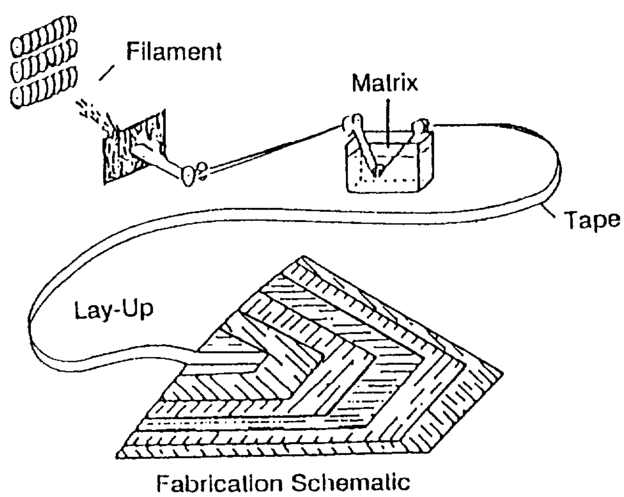
1. C. C. Chamis and P.L.N. Murthy: Probabilistic Composite Analysis. NASA CP 3104, Part 2, 1991, pp. 891-900.

2. G. T. Mase, P.L.N. Murthy and C. C. Chamis: Probabilistic Micromechanics and Macromechanics of Polymer Matrix Composites. NASA TM 103669, January 1991.

3. M. C. Shiao and C. C. Chamis: Probabilistic Evaluation of Fuselage-Type Composite Structures. NASA TM 105881, 1992.

Table 1 - Pican Verification for Laminate Stiffness

Laminate	Lower bound (95% confidence)	Mean	Experimental value	Upper bound (95% confidence)
$[0/\pm 45_2/0/\pm 45]_s$				
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	0.771	0.792	0.803	0.813
$[0_2/\pm 45/0_2/90/0]_s$				
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	0.305	0.312	0.325	0.318
$[(0/\pm 45/90)_2]_s$				
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	0.310	0.315	0.350	0.320



- o Constituents
- o Fiber Misalignment
- o Fiber Volume Ratio
- o Void Volume Ratio
- o Ply Orientation Angle
- o Ply Thickness

Figure 1 - Sources of Scatter - Fabrication Process

- 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.

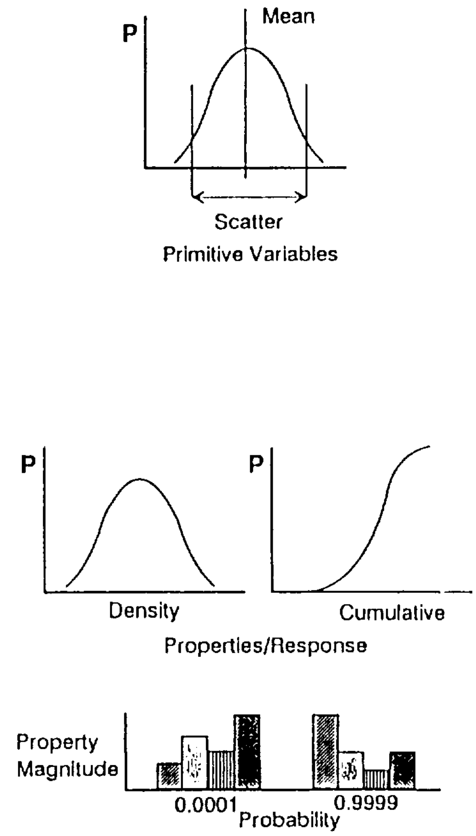
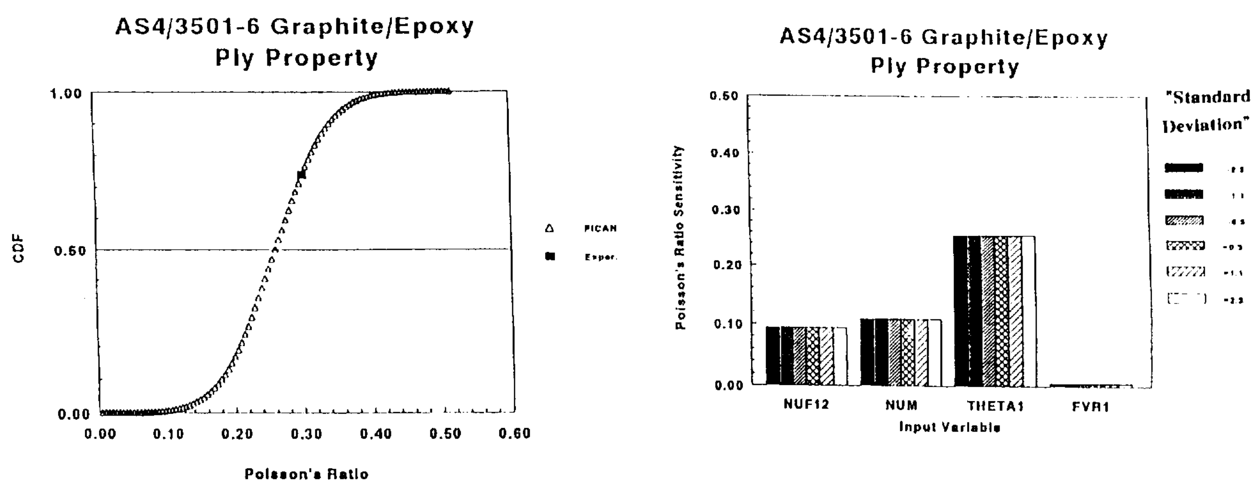


Figure 2 - Probabilistic Simulation



Cumulative Distribution Function

Sensitivity Factors

Figure 3 - Probabilistic Composite Micromechanics Simulation Results - Major Poisson's Ratio (AS4/3501-6 Graphite/Epoxy)

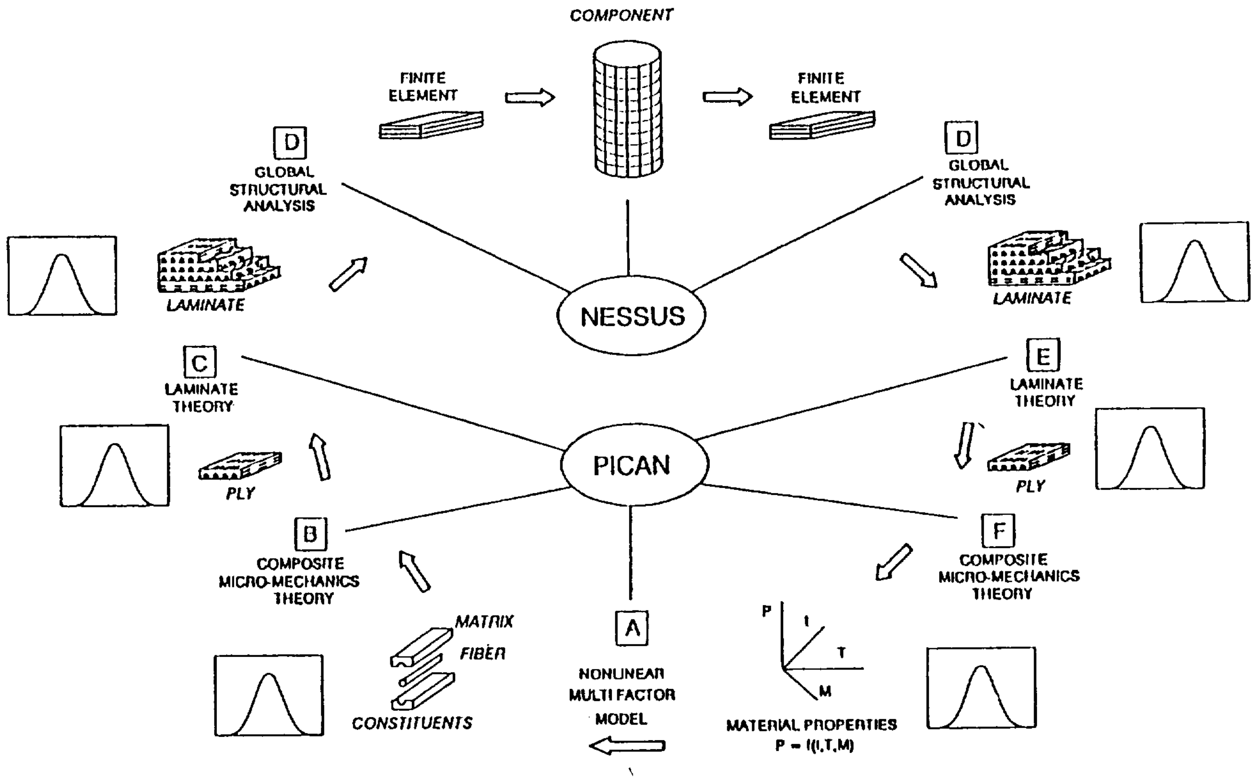


Figure 4 - IPACS: Integrated Probabilistic Assessment of Composite Structures

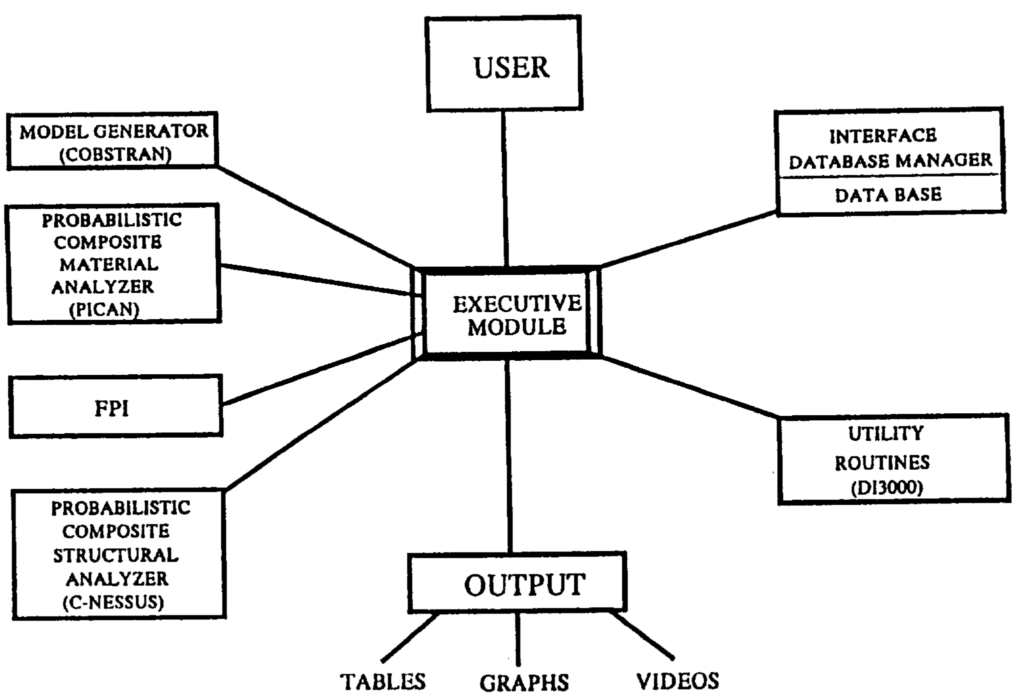


Figure 5 - Integrated Probabilistic Assessment of Composite Structures (IPACS) Architecture of Software System

GEOMETRY OF THE PLATE

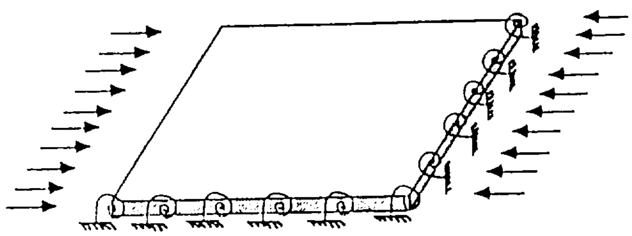


Plate Geometry

IPACS VERIFICATION FOR BUCKLING LOADS

Laminate	lower bound (mean-2σ)	mean	experimental value	upper bound (mean-1-2σ)
20[0]20 buckling load	247	284	271	322
20[90]20 *buckling load	173	195	251	293
10[$\pm$30]5S, 10($\mp$30) *buckling load	513	567	662	688
10[$\pm$45]5S, 10($\mp$45) buckling load	555	609	592	663
10[$\pm$60]5S, 10($\mp$60) buckling load	562	623	661	684

*with uncertainties in the boundary conditions

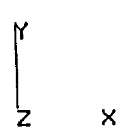
Buckling Loads Summary

Figure 6 - Probabilistically Simulated Buckling Loads of Boron/Epoxy Composite Plates

FINITE ELEMENT MODELING:

For Coarse Mesh:
No. of Nodes = 180
No. of Elements = 160

For Fine Mesh:
No. of Nodes = 680
No. of Elements = 640



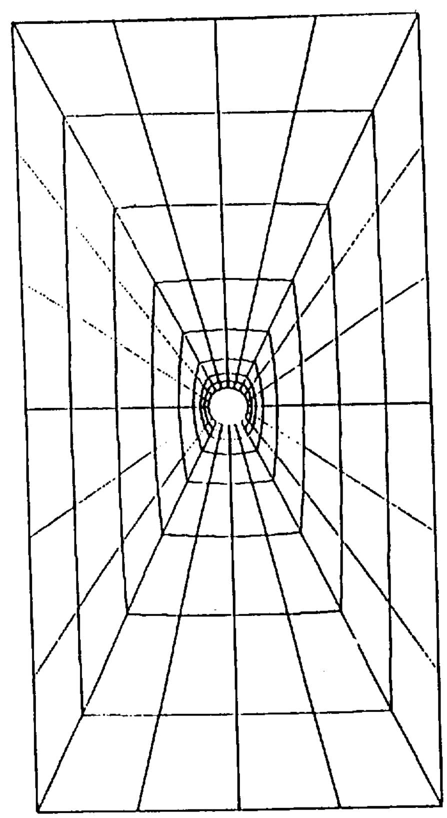


Figure 7 - Composite Panel with Center Hole

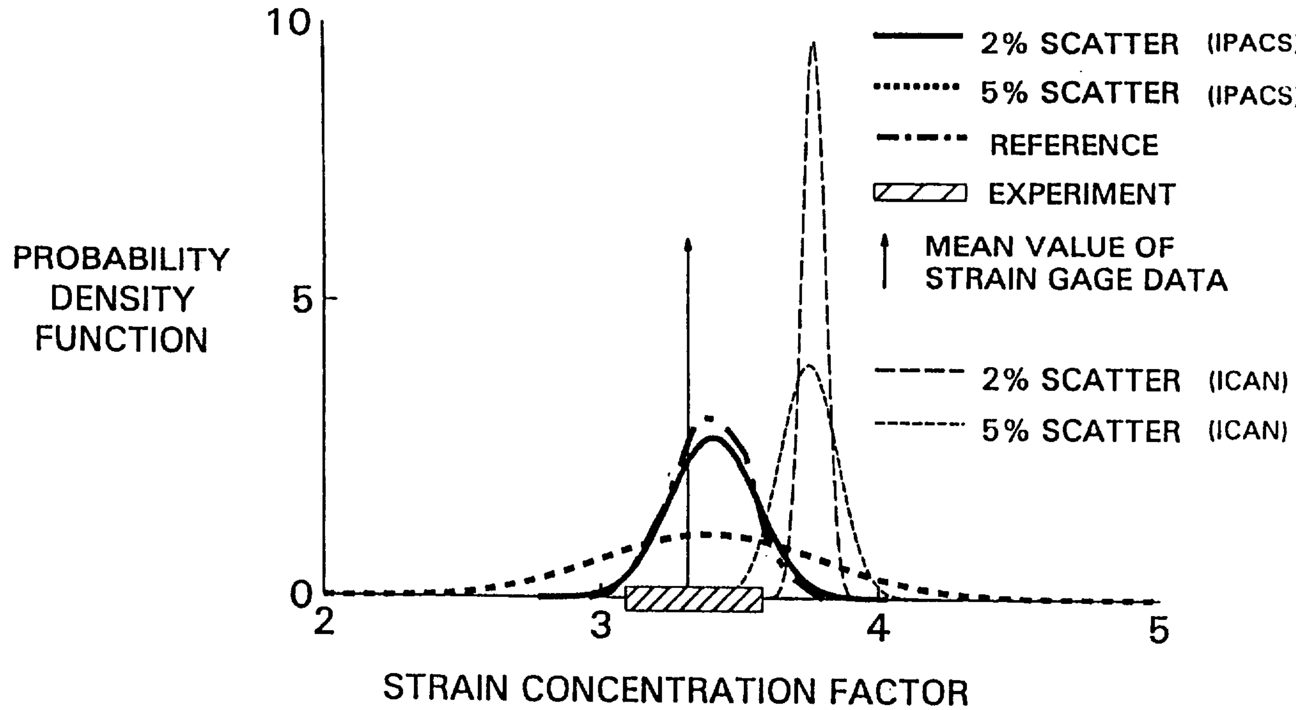


Figure 8 - Probabilistic Strain Concentration Factor of a (0/45/-45/0/90)s Laminate Plate (Boron/Epoxy)

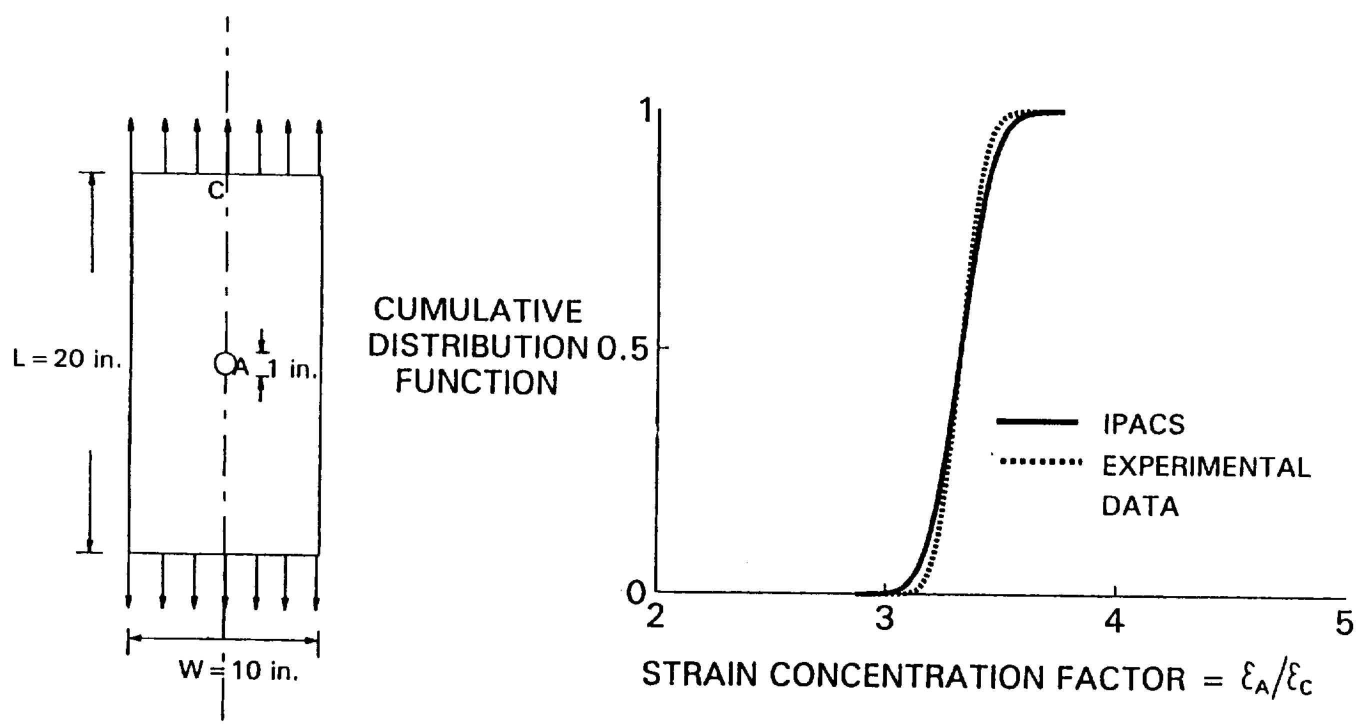


Figure 9 - Probabilistic Strain Concentration Factor of a (0/45/-45/0/90)s Laminate Plate (Boron/Epoxy with 1.5% Scatter)

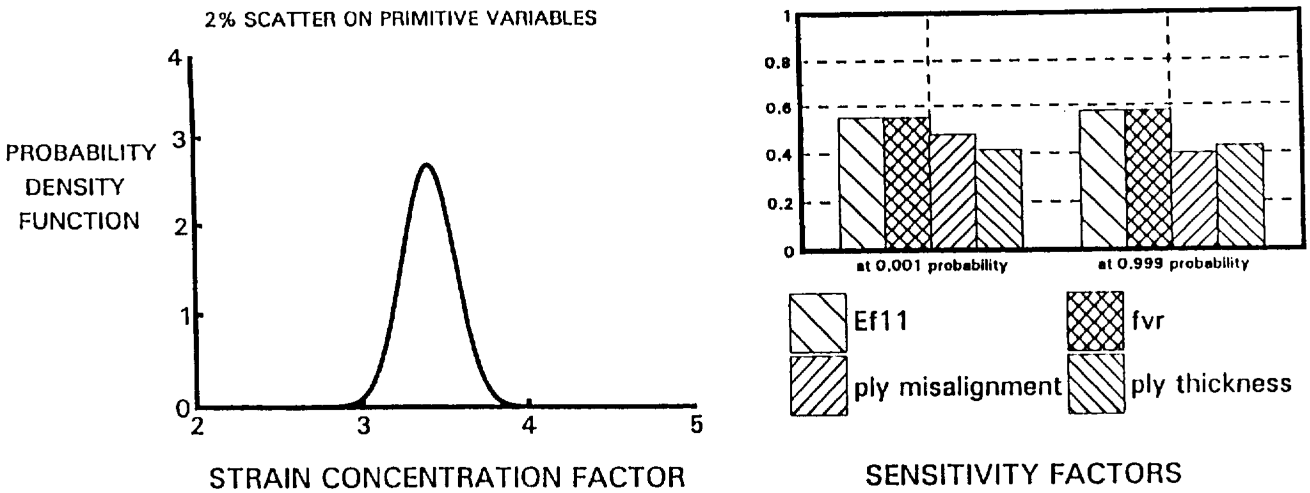


Figure 10 - Probability Density Function of the Strain Concentration Factor (SCF) and the Sensitivity of Each Primitive Variable to the Probabilistic SCF of a Boron/Epoxy Laminate Plate is Simulated by IPACS

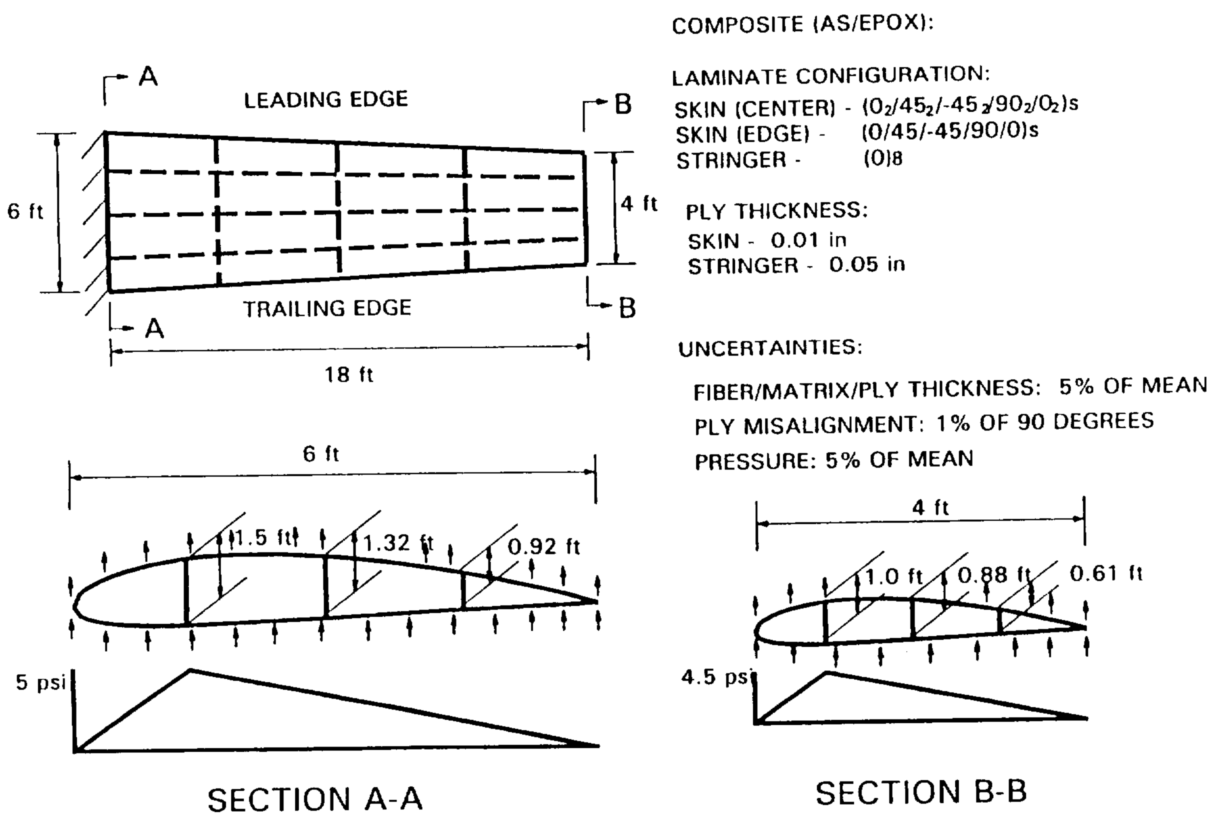


Figure 11 - Geometry and Loading for a Composite Wing

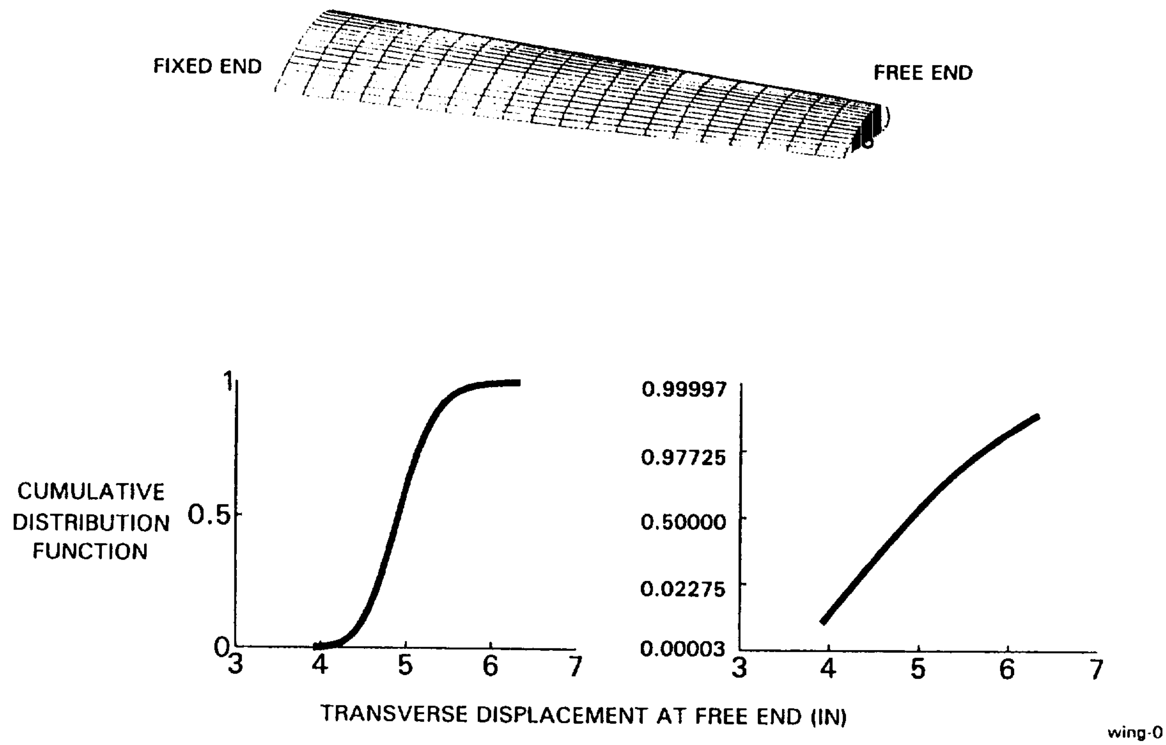


Figure 12 - Probabilistic Transverse Displacement of a Composite Wing

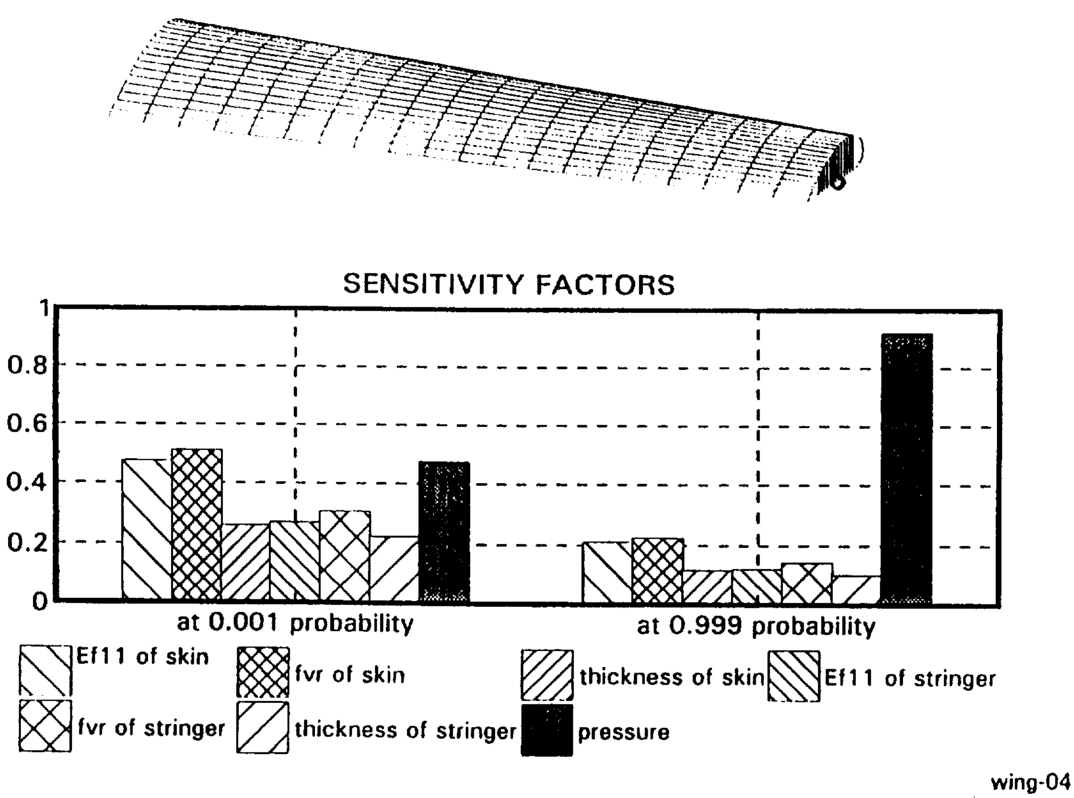


Figure 13 - Sensitivity Analysis of Probabilistic Transverse Displacement of the Composite Wing

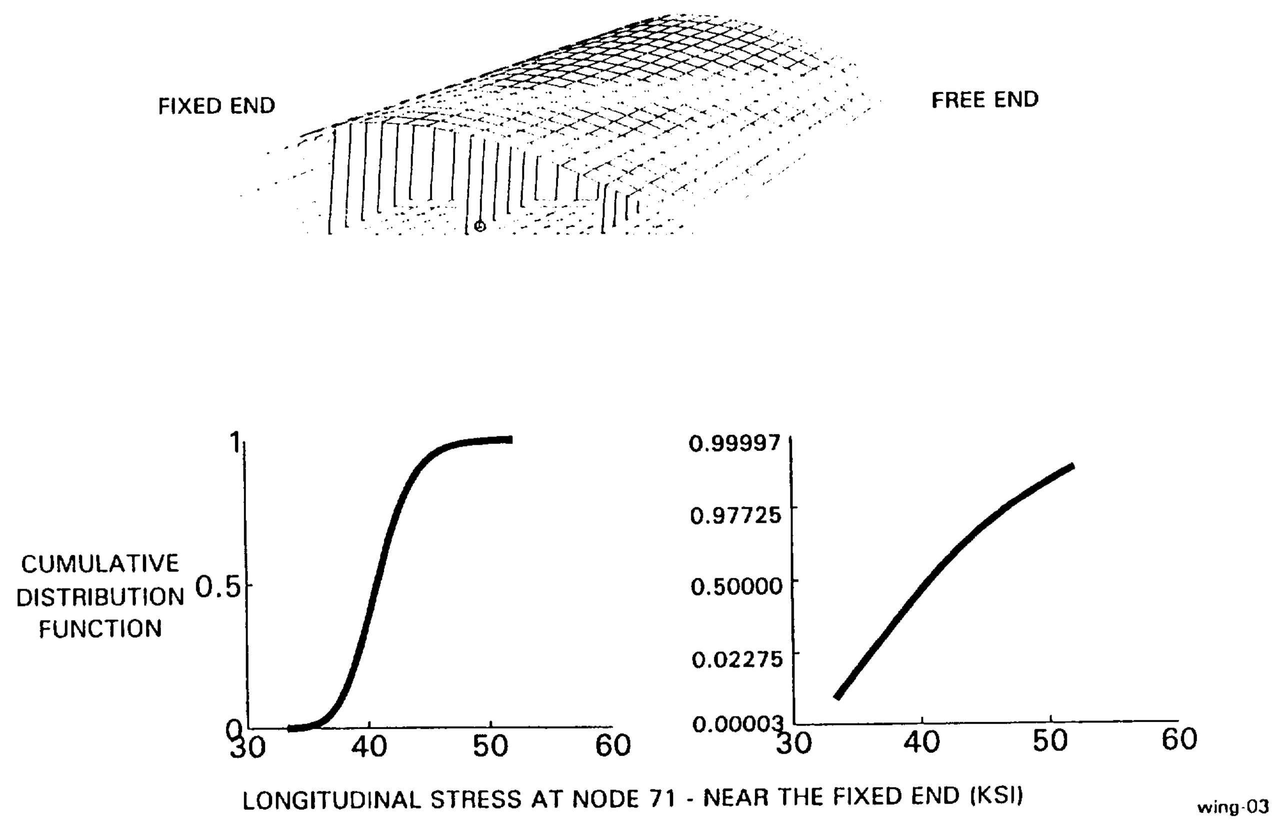


Figure 14 - Probabilistic Longitudinal Stress of a Composite Wing

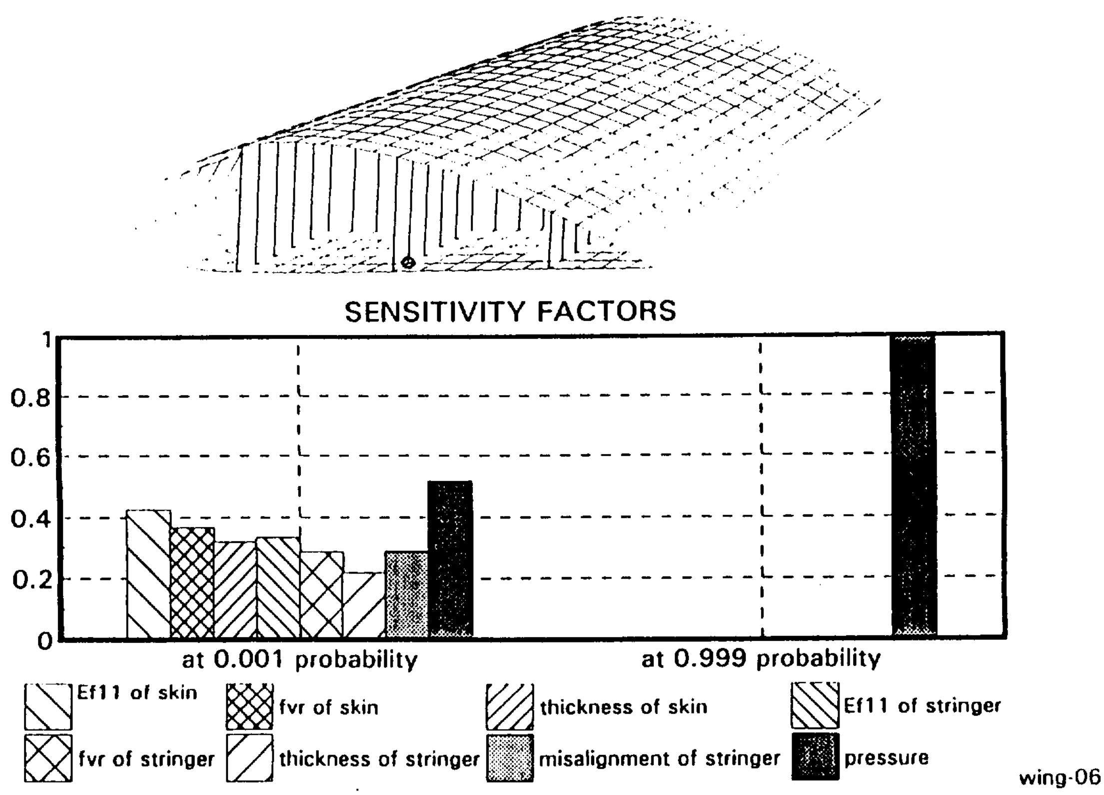


Figure 15 - Sensitivity Analysis of Probabilistic Longitudinal Stress of the Composite Wing

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