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NASA Technical Memorandum 106384

A Method for the Probabilistic Design Assessment of Composite Structures

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Prepared for the
24th International SAMPE Technical Conference
sponsored by the Society for the Advancement of Materials & Process Engineering
Toronto, Canada, October 20–22, 1992

National Aeronautics and
Space Administration

A METHOD FOR THE PROBABILISTIC DESIGN ASSESSMENT OF COMPOSITE STRUCTURES

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SUMMARY

A formal procedure for the probabilistic design assessment of a composite structure is described. The uncertainties in all aspects of a composite structure (constituent material properties, fabrication variables, structural geometry, and service environments, etc.), which result in the uncertain behavior in the composite structural responses, are included in the assessment. The probabilistic assessment consists of (1) design criteria, (2) modeling of composite structures and uncertainties, (3) simulation methods, and (4) the decision-making process. A sample case is presented to illustrate the formal procedure and to demonstrate that composite structural designs can be probabilistically assessed with accuracy and efficiency.

INTRODUCTION

Composite materials are widely used in modern structures for high performance and reliability. However, because these structures usually operate in hostile and random service environments, it is difficult to predict the structural performance. In addition, experiments show that the composite structural behavior exhibits wide scatter as a result of the inherent uncertainties in design variables. The design variables, known as primitive variables, include the fiber and matrix material properties at the constituent level; fiber and void volume ratios, ply misalignment and ply thickness for the fabrication process; and random structure size, loadings, and temperature.

The scatter in the structural behavior cannot be computationally simulated by the traditional deterministic methods that use a safety factor to account for uncertain structural behavior; thus, the structural reliability cannot be discerned. A probabilistic design methodology is needed to accurately determine the structural reliability of a composite structure. In the past, Monte Carlo methods have been widely used for probabilistic composite structural analysis (ref. 1). However, these methods are computationally intensive and can be used for verification purposes only. Likewise, when perturbation techniques (ref. 2) are used to account for uncertainties, only the first few statistical moments of the structural responses — and not the cumulative distribution function (CDF) — are obtained.

NASA Lewis Research Center has developed a formal methodology to efficiently and accurately quantify the scatter in the composite structural response and to assess the composite structural design, while accounting for the uncertainties at all composite levels (constituent, ply, laminate, and structure) (fig.1). This methodology, which integrates micro- and macrocomposite mechanics and laminate theories, finite element methods, and probability algorithms, was implemented through the computer code IPACS (Integrated Probabilistic Assessment of Composite Structures) (fig. 2) (ref. 3). IPACS is used to assess composite structures probabilistically for all types of structural performances such as instability, clearance, damage initiation, delamination, microbuckling, fiber crushing, and resonance damage. Since IPACS uses a special probability algorithm FPI (fast probability integrator) (ref. 4) instead of the conventional Monte Carlo simulation, tremendous computational time can be saved (ref. 5). Therefore, a probabilistic composite structural analysis, which cannot be done traditionally, becomes desirable especially for large structures with many uncertain variables. A typical case is analyzed herein to demonstrate the code IPACS for the probabilistic assessment of composite structures and to illustrate the formal design assessment methodology.

FUNDAMENTAL APPROACH

The fundamental approach for the probabilistic assessment is as follows:

(1) Identify all possible uncertain variables at all composite scale levels.

(2) Determine the probabilistic distribution function (PDF) for each variable.

(3) Process all random variables through an analyzer that consists of micro- and macrocomposite mechanics and laminate theories, structural mechanics, and probability theories.

(4) Extract useful information from the output of the analyzer and check against the probabilistic design criteria.

The uncertainties in a composite structural design can originate at different composite scale levels. At the constituent level, the material properties for the fiber and matrix are the major sources of uncertainties. The primitive variables are defined in the appendix and their typical values are listed in table I. At all stages of the fabrication process, the fabrication variables such as fiber volume ratio, void volume ratio, ply misalignment, and ply thickness show considerable scatter. At the structure level, variation of the geometry during the assembly stage, uncertain boundary conditions, and random thermal-mechanical loads contribute significantly to the scatter in the composite structural response.

Once the uncertainties in the primitive variables are identified, micro- and macrocomposite mechanics and laminate theories are used to propagate them in the constituent material properties and in the fabrication variables from the lower composite levels (ply) to the higher composite levels (laminate). The scatter in the structural response is then computationally simulated through structural mechanics (or finite element methods) and through probability theories (Monte Carlo simulation or FPI) to account for uncertainties in the laminate material properties, geometry, boundary conditions, and thermal-mechanical loads.

Probabilistic design assessment includes probabilistic design criteria that are based on considerations such as safety, performance, economics, and other requirements that could introduce uncertainties in a specific design. These factors contribute to the uncertainties of the structural response and provide inclusive information for judicious decisions on design acceptance or rejection.

PROBABILISTIC COMPOSITE STRUCTURAL DESIGN ASSESSMENT

This report describes a probabilistic design assessment methodology for composite structures with an acceptable or preassigned reliability. The details of the assessment are described in the following three steps.

Step 1: Probabilistic Design Criteria Setup

A typical design criterion can be stated as follows: The probability of a failure event should be less than an acceptable value, say 10^{-3}. A failure event occurs when a structural response is less than the allowable response. This probability is defined as the failure probability. The allowable response divides the possible response domain into safe and failure regions as shown in figure 3. The predicted failure probability is the area under the probability density function in the failure region. The critical response (fig. 3) is determined by IPACS such that the probability of a response exceeding this critical value is in the safe region. When the critical response falls within the safe region, the design is acceptable. When the critical response falls within the failure region, the design is unacceptable and requires a redesign. Sample probabilistic design criteria for the various failure modes are described as follows:

(1) Instability—The probability that the buckling load is smaller than the design load should be less than 10^{-3}.

(2) Clearance—The probability that the nodal displacement is greater than the allowable tolerance should be less than 10^{-3}.

(3) Resonance avoidance—The probability that the natural frequency is greater that its upper bound should be less than 10^{-3}.

(4) Delamination—The probability of delamination occurrence should be less than 10^{-3}.

Step 2: Probabilistic Simulation Using IPACS

IPACS integrates several NASA in-house computer codes developed in recent years such as COBSTRAN (Composite Blade Structural Analyzer) (ref.6), PICAN (Probabilistic Integrated Composite Analyzer) (ref. 7) and MHOST (Marc Hot Section Technology) (ref. 8). COBSTRAN is a dedicated finite element model generator for structural analysis of composite structures. PICAN uses ICAN (Integrated Composite Analyzer) computer code (ref. 9) for composite mechanics. This code has evolved over the last 20 years and has been verified with experimental data for all aspects of composites. PICAN enables the computation of the perturbed and probabilistic composite material properties at the ply and laminate levels. MHOST performs structural analyses using verified finite element methods. These analyses determine the perturbed and probabilistic structural response at global, laminate, and ply levels. PICAN and MHOST share the FPI module (ref. 4) for the application of the fast probability integration algorithm to obtain cumulative distribution functions (CDF's) of the material properties and the structural responses.

FPI is an approximate technique for the probabilistic analysis of the structural performance and has the major advantage of speed. FPI techniques are orders of magnitude more efficient than Monte Carlo simulation methods. This is especially true in the tails regions of the distribution; that is, at very high or low probabilities since the FPI solution time is independent of the probability level. Conversely, in Monte Carlo simulation methods, the computational time increases with very high or low probability levels. Also, FPI allows evaluation of information that describes the relative importance of each random variable. These sensitivity factors can be a valuable aid in optimizing a design.

In IPACS, the probabilistic assessment of composite structures starts with the identification of uncertain primitive variables at constituent and ply levels. These variables are then selectively perturbed several times to create a data base. The data base is used to establish the relationship between the desired structural response (or the desired material property) and the primitive variables. For every given perturbed variable, micromechanics is applied to determine the corresponding perturbed mechanical properties at the ply and laminate levels. Laminate theory is then used to ascertain the resultant force-moment–strain-curvature relationship. With this relationship at the laminate level, a finite element perturbation analysis is performed to find the structural response that corresponds to the selectively perturbed primitive variables. This process is repeated until enough data are generated and the proper relationship between structural response and primitive variables can be established through a numerical procedure.

Given the probabilistic distributions of primitive variables and a numerically determined relationship between them and the structural response, FPI is applied. For every discrete response value, a corresponding cumulative probability can be computed quickly by FPI. This process is repeated until the CDF can be appropriately represented. The probabilistic material properties at ply and laminate levels are also computed in this same way. The output information from FPI for a given structural response includes its discrete CDF values, the coefficients for the PDF that was used for the uncertainties in the primitive variables, and the variables' sensitivity factors to the structural response. It is important to restate that the process consists of multiple deterministic analyses using verified structural and composite mechanics computer codes. Therefore, the probabilistic simulations are mechanistically accurate and reflect the uncertainties of the primitive variables in the uncertainties of the structural response.

Step 3: Decision Making and Redesign

IPACS simulates the PDF of a given structural response, such as buckling load, displacement, local stress, local strength, vibration frequencies, and fatigue life. The probability of a design violation for each criterion can be calculated with these PDF functions. When the failure probability is greater than the acceptable value, say 10^{-3}, the composite structural design should be rejected. To redesign a composite structure, one can use the sensitivity factors from the IPACS analysis. Sensitivity factors rank the random variables based on their contribution to this failure probability. Therefore, a redesign will be guided by this information with manufacturing control of the mean and the standard deviation (stdv) of the appropriate random variables.

DEMONSTRATION CASE AND DISCUSSION

A stiffened composite cylindrical pipe is probabilistically assessed against probabilistic design criteria. The cylindrical pipe is 2 ft in diameter and 20 ft long (fig. 4). The structure is modeled by 588 four-noded shell elements and 600 active nodes (6 degrees of freedom per node). The composite pipe consists of the skin, three horizontal circumferential frames, and four vertical stringers. The laminate configurations for the 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 the other end. When the spring constant approaches infinity, a completely fixed boundary condition is simulated. When the spring constants are set to zero, a free boundary condition is simulated. For a given set of spring constants, a partially fixed boundary condition is modeled. The pipe is subjected to axial (F_x) and lateral (F_y) loads as well as torsional moments (M_{xx}) at its free end (fig. 5).

The uncertain variables are identified at the constituent, ply, and structure levels. At the constituent level, 17 material properties for the graphite fiber and 12 for the epoxy matrix of the skin, frames, and stringers are assumed to be uncertain variables. Their probability distribution types and associated parameters are listed in table I. At the ply level, the fabrication variables (fiber and void volume ratio, ply orientation, and ply thickness) are treated as random variables. Their statistics are shown in table II. At the structure level, spring constants that simulate a partially fixed boundary condition are assigned by a probability distribution as are the loading conditions. Their statistics are shown in table III.

In the following paragraphs, the composite pipe is assessed or checked against two design criteria: clearance and delamination; and the results are discussed.

Clearance Assessment

The clearance criterion is violated 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 6. 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, and the clearance criterion is satisfied. If the allowable displacement is 5 in., then the critical displacement falls in the failure region. The clearance design criterion is violated and the pipe needs to be redesigned. From the IPACS sensitivity analysis, the fiber modulus, fiber volume ratio, ply thickness of the skin, and random loads in lateral direction have the most significant contribution to the failure probability (fig. 7).

Delamination Assessment

Delamination occurs when the ply stress is greater than the ply delamination strength. From the IPACS analysis, the relationship between the ply stress S_{pl} and the independent random variables $\mathbf{X}$ is numerically determined as shown in equation (1).

$$S_{pl} = a_0 + \sum_{i=1}^{N} a_i \mathbf{X}_i + \sum_{i=1}^{N} b_i \mathbf{X}_i^2 \tag{1}$$

where a_0, a_i and b_i are constants; N is number of independent random variables. The ply delamination strength S_{DL} (ref. 9) is shown in equation (2).

$$S_{DL} = 10\ S_l + 2.5\ S_{mT}\ A \tag{2}$$

$$S_l = \left[1 - \left[\sqrt{fvr} - fvr\right]\left[1 - \frac{G_m}{G_{f12}}\right]\right] S_{mS}\ A \tag{3}$$

and

$$A = 1 - \sqrt{\frac{4vvr}{\pi\left[1 - fvr\right]}} \tag{4}$$

where fvr and vvr are fiber volume ratio and void volume ratio; G_{f12} and G_m are fiber and matrix shear modulus; S_{mT} and S_{mS} are the matrix tensile and shear strength. A limit state function (LSF) is defined as

$$LSF = S_{DL} - S_{pl} \tag{5}$$

If the LSF is less than 0, it indicates that the ply stress is greater than the ply delamination strength. Therefore, delamination will occur. The probability of LSF ≤ 0, computed by FPI, is 0.0008, which is smaller than the acceptable failure probability (10^{-3}). From the sensitivity analysis, the eight most influential random variables that contribute to the failure probability are identified in figure 8. The matrix shear strength is the most important (sensitivity factor about 0.8) followed by the ply thickness of the composite skin (sensitivity factor about 0.4). If the acceptable failure probability is reduced to 10^{-4}, redesign is necessary. The redesign can be achieved most efficiently by manufacturing tolerance control or by controlling the mean or scatter of the significant primitive variables. For example, if the coefficient of variation (scatter) of the ply shear strength is reduced from 5 to 4 percent, the failure probability is reduced to 0.0003. However, if the scatter of the ply thickness is also reduced from 5 to 4 percent, the failure probability can only be reduced to 0.0006. This demonstrates that the failure probability can be reduced more effectively by reducing the scatter of the ply shear strength, the most important random variable.

Any other structural response can be similarly evaluated. These two examples demonstrate how the probabilistic design assessment is performed by using IPACS.

CONCLUDING REMARKS

A formal methodology is described in this report for the probabilistic design assessment of composite structures. This methodology, integrating micro- and macrocomposite theory, structural mechanics (finite element methods), and probability algorithms, performs a probabilistic assessment of composite structural designs considering all identifiable uncertain variables at all composite levels. Composite structural designs can be assessed against specific probabilistic design criteria demonstrating that such designs can be computationally assessed by using the probabilistic computer code IPACS. Information for an efficient design can also be obtained. Specifically, for the demonstration case, the uncertainty range in the end displacement was between 1 and 3 percent of the pipe length and was most sensitive to the uncertainties in the skin-related primitive variables. Conversely, probable delamination failure was most sensitive to the shear strength of the skin.

APPENDIX—SYMBOLS

C_f	fiber heat capacity, Btu/in. °F
C_m	matrix heat capacity, Btu/in. °F
D_m	matrix diffusivity, in.^{3}/sec
d_f	filament equivalent diameter, in.
E_{f11}	fiber modulus in longitudinal direction, Mpsi
E_{f22}	fiber modulus in transverse direction, Mpsi
E_m	matrix elastic modulus, Mpsi
F_x	axial loads, kip
F_y	lateral loads, kip
fvr	fiber volume ratio
G_{f12}	in-plane fiber shear modulus, Mpsi
G_{f23}	out-of-plane fiber shear modulus, Mpsi
G_m	matrix shear modulus, Mpsi
K_{cTR}	translational spring constant, lb/in.
K_{cTO}	torsional spring constant, lb-in./rad
K_{f11}	fiber heat conductivity in longitudinal direction, Btu·in./hr in.^{2} °F
K_{f22}	fiber heat conductivity in in-plane transverse direction, Btu·in./hr in.^{2} °F
K_{f33}	fiber heat conductivity in out-of-plane transverse direction, Btu·in./hr in.^{2} °F
K_m	matrix heat conductivity, Btu·in./hr in.^{2} °F
M_{xx}	torsional moment, kip-ft
N_f	number of fibers per end
S_{DL}	ply delamination strength, ksi
S_{fC}	fiber compressive strength, ksi
S_{fT}	fiber tensile strength, ksi
S_{mC}	matrix compressive strength, ksi
S_{mS}	matrix shear strength, ksi
S_{mT}	matrix tensile strength, ksi
S_{pl}	ply stress
stdv	standard deviation
t_{psk}	ply thickness of skin, in.
t_{pst}	ply thickness of stringer, in.
vvr	void volume ratio
$\mathbf{X}$	vector of independent random variables
α_{f11}	fiber thermal expansion coefficient in longitudinal direction, ppm/ °F
α_{f22}	fiber thermal expansion coefficient in transverse direction, ppm/ °F
α_m	matrix thermal expansion coefficient, ppm/ °F
β_m	matrix moisture coefficient, in./in.
θ_p	ply misalignment, deg
ν_{f12}	in-plane fiber Poisson's ratio
ν_{f23}	out-of-plane fiber Poisson's ratio
ν_m	matrix Poisson's ratio
ρ_f	fiber mass density, lb/in.^{3}
ρ_m	matrix mass density, lb/in.^{3}

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TABLE I.—MATERIAL PROPERTIES AT THE CONSTITUENT LEVEL FOR SKIN AND STRINGERS

Property	Assumed distribution type	Mean[a]	Assumed uncertainty scatter
E_{f11}, Mpsi	Normal	31.0	0.05
E_{f22}, Mpsi		2.0	
G_{f12}, Mpsi		2.0	
G_{f23}, Mpsi		1.0	
ν_{f12}		0.2	
ν_{f23}		.25	
α_{f11}, ppm/ °F		−.55	
α_{f22}, ppm/ °F		5.6	
ρ_f, lb/in.^{3}		.063	
N_f	Constant	10 000	
d_f, in.	Normal	.0003	
C_f, Btu/in. °F		.17	
K_{f11}, Btu· in./hr in.^{2} °F		580	
K_{f22}, Btu· in./hr in.^{2} °F		58	
K_{f33}, Btu· in./hr in.^{2} °F		58	
S_{fT}, ksi	Weibull	400	
S_{fC}, ksi	Weibull	400	
E_m, Mpsi	Normal	.5	
G_m, Mpsi		.185	
ν_m		.35	
α_m, ppm/ °F		42.8	
ρ_m, lb/in.^{3}		.0443	
C_m, Btu/in. °F		.25	
K_m, Btu· in./hr in.^{2} °F		1.25	
S_{mT}, ksi	Weibull	15	
S_{mC}, ksi	Weibull	35	
S_{mS}, ksi	Weibull	13	
β_m,(in./in.)/1% moist	Normal	.004	
D_m, in.^{3}/sec	Normal	.002	

[a]Typical values for graphite-fiber/epoxy-matrix composites at 0.6 fiber volume ratio.

TABLE II.—FABRICATION VARIABLES AT PLY LEVEL

Variable	Assumed distribution type	Mean	Assumed uncertainty scatter
fvr	Normal	0.60	0.05
vvr		.02	.05
θ_p, deg		.00	.9 (stvd)
t_{psk}, in.		.005	.05
t_{pst}, in.		.02	.05

TABLE III.—UNCERTAINTIES IN STRUCTURAL LEVEL

Uncertainty	Assumed distribution type	Mean	Assumed uncertainty scatter
K_{cTR}, lb/in.	Normal	30×10^6	0.20
K_{cTO}, lb-in./rad	↓	12×10^2	.20
F_x, kip	↓	288	.05
F_y, kip	↓	5.76	.05
M_{xx}, kip-ft	↓	576	.05

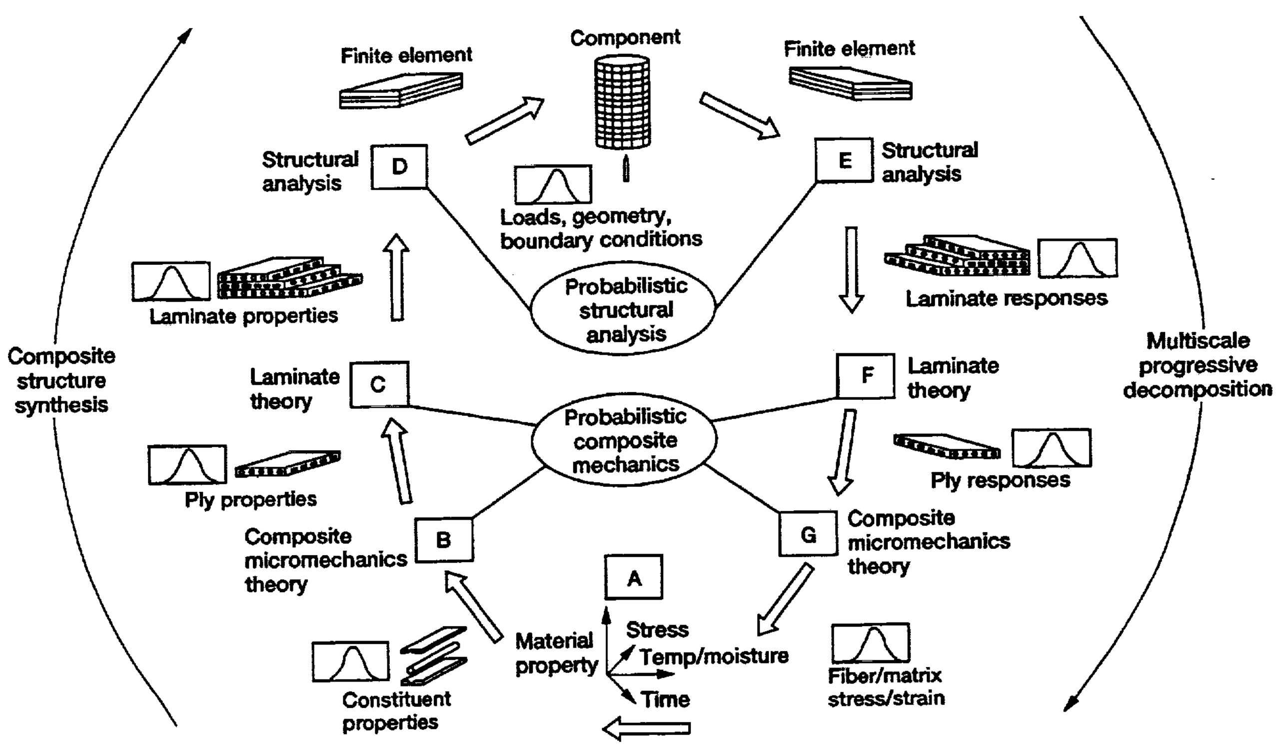

Figure 1.—Concept of probabilistic assessment of composite structures.

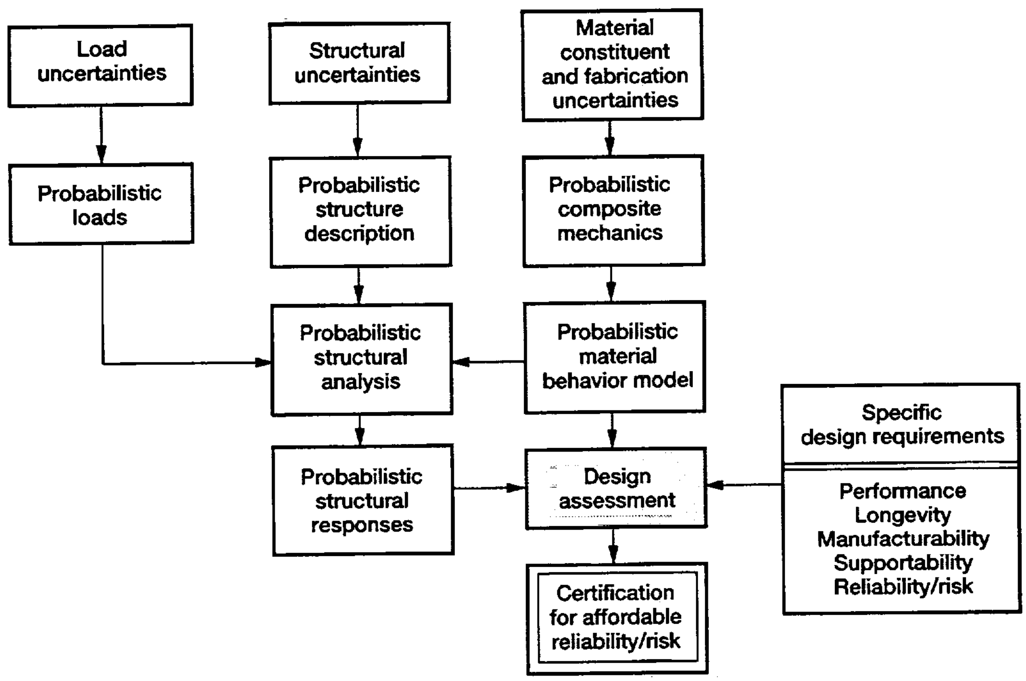

Figure 2.—Probabilistic design assessment of composite structures.

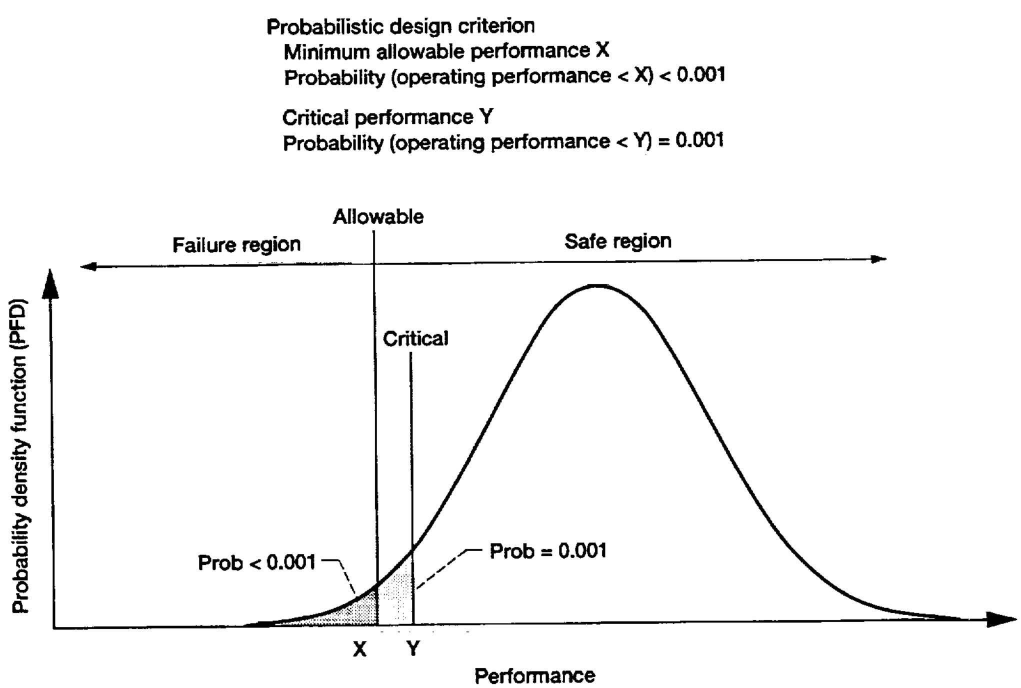

Figure 3.—Safe and failure regions in a probability space.

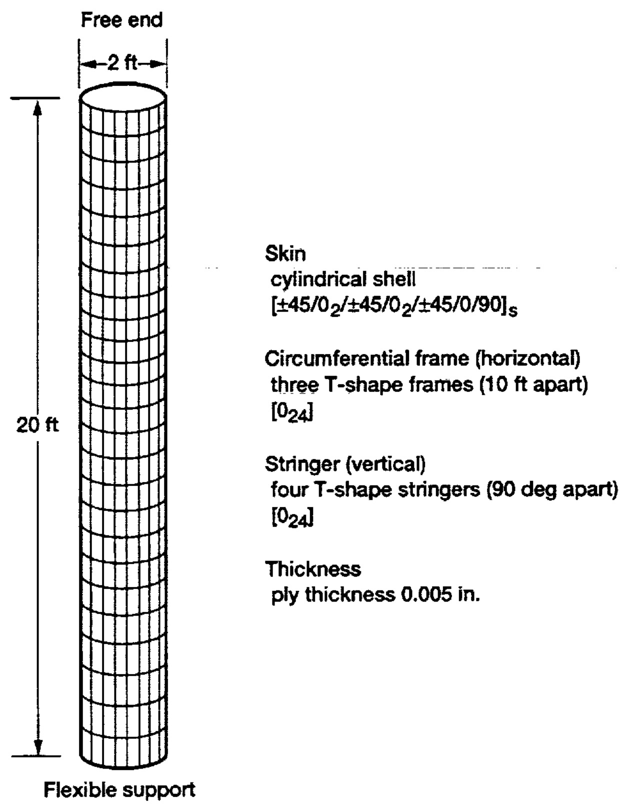

Figure 4.—Geometry and composite configuration of stiffened composite pipe.

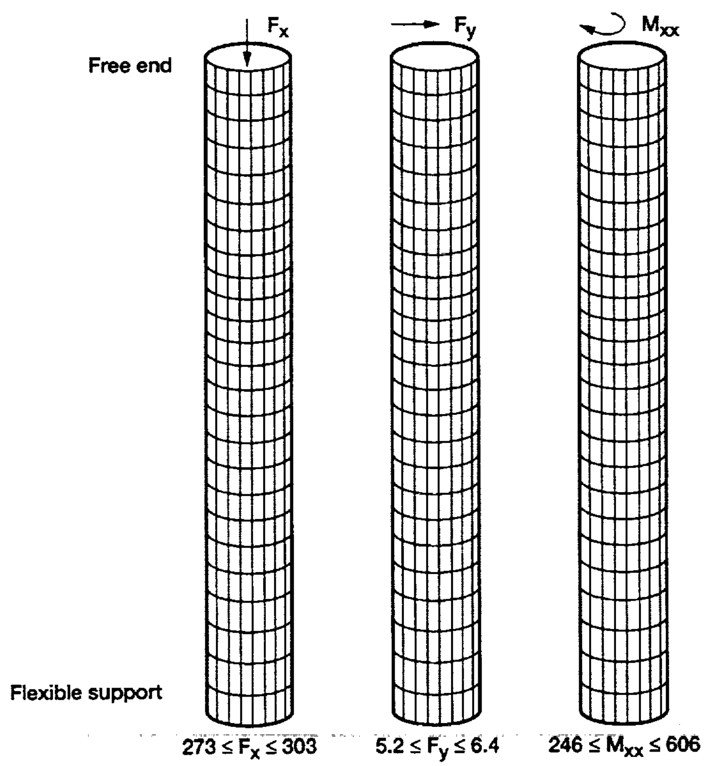

Figure 5.—Probabilistic loading conditions (kip) of stiffened composite pipe.

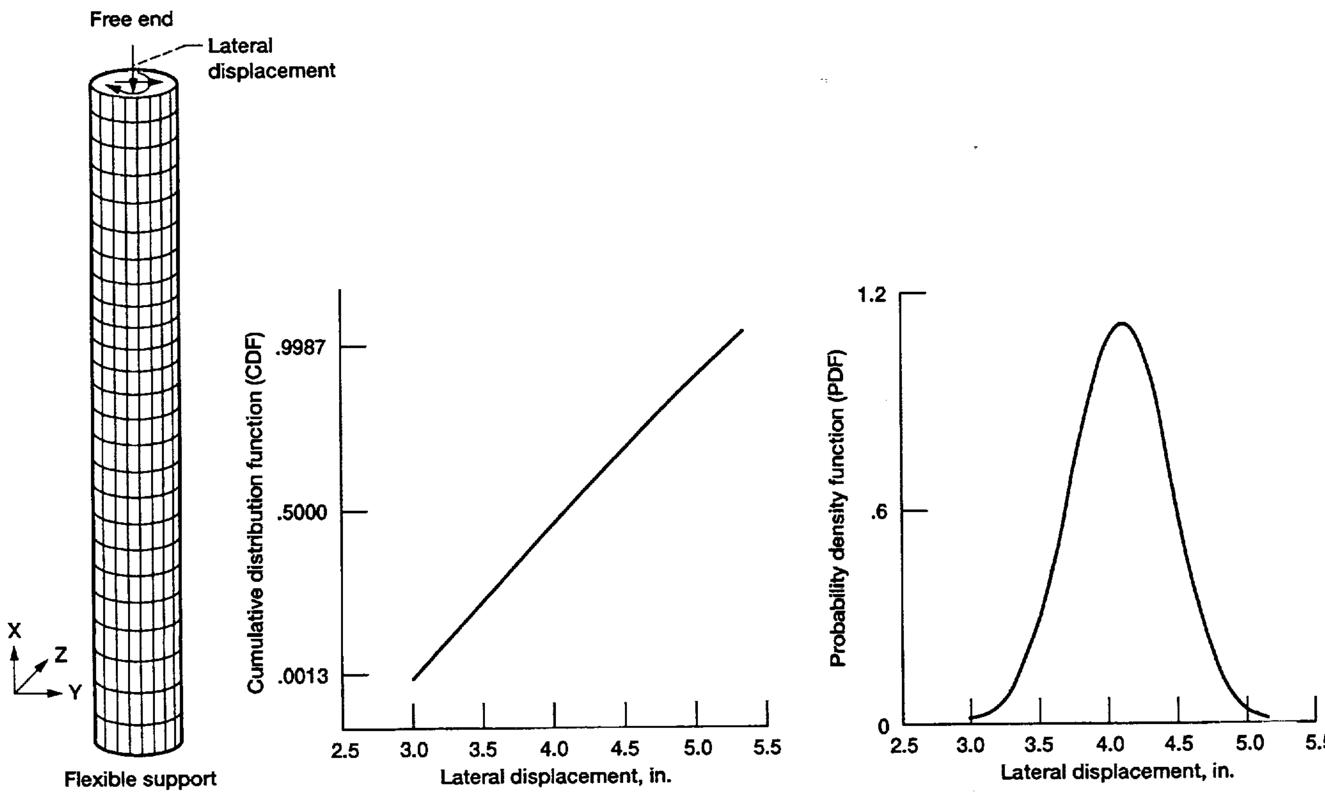

Figure 6.—Cumulative distribution function (CDF) and probability density function (PDF) of lateral displacement at free end.

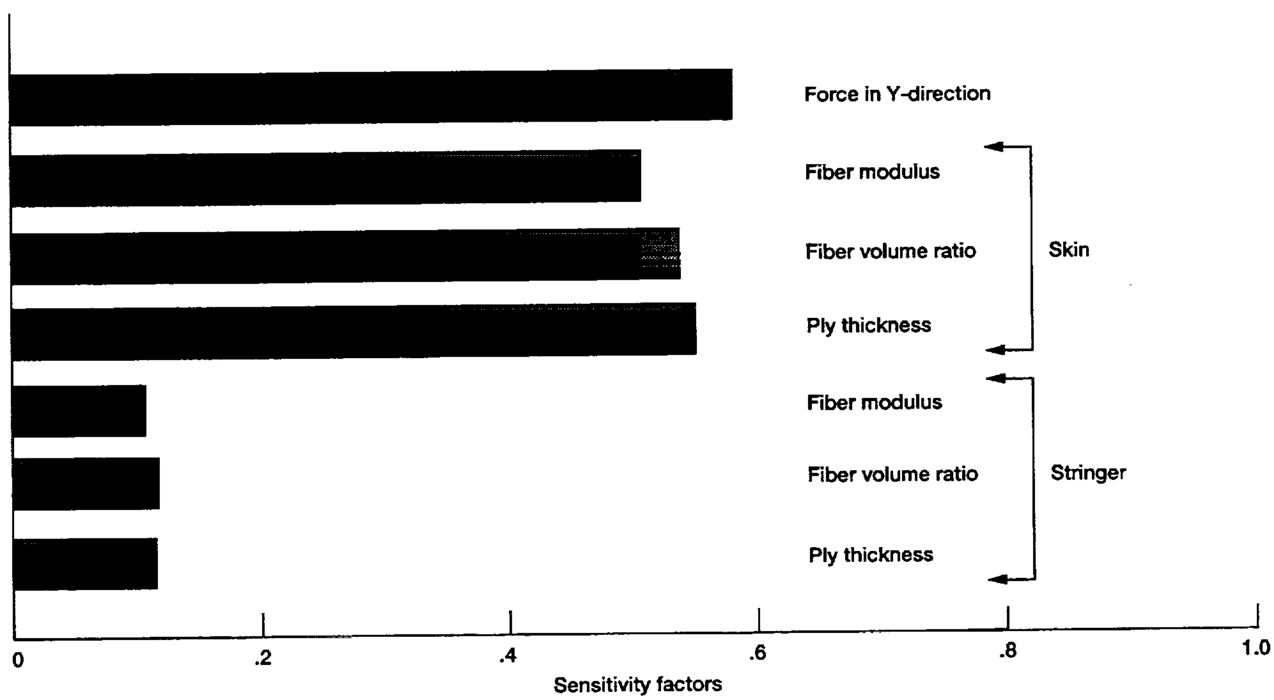

Figure 7.—Sensitivity factors of lateral displacement at free end at 0.001 failure probability.

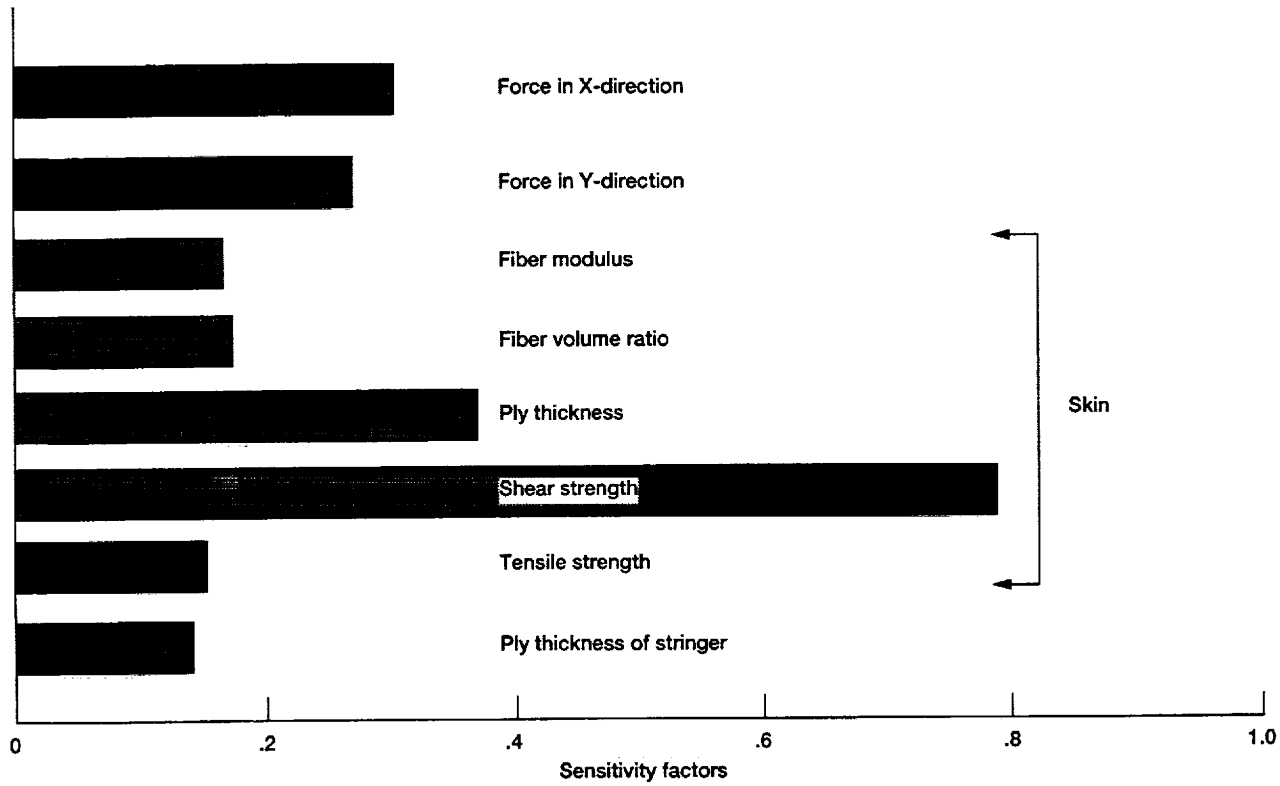

Figure 8.—Sensitivity factors for 0.0008 delamination probability.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	March 1994	Technical Memorandum

4. TITLE AND SUBTITLE

A Method for the Probabilistic Design Assessment of Composite Structures

5. FUNDING NUMBERS

WU–510–02–12

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
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Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E–8204

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, D.C. 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM–106384

11. SUPPLEMENTARY NOTES

Prepared for the 24th International SAMPE Technical Conference sponsored by the Society for the Advancement of Materials & Process Engineering, Toronto, Canada, October 20–22, 1992. Michael C. Shiao and Surendra N. Singhal, Sverdrup Technology, Inc., Lewis Research Center Group, 2001 Aerospace Parkway, Brook Park, Ohio 44142 and Christos C. Chamis, NASA Lewis Research Center. Responsible person, Christos C. Chamis, organization code 5200, (216) 433–3252.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Category 39

12b. DISTRIBUTION CODE

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

A formal procedure for the probabilistic design assessment of a composite structure is described. The uncertainties in all aspects of a composite structure (constituent material properties, fabrication variables, structural geometry, and service environments, etc.), which result in the uncertain behavior in the composite structural responses, are included in the assessment. The probabilistic assessment consists of (1) design criteria, (2) modeling of composite structures and uncertainties, (3) simulation methods, and (4) the decision-making process. A sample case is presented to illustrate the formal procedure and to demonstrate that composite structural designs can be probabilistically assessed with accuracy and efficiency.

14. SUBJECT TERMS

Design criterion; Uncertainty; Probability; Reliability; Composite; Laminate; Sensitivity

15. NUMBER OF PAGES

16

16. PRICE CODE

A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	