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SUMMARY

A probabilistic design method is described and demonstrated using a smart composite wing. Probabilistic structural design incorporates naturally occurring uncertainties including those in constituent (fiber/matrix) material properties, fabrication variables, structure geometry and control-related parameters. Probabilistic sensitivity factors are computed to identify those parameters that have a great influence on a specific structural reliability. Two performance criteria are used to demonstrate this design methodology. The first criterion requires that the actuated angle at the wing tip be bounded by upper and lower limits at a specified reliability. The second criterion requires that the probability of ply damage due to random impact load be smaller than an assigned value. When the relationship between reliability improvement and the sensitivity factors is assessed, the results show that a reduction in the scatter of the random variable with the largest sensitivity factor (absolute value) provides the lowest failure probability. An increase in the mean of the random variable with a negative sensitivity factor will reduce the failure probability. Therefore, the design can be improved by controlling or selecting distribution parameters associated with random variables. This can be implemented during the manufacturing process to obtain maximum benefit with minimum alterations.

INTRODUCTION

Aerospace structures are complex assemblages of structural components that operate under severe and often *uncertain* service environments. These structures require durability, high reliability, light weight, high performance, and affordable cost. In order to meet these requirements, composite materials are attractive potential candidates. Composite materials possess outstanding mechanical properties which are derived from a wide variety of variables such as constituent material properties and laminate characteristics, which in turn are influenced by fiber and void volume ratios, ply orientation, and ply thickness. These variables are known to be uncertain in nature.

In order to further enhance structural performances to meet new challenges, other advanced concepts should be investigated. Recent developments in smart structure concepts that use actuation materials, such as piezoelectric ceramics, show great potential to enhance structural performance as well as durability and reliability (refs. 1 and 2). Figure 1 depicts a conceptual diagram of a smart composite wing system. The essential parts of a smart composite structure include: (1) a composite structure, (2) strategically located sensors, (3) signal processors, which process the signals generated by the sensors, (4) dedicated computers with suitable hardware and software which continuously check the structural response magnitudes and compare them to predetermined acceptable "red line" values and provide desired corrections to the controller, (5) a controller which signals the actuators to implement the desired corrections, and (6) actuators.

The control devices in smart structures consist of: (1) a polarized material, (2) an electric field parallel to the direction of polarization, and (3) the expansion-contraction effects of the polarized material. When a control voltage is applied, the actuation material expands or contracts so that the structural behavior is altered by a desired amount and its reliability is affected. Present piezoelectric technology has been successfully applied to small-scale and low-stress structures (ref. 3). However, there are inevitable difficulties when current technology is applied to large-scale and high-stress composite structures. Those adversities can be alleviated if (1) special fibers such as piezoelectric fibers, and (2) fast actuation capability, are combined with regular high-strength high-modulus fiber to form the smart intraply hybrid composites (ref. 4). This combination can be readily integrated into a smart composite structure by using combinations of intraply and interply hybrid composites to insure that the smart composite structures will operate in the design-specified range.

The adaptation of the intraply hybrid composite concept (refs. 4 and 5) to smart composite structures is depicted schematically in figure 2. In figure 2(a), the intraply hybrid configuration is shown, while in figure 2(b), its adaptation to smart composite structures is shown. In figure 2, the smart composite consists of (1) regular plies which are made of traditional composite materials and (2) control plies which are composed of strips of traditional composite materials interspersed with strips of mixed traditional and actuation materials. Actuators, made of actuation materials such as piezoelectric ceramics or fibers, are used to control the behavior of the composite structure by expanding or contracting the actuation strips to achieve the requisite design and operational goals. Because of the similarity between the thermal strain and the strain in the actuation materials, the actuation strains are simulated using thermal strains computed from a temperature field (representing the electric field strength) and thermal expansion coefficients (representing the actuation strain coefficients). However, the strains induced by the actuator are also affected by uncertainties in several factors that must be quantified probabilistically. These include: (1) inaccurate measurements made by the sensors, (2) deviation from intended electric field, (3) uncertain relationship between actuation strain and electric field strength, (4) uncertain material properties for the actuation materials, (5) uncertain electric field strength, and (6) improper location of the sensor/control materials. Because of these factors, the use of control devices increases the uncertainty in an already uncertain composite structural behavior.

In order to account for the various uncertainties and to satisfy design requirements, knockdown (safety) factors are used extensively. These knockdown factors significantly reduce the design load of composite structures without a quantifiable measure of their reliability. In this paper, an alternative approach, based on probabilistic methods, is described for a comprehensive probabilistic design assessment of smart composite structures.

SYMBOLS

CDF	cumulative distribution function
E_{f11}	fiber modulus in longitudinal direction
E_{f22}	fiber modulus in transverse direction
E_m	matrix elastic modulus
G_{f12}	in-plane fiber shear modulus
G_{f23}	out-of-plane fiber shear modulus
G_m	matrix shear modulus
m_i	mean value of i^{th} random variable
P_f	probability of failure
SF	safety factor

S_{fC}	fiber compressive strength
S_{fT}	fiber tensile strength
S_{mC}	matrix compressive strength
S_{mS}	matrix shear strength
S_{mT}	matrix tensile strength
u^*	most probable point
X_i	design parameter
Z	performance
α_{RL}	red line (critical) value for the angle of attack
β	reliability index
σ_i	standard deviation of i^{th} random variable
$\Delta\beta$	change of reliability index
ν_{f12}	in-plane fiber Poisson's ratio
ν_{f23}	out-of-plane fiber Poisson's ratio
ν_m	matrix Poisson's ratio
Φ	*CDF* of a standardized normally distributed random variable

PROBABILISTIC DESIGN WITH IPACS COMPUTER CODE

The Computer Code IPACS (Integrated Probabilistic Assessment of Composite Structures) (ref. 6) has evolved from extensive research activities at NASA Lewis Research Center to develop probabilistic structural analysis methods (ref. 7) and computational composite mechanics (ref. 5). The composite micromechanics, macromechanics, and laminate theory (including interply and intraply hybrids) are embodied in ICAN (ref. 5). IPACS consists of two stand-alone computer modules: PICAN and NESSUS. PICAN is used to simulate probabilistic composite mechanics (ref. 8). NESSUS uses the information from PICAN to simulate probabilistic structural responses (ref. 9). A block diagram of IPACS is shown in figure 3. Direct coupling of these two modules makes it possible to simulate the uncertainties in all inherent scales of the composite—from constituent materials to the composite structure including its boundary and loading conditions as well as environmental effects. Note that special algorithms (ref. 10) are used instead of the conventional Monte Carlo simulation to achieve substantial computational efficiencies which are acceptable for practical applications. Therefore, a probabilistic composite structural analysis, which cannot be done traditionally, becomes feasible especially for composite structures which have a large number of variables.

A wealth of information is obtained with IPACS through a comprehensive probabilistic assessment of composite structural analysis, which includes the cumulative distribution function of a response, reliability for a design criterion, and the probabilistic sensitivity factors of the uncertain variables to a cumulative probability of a structural response and structural reliability. The commonly used sensitivity in a deterministic analysis is the performance sensitivity, $\partial Z/\partial X_i$, which measures the change in the performance Z due to the change in a design parameter X_i. This concept is extended to the probabilistic analysis to define the probabilistic sensitivity which measures the change in the reliability relative to the change in each random variable. The failure probability for a given performance is defined as (ref. 11)

$$P_f = \Phi(-\beta) \tag{1}$$

where β is the reliability index; Φ is the cumulative distribution function (CDF) of a standardized, normally distributed, random variable. Probabilistic sensitivity factor (SF_i) for i^{th} random variable is defined as

$$SF_i = \frac{\partial \beta}{\partial X_i} = \frac{u_i^*}{\beta} \tag{2}$$

where u^* is the most probable failure point of a limit state function in a unit of normal probability space (most probable point). These factors provide quantifiable information on the sensitivity of the reliability to the uncertain variable.

The next step is to extract useful information from the output of the simulation and to check it against probabilistic design criteria. If target reliability is not satisfied, redesign is guided by adjusting or controlling parameters associated with the primitive variables which significantly influence the design reliability. For example, the change in β ($\Delta\beta$) caused by a change in the mean of random variable X_i (Δm_i) can be estimated by equation (3) (ref. 11).

$$\Delta\beta \cong - \frac{SF_i}{\sigma_i} \Delta m_i \tag{3}$$

Similarly, the change in β ($\Delta\beta$) caused by a change in the standard deviation of the i^{th} random variable X_i ($\Delta\sigma_i$) can be estimated by equation (4).

$$\Delta\beta \cong - \frac{SF_i \, u_i^*}{\sigma_i} \Delta\sigma_i \tag{4}$$

With this information, alterations can be made to improve the structural reliability, as will be demonstrated later.

DEMONSTRATION OF A SMART COMPOSITE WING

The probabilistic design of a smart composite structure will be demonstrated by evaluating a smart composite wing. The optimum exact deformed shape of a wing is a function of the particular flight condition. With smart structure concepts, proper deformation change can be obtained from flight condition to flight condition. To achieve these desirable geometries at required accuracy, the changes have to be inducible within an acceptable range. The feasibility of achieving the desired range of uncertainties has been studied here in a simplified form of what a practical system could be. Figure 4 illustrates the geometry and loads for a composite wing in this simplified system. The geometry of the internal structure of the composite wing is shown in figure 4(a). The wing is loaded with nonuniform pressure which varies from root to tip and from leading edge to trailing edge as shown in figure 4(b).

The composite configurations for the skin, spars, and bulkheads are $[\pm45/0/90_2/0/\mp45]_s$, $[0_8]$ and $[0_8]$, respectively. The 45° plies are selected to be control plies. In each control ply, both control (hybridizing actuation) and traditional strips exist. However, in this paper, control strip is assigned throughout the control ply for computational simplicity. The control volume ratio is the percentage of control-related material (or control device) in a control ply. The percentage of the actuation materials in a control-related material is denoted by actuation fiber (control) volume ratio. The constituent materials properties for traditional plies, their assumed probabilistic distribution, and coefficient of variation (representing range of the scatter) are summarized in table 1. The corresponding fabrication variables used to make the smart composite wing are summarized in table 2. Those for the control are summarized in table 3. Since actuation materials are more expensive than traditional materials, control volume ratio should be determined such that total cost for a smart composite structure subjected to multidesign constraints is minimized. General constraints include (1) those typical for traditional composite structural designs, and (2) those for actuation materials due to their particular material characteristics such as strain, stress, applied voltage requirements, etc. This paper emphasizes the demonstration of the probabilistic design assessment of smart composite structures by using intraply hybrid composites with actuation materials. Optimization issues are not considered herein.

In this probabilistic study, we evaluate a change in the angle of attack due to control; investigate the relationship between improvement of reliability and sensitivity factors; examine a proposed design concept by varying the distribution parameters associated with a random variable (such as the mean and the standard deviation) and with their respective sensitivity information. Also, similar to the examination of a proposed design concept, study ply damage in the smart composite wing caused by random impact loads (represented by an equivalent static load for the analysis).

Change in Angle of Attack Caused by Control

The uncertainty in the change of the angle of attack caused by control with actuation material is evaluated as the scatter from a reference position. The probability density function for the actuated change in the angle of attack at wing tip is shown in figure 5(a). Figure 5(b) illustrates the sensitivity factors at 0.999 probability. Two performance criteria are examined. The first criterion requires that the change in the angle of attack caused by control at wing tip be less than $-1.3°$ (upper bound). The second criterion requires that the change in the angle of attack be greater than $-1.9°$ (lower bound).

To fully understand the structural behavior, a parametric study is performed by varying the distribution parameters of random variables. The probability density function of the actuated angle for an increase in the mean of a given random variable is shown in figure 6(a). The mean value of the actuated angle caused by a 5-percent increase in the mean value of the control strain coefficient decreases most while scatter remains the same. The probability density function of the actuated angle for a 40-percent reduction in the scatter of a given random variable is shown in figure 6(b). The mean response (a change in the angle of attack) remains the same. The scatter of the response is reduced most with a 40-percent reduction in the scatter of the control strain coefficient. This observation is confirmed by the sensitivity analysis, which finds that control strain coefficient has the largest sensitivity factor.

A study for reliability improvement by varying distribution parameters is conducted and discussed in the next section of this paper. Selection from among possible arrangements for reliability improvement may depend on other considerations such as the cost of changing the mean value and the cost of quality improvement, and these can be readily incorporated in the assessment.

Upper bound for the change in the angle of attack due to control.—The failure probability for this performance requirement is 0.0075 (reliability index $\beta = 2.430$) with reference distribution parameters. For a 5-percent increase in the mean or a 40-percent reduction in the scatter for each random variable, the change in the reliability index β, which is estimated by using sensitivity information, is shown in table 4. As indicated in the table, the control strain coefficient has the largest (absolute) sensitivity factor (-0.785), followed by the fiber modulus and the matrix modulus of the control ply (-0.319 and 0.220, respectively). Notice that the sensitivity factor for the matrix modulus is positive. This means that an increase in the mean of the matrix modulus will decrease the reliability (due to a reduction in β), as indicated in equation (3). The reliability index for each case, calculated with IPACS as shown in table 5, finds that estimated and calculated β agree very well. Therefore, a good estimation of β for a new distribution parameter can be calculated without running IPACS again. The results also show that a reduction in the scatter of a random variable always increases the reliability index (a reduction in failure probability) as indicated in equation (4). Based on the information in table 4, a designer can easily set up a strategy to improve the reliability without extensive analyses. In this particular example, one should increase the mean of the control strain coefficient by 5-percent, followed by a reduction in the scatter of the same variable by 40 percent, etc. This procedure should be continued until the target reliability is met with a minimum of design alterations.

Lower bound for the change in the angle of attack due to control.—The failure probability for this performance requirement is 0.0034 (reliability index $\beta = 2.70$) with reference distribution parameters. As indicated in table 6, the control strain coefficient has the largest sensitivity factor (0.785), followed by the fiber modulus and the matrix modulus of the control ply (0.319 and -0.220, respectively). Notice that the sign of the sensitivity factor is opposite to those for upper bound. Therefore, an increase in the mean of the matrix modulus will increase the reliability. For a 5-percent increase in the mean or a 40-percent reduction in the scatter for each random variable, the change in the reliability index β, which is estimated by using sensitivity information, is shown in table 6. The reliability index for each case is also calculated with IPACS, as shown in table 7. Again, the estimated and calculated β agree very well. As shown before, a reduction in the scatter of a random variable always increases the reliability index. However, an increase in the mean of random variables such as fiber volume ratio or control strain coefficient, which have positive sensitivity factors, will result in a reduction in the reliability. To improve the reliability for this case, one should reduce 40 percent of the scatter of the control strain coefficient, and then increase the mean of the matrix modulus by 5 percent, followed by a reduction in the scatter of the same variable by 40 percent.

Ply Damage Due to Random Impact Load

Assume that the wing is struck by a foreign object with the direction and location of the impact loads as shown in figure 4(c). The impact load is represented by an equivalent load for a static analysis. Ply damage in the vicinity of the impact is assessed. The modified distortion energy is used for combined stress failure criterion (ref. 5). The probability density function of the safety margin (ref. 5) and the sensitivity factors at failure are shown in figure 7. Actuation fiber volume ratio has the largest sensitivity factor (0.645) followed by matrix tensile strength (–0.5), impact load (0.33), and matrix modulus (0.311). The sensitivity factors for both expansion and contraction electric field strengths are small (0.060 and 0.083, respectively). A parametric study is conducted by varying the distribution parameters. A 5-percent increase in the mean or a 40-percent reduction in the scatter for actuation fiber volume ratio, matrix modulus and matrix tensile strength are first considered for their large sensitivity values. For random variables with a small sensitivity factor, it can be seen from equation (4) that even with a 100-percent reduction in the scatter ($\Delta\sigma = \sigma$), $\Delta\beta$ is still negligible. However, if one can increase the ratio between Δm and σ in equation (3), $\Delta\beta$ will be sizable. Therefore, another assessment is performed for a 25-percent reduction in the mean of one of the electric field strengths. The ratio between Δm and σ is equal to 5 which is much larger than the ratios in other cases. The estimated β and β calculated with IPACS are listed in tables 8 and 9 and show that estimated β agrees very well with calculated β. Reliability is improved by a reduction in the mean of the random variable with a negative sensitivity factor and vice versa. Moreover, efficient and economic redesign can be achieved by enhancing the quality of the random variable with a large (absolute) sensitivity factor. When the sensitivity factor of a random variable is small, quality of the random variable is not crucial for reliability improvement. However, the change in the mean of this random variable may have a significant effect on the reliability.

CONCLUSIONS

We have presented a formal methodology that can be used to probabilistically design smart composite structures by using the IPACS (Integrated Probabilistic Assessment of Composite Structures) computer code. This methodology integrates micro- and macro-composite mechanics, laminate theory, structural mechanics (finite element methods), smart structure concepts, and probability algorithms to perform a probabilistic assessment of composite structural design that accounts for uncertainties involved in the design process. Probabilistic sensitivity factors are key results from the probabilistic assessment of composite structures using the computer code IPACS. These factors provide quantifiable information about the relative sensitivity of design parameters on structural responses. We found from this study that the reduction in the scatter of the random variable with the highest sensitivity factor (absolute value) provides the lowest failure probability. An increase in the mean of the random variables may result in reliability reduction if the sensitivity factor is positive. When the sensitivity factor of a random variable is small, the quality of the random variable is not crucial for reliability improvement. However, a change in the mean of this random variable may have a significant effect on reliability. With this information, a smart composite structure can be redesigned efficiently by controlling and/or adjusting the parameters associated with random variables during manufacturing to obtain maximum benefit with a minimum number of alterations.

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TABLE I.—STATISTICS OF FIBER AND MATRIX PROPERTIES FOR GRAPHITE-EPOXY COMPOSITE

Property	Typical distribution type	Typical mean	Assumed coefficient of variation
Fiber modulus direction, Mpsi	Normal		0.05
Longitudinal, E_{f11}		31.0	
Transverse, E_{f22}		2.0	
Fiber shear modulus, Mpsi			
In-plane, G_{f12}		2.0	
Out-of-plane, G_{f23}		1.0	
Fiber Poisson's ratio			
In-plane, ν_{f12}		0.2	
Out-of-plane, ν_{f23}		0.25	
Matrix			
Elastic modulus, E_m, Mpsi		0.5	
Shear modulus, G_m, Mpsi		0.185	
Poisson's ratio, ν_m		0.35	
Fiber strength, kpsi	Lognormal		
Tensile, S_{fT}		400.0	
Compressive, S_{fC}		400.0	
Matrix strength, kpsi			
Tensile, S_{mT}		15.0	
Compressive, S_{mC}		35.0	
Shear, S_{mS}		15.0	

TABLE II.—STATISTICS OF FABRICATION VARIABLES

Property	Unit	Typical distribution type	Typical mean	Assumed coefficient of variation
Fiber volume ratio	--	Normal	0.60	0.05
Void volume ratio	--		.02	.05
Ply misalignment angle	deg		.00	1.0[a]
Ply thickness (regular skin)	in.		.015	0.05
Ply thickness (stringer/frame)	in.		.090	.02
Ply thickness (control ply)	in.		.060	.025

[a]Standard deviation.

TABLE III.—STATISTICS OF CONTROL RELATED VARIABLES

Property	Unit	Typical dstribution type	Typical mean	Assumed coefficient of variation
Control strain coefficient	in./V	Normal	10^{-8}	0.05
Electric field strength	V/in.	Normal	10^{5}	0.05

TABLE IV.—ESTIMATED β FOR UPPER BOUND CRITERION OF CHANGE IN ANGLE OF ATTACK AND SENSITIVITY FACTORS WITH MANUFACTURING-CONTROLLED RANDOM VARIABLES

Random variable being controlled (actuation material)	Sensitivity factor	5-percent increase in mean		40-percent decrease in scatter	
		$\Delta\beta^a$	β	Δβ	β
Matrix modulus	0.220	-0.220	2.210	0.047	2.477
Fiber modulus	-.319	.319	2.749	.099	2.529
Control strain coefficient	-.785	.785	3.215	.599	3.029

[a] $P_f = \Phi(-\beta)$.

TABLE V.—CALCULATED β FOR UPPER BOUND CRITERION OF CHANGE IN ANGLE OF ATTACK AND FAILURE PROBABILITY WITH MANUFACTURING-CONTROLLED RANDOM VARIABLES

Random variable being controlled (actuation material)	Sensitivity factor	5-percent increase in mean		40-percent decrease in scatter	
		β^a	P_f^a	β	P_f
Matrix modulus	0.220	2.343	0.0095	2.469	0.0068
Fiber modulus	-.319	2.782	.0027	2.513	0.0060
Control strain coefficient	-.785	3.230	.0006	3.125	0.0009
Original	----	2.430	.0075	2.430	0.0075

[a] $P_f = \Phi(-\beta)$.

TABLE VI.—ESTIMATED β FOR LOWER BOUND CRITERION OF CHANGE IN ANGLE OF ATTACK AND SENSITIVITY FACTORS WITH MANUFACTURING-CONTROLLED RANDOM VARIABLES

Random variable being controlled (actuation material)	Sensitivity factor	5-percent increase in mean		40-percent decrease in scatter	
		$\Delta\beta^a$	β	Δβ	β
Matrix modulus	-0.220	0.220	2.920	0.054	2.754
Fiber modulus	.319	-.319	2.381	.110	2.810
Control strain coefficient	.785	-.785	1.915	.667	3.367

[a] $P_f = \Phi(-\beta)$.

TABLE VII.—CALCULATED β FOR LOWER BOUND CRITERION OF CHANGE IN ANGLE OF ATTACK AND FAILURE PROBABILITY WITH MANUFACTURING-CONTROLLED RANDOM VARIABLES

Random variable being controlled (actuation material)	Sensitivity factor	5-percent increase in mean		40-percent decrease in scatter	
		β^a	P_f^a	β	P_f
Matrix modulus	-0.220	2.808	0.0025	2.744	0.0030
Fiber modulus	.319	2.315	.0103	2.791	.0026
Control strain coefficient	.785	1.820	.0344	3.472	.0003
Original	-----	2.700	.0034	2.700	.0034

[a] $P_f = \Phi(-\beta)$.

TABLE VIII.—ESTIMATED β USING SENSITIVITY FACTORS FOR PLY DAMAGE DUE TO IMPACT LOADS WITH MANUFACTURING-CONTROLLED RANDOM VARIABLES

Random variable being controlled (actuation material)	Sensitivity factor	5-percent increase in mean		40-percent decrease in scatter	
		$\Delta\beta^a$	β	$\Delta\beta$	β
Actuation fiber (control) volume ratio	0.645	−0.645	2.273	0.486	3.404
Matrix modulus	.334	−.334	2.584	.130	3.048
Matrix tensile strength	−.500	.500	3.418	.301	3.219
Electric field strength (expansion)	.060	.300[b]	3.218[b]	----	----
Electric field strength (contraction)	.083	.415[b]	3.333[b]	----	----

[a] $P_f = \Phi(-\beta)$.
[b] 25-percent reduction in the mean.

TABLE IX.—CALCULATED β OF PLY DAMAGE ASSESSMENT DUE TO RANDOM IMPACT LOADS AND FAILURE PROBABILITY WITH MANUFACTURING-CONTROLLED RANDOM VARIABLES

Random variable being controlled (actuation material)	Sensitivity factor	5-percent increase in mean		40-percent decrease in scatter	
		β^a	P_f^a	β	P_f
Actuation fiber (control) volume ratio	0.645	2.106	0.0180	3.375	0.0004
Matrix modulus	.334	2.435	.0074	3.025	.0012
Matrix tensile strength	−.500	3.616	.0001	3.173	.0007
Electric field strength (expansion)	.060	3.395[b]	.0003[b]	----	-----
Electric field strength (contraction)	.083	3.666[b]	.0001[b]	----	-----
Original	----	2.918	.0018	2.918	.0018

[a] $P_f = \Phi(-\beta)$.
[b] 25-percent reduction in the mean.

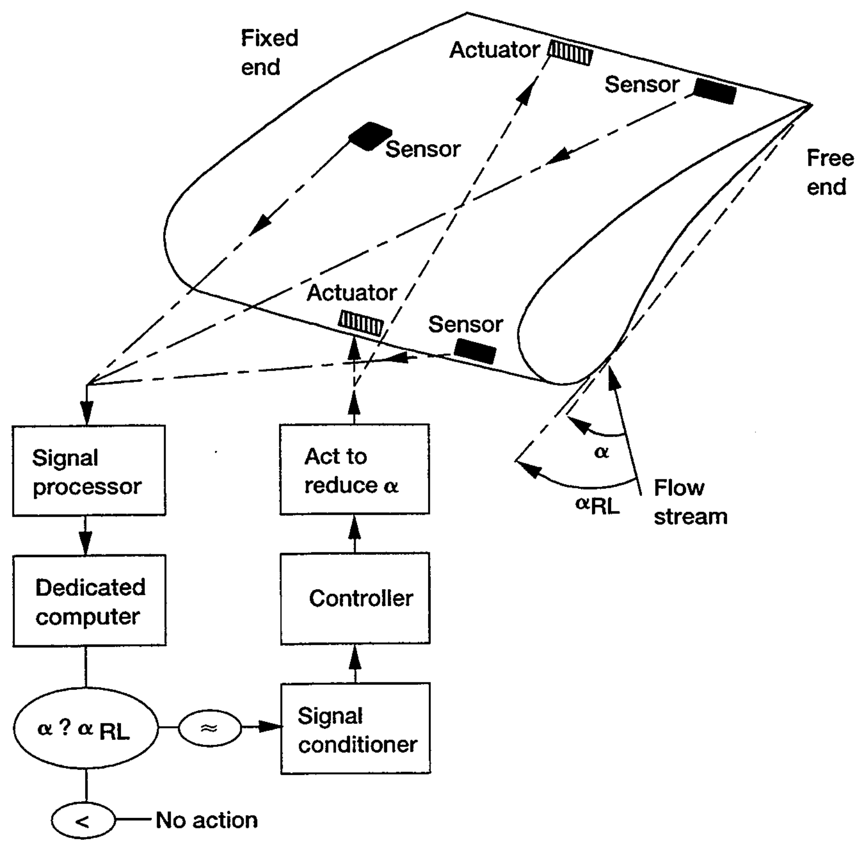

Figure 1.—Conceptual diagram of smart composite aircraft wing system.

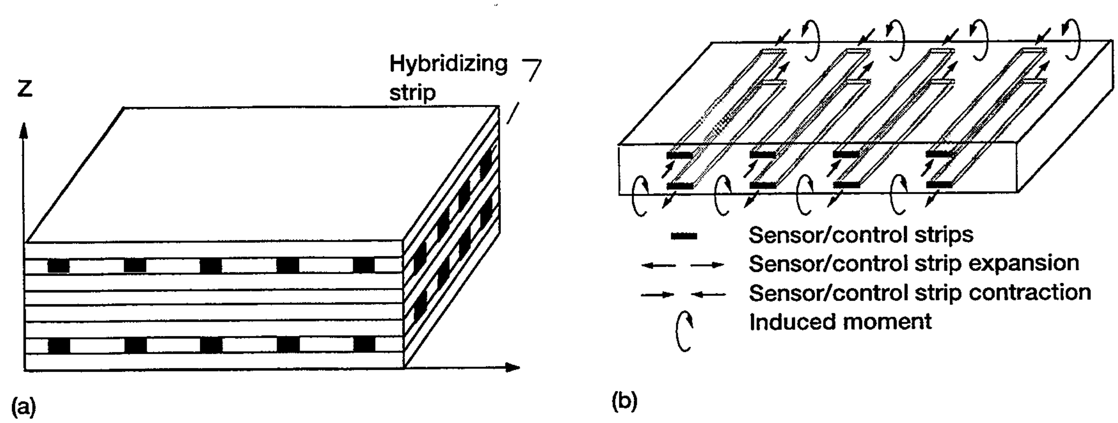

Figure 2.—Adaptation of intraply hybrid to smart composite system. (a) Intraply hybrid composite system. (b) Structural control using sensor/control materials.

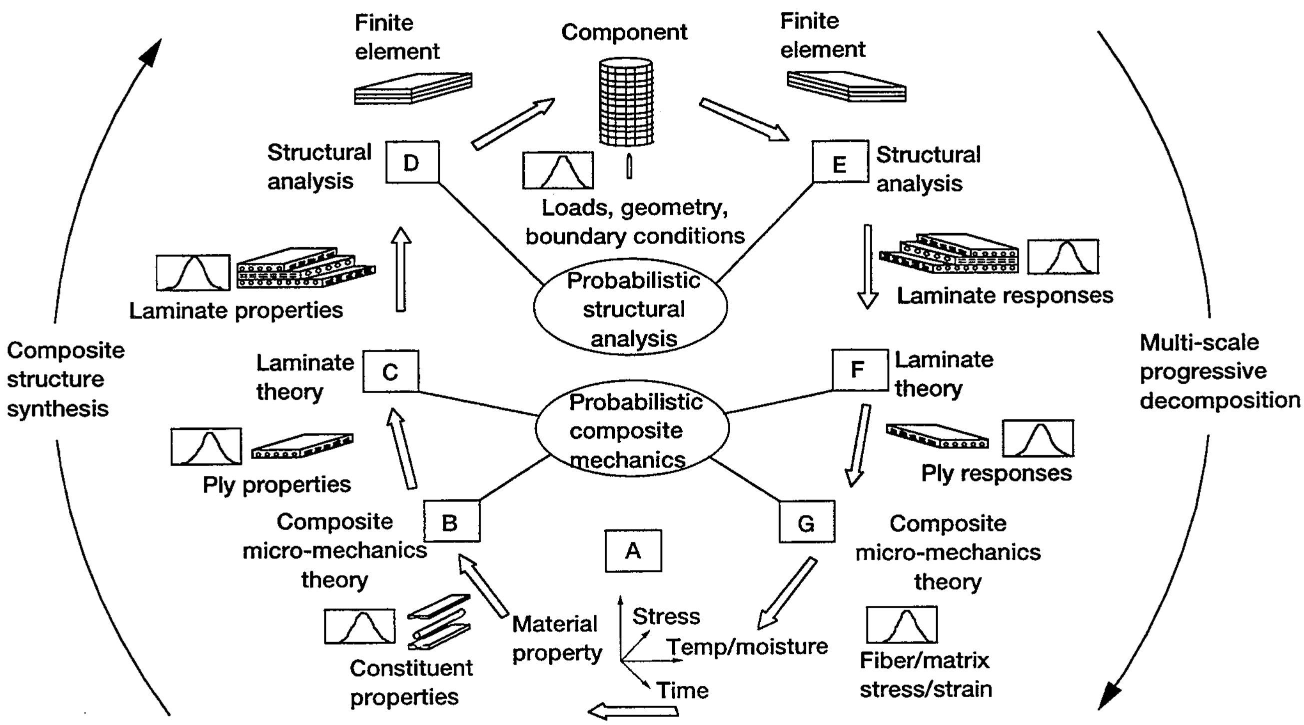

Figure 3.—Concept of integrated probabilistic assessment of composite structures (IPACS).

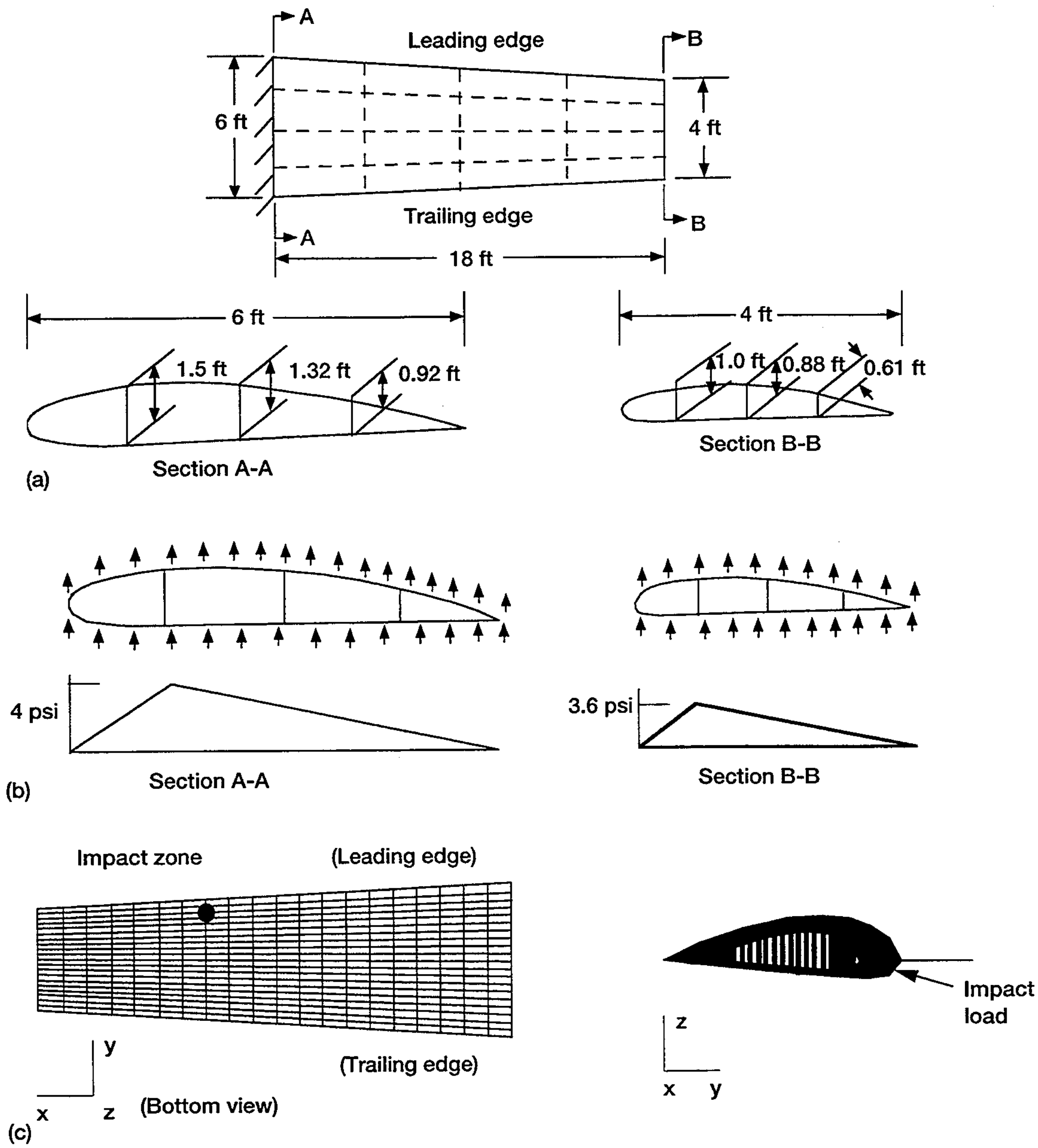

Figure 4.—Geometry and loads for a composite wing. (a) Geometry of a composite wing. (b) Variation of pressure on a composite wing. (c) Location and direction of random impact loads.

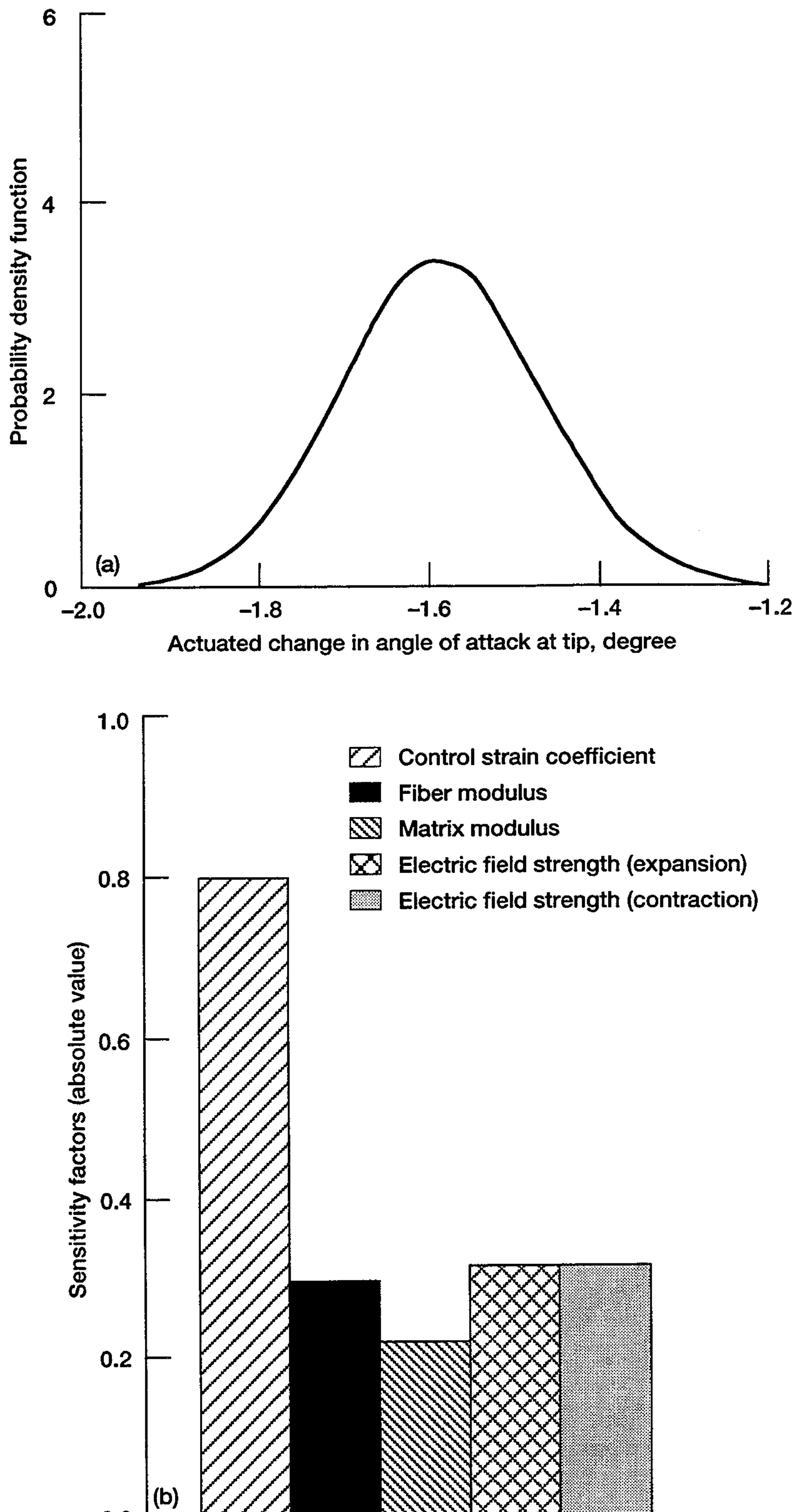

Figure 5.—Probability density function factors at 0.999 probability. (a) Actuated change in angle of attack. (b) Sensitivity.

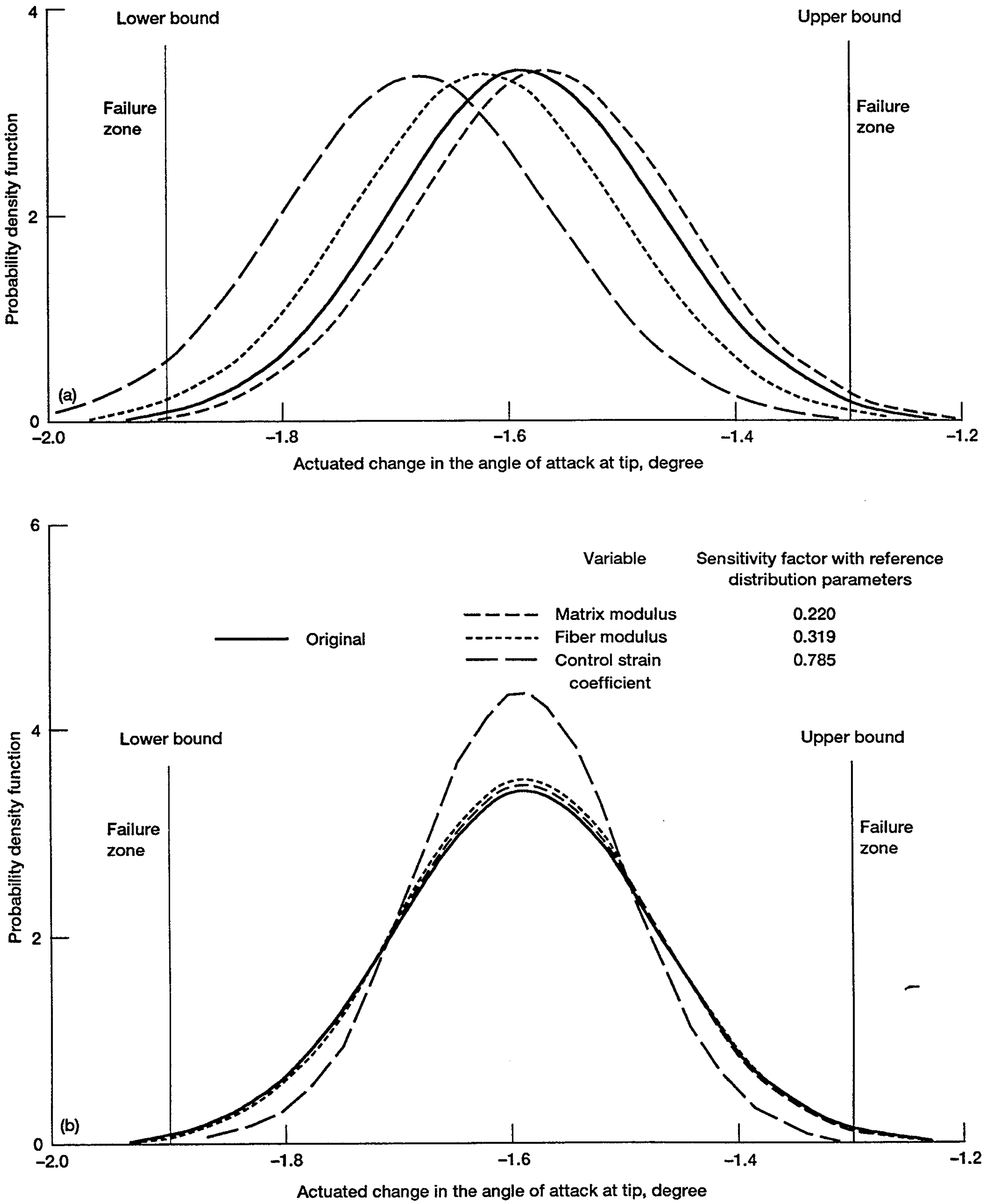

Figure 6.—Probability density function of actuated change in the angle of attack. (a) With 5 percent increase in mean of one random variable. (b) With 40 percent reduction in scatter of one random variable.

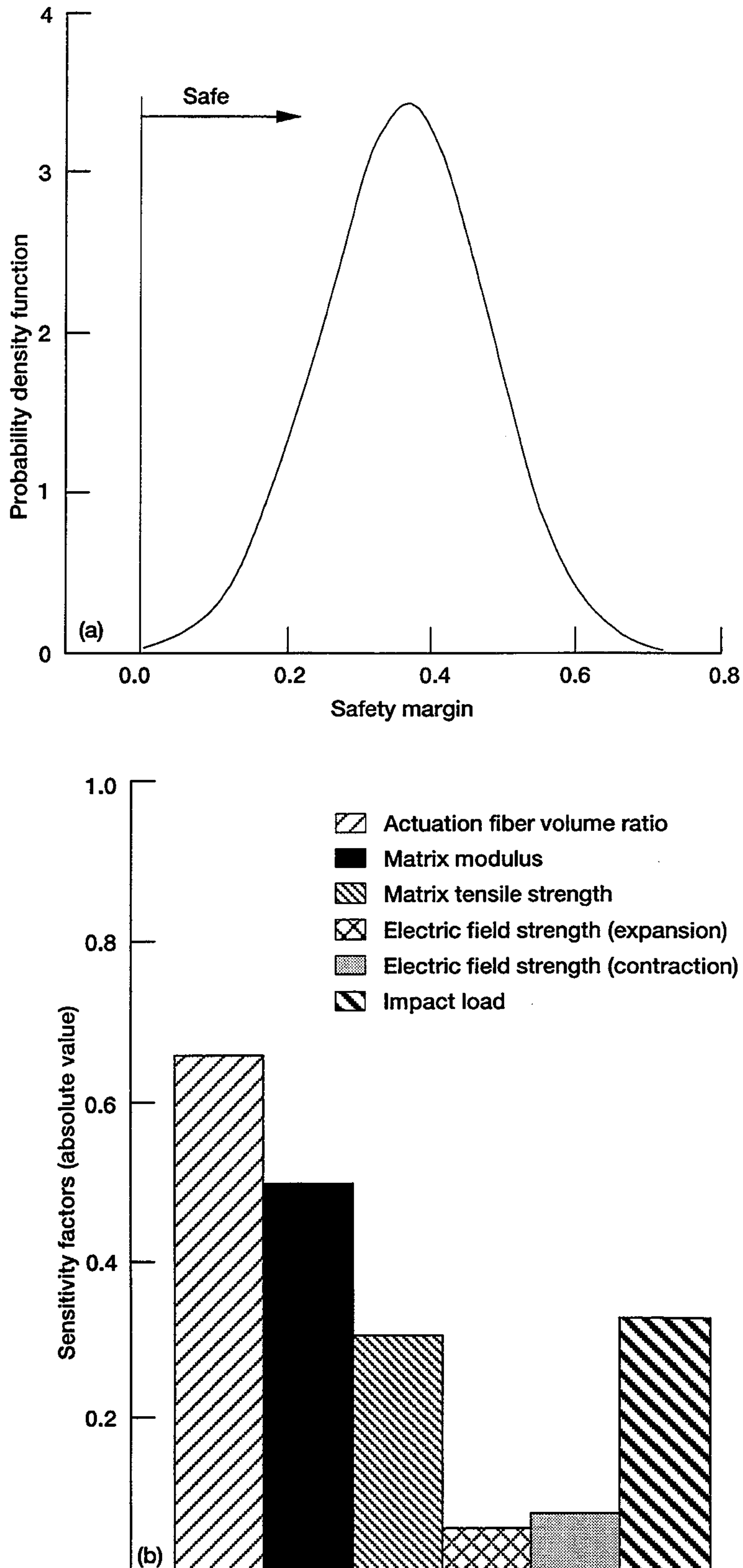

Figure 7.—Probability density function at safety margin equal to zero. (a) Safety margin. (b) Sensitivity factors.

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13. ABSTRACT *(Maximum 200 words)*

A probabilistic design method is described and demonstrated using a smart composite wing. Probabilistic structural design incorporates naturally occurring uncertainties including those in constituent (fiber/matrix) material properties, fabrication variables, structure geometry and control-related parameters. Probabilistic sensitivity factors are computed to identify those parameters that have a great influence on a specific structural reliability. Two performance criteria are used to demonstrate this design methodology. The first criterion requires that the actuated angle at the wing tip be bounded by upper and lower limits at a specified reliability. The second criterion requires that the probability of ply damage due to random impact load be smaller than an assigned value. When the relationship between reliability improvement and the sensitivity factors is assessed, the results show that a reduction in the scatter of the random variable with the largest sensitivity factor (absolute value) provides the lowest failure probability. An increase in the mean of the random variable with a negative sensitivity factor will reduce the failure probability. Therefore, the design can be improved by controlling or selecting distribution parameters associated with random variables. This can be implemented during the manufacturing process to obtain maximum benefit with minimum alterations.

14. SUBJECT TERMS

Composite; Laminate; Ply; Fiber; Matrix; Uncertainty; Sensitivity; Probabilistic; Reliability; Smart structure; Design; Adaptive; Intraply hybrid; Control; Actuation

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