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Probabilistic Assessment of Uncertain Adaptive Hybrid Composites

Michael C. Shiao and Surendra N. Singhal
Sverdrup Technology, Inc.
Lewis Research Center Group
Brook Park, Ohio

and

Christos C. Chamis
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

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Michael C. Shiao and Surendra N. Singhal
Sverdrup Technology, Inc.
Lewis Research Center Group
Brook Park, Ohio 44142

and

Christos C. Chamis
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

SUMMARY

Adaptive composite structures using actuation materials, such as piezoelectric fibers were assessed probabilistically utilizing intraply hybrid composite mechanics in conjunction with probabilistic composite structural analysis. Uncertainties associated with the actuation material as well as the uncertainties in the regular (traditional) composite material properties were quantified and considered in the assessment. Static and buckling analyses were performed for rectangular panels with various boundary conditions and different control arrangements. The probability density functions of the structural behavior, such as maximum displacement and critical buckling load, were computationally simulated. The results of the assessment indicate that improved design and reliability can be achieved with actuation material.

INTRODUCTION

Aerospace structures are complex assemblages of structural components that operate under severe and often uncertain service environments. These types of structures require durability, high reliability, light weight, high performance, and affordable cost. Composite materials are attractive potential candidates that meet these requirements because they possess outstanding mechanical properties derived from a wide variety of variables such as constituent material properties and laminate characteristics (fiber and void volume ratios, ply orientation, and ply thickness). These variables are statistical in nature and can be represented by cumulative distribution functions (CDF). To deal with these uncertainties the current design practice enforces a knockdown factor for each unknown. With such an exercise, the advantages of using composite materials for structural designs disappear. Therefore, to properly use composite materials, a probabilistic assessment of composite structures is needed to quantify their uncertain structural behavior (ref. 1).

Future structures for aerospace applications require performance characteristics beyond the capability of those currently being used. Adaptive structures using actuation materials such as piezoelectric fibers have shown great potential to enhance structural performance (ref. 2). Present piezoelectric technology has been successfully applied to small-scale and low-stress structures. However, there are inevitable difficulties when this technology is applied to large-scale and high-stress composite structures. These difficulties can be alleviated if the special fiber with the actuation capability is combined with a regular high-strength, high-modulus fiber to form the adaptive intraply hybrid composite (ref. 1).

The integration of traditional composites and actuation materials into the composite structural design makes it possible to ascertain whether the composite structure will operate in the design-specified range. At NASA Lewis Research Center, the intraply hybrid composite concept is adopted in the computer code ICAN (ref. 3). The adaptive composites comprise (1) regular plies consisting of traditional composite materials only and (2) control plies consisting of strips of traditional composite materials and interspersed control (hybridizing actuation) strips of mixed actuation and traditional materials for structural control (see fig. 1). Actuation materials such as piezoelectric ceramics and 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. However, the strains induced by the actuator are affected by several factors and their respective uncertainties which can only be quantified probabilistically: (1) inaccurate measurements made by the sensors, (2) uncertain material properties for the actuation materials including an uncertain relationship between actuation strain and electric field strength, (3) deviation from intended electric field strength, and (4) uncertain placement of the actuation materials. Because of these factors, the use of control devices increases the uncertainty in the already uncertain composite structural behavior. To properly quantify the effects, a comprehensive probabilistic assessment is needed.

A methodology for the probabilistic assessment of composite structures was developed at the NASA Lewis Research Center (ref. 4). The physical representation of the methodology is depicted in figure 2. The methodology, which integrates the composite mechanics, structural mechanics, and probability theory, is incorporated into a single integrated computer code IPACS (Integrated Probabilistic Assessment of Composite Structures) (ref. 4).

The objective of the computational simulation presented in this report was to use IPACS to assess hybrid composite panels made with activation material under various loads, boundary conditions and different control arrangements. Critical structural behavior represented in terms of probability density functions (pdf) is simulated with and without actuation strains. The benefit and reliability enhancements using adaptive hybrid composites are investigated. Results from this assessment provide valuable information for reliability-based designs of adaptive composite structures.

SYMBOLS

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
t_p	ply thickness
X	independent random variable
Z	performance variable
θ_p	ply misorientation
ν_{f12}	in-plane fiber Poisson's ratio
ν_{f23}	out-of-plane fiber Poisson's ratio
ν_m	matrix Poisson's ratio
$\sigma_{L,T,S}$	ply stress, longitudinal, transverse, shear, respectively

FUNDAMENTAL CONSIDERATIONS

The four fundamental considerations for the probabilistic assessment of adaptive composite structures described herein are now discussed. (1) Because of the analogy between the thermally and electrically induced strain in the actuation material, the induced strain is simulated with thermal strain computed from an uncertain temperature field representing the electric field strength and from the uncertain thermal expansion coefficients representing the actuation strain coefficients; (2) primitive variables that described composites are identified at the micro- and macrocomposite levels; (3) the scatter in the primitive variables is represented by specified probabilistic distributions; and (4) the uncertainties in the primitive variables are propagated through the computational simulation methodology that consists of composite mechanics, structural mechanics, and probability methods.

The primitive variables recognized by the computer code IPACS are (1) fiber and matrix properties at the constituent level, (2) fabrication variables such as fiber volume ratio, void volume ratio, ply misorientation and thickness, (3) uncertain loads, temperature/moisture fields, and geometry and boundary conditions at the structural level, and (4) control-related uncertain variables such as the electric field strength and the actuation strain coefficient.

PROBABILISTIC COMPUTER CODE IPACS

IPACS, a computer code used for the probabilistic analysis of composite structures, integrates several NASA in-house computer programs developed in recent years; COBSTRAN (ref. 5), PICAN (ref. 6), and NESSUS (ref. 7). COBSTRAN (COmposite Blade STRuctural Analysis) is a dedicated finite-element model generator for composite structures. PICAN (Probabilistic Integrated Composite Analyzer) enables the computation of the perturbed and probabilistic composite material properties at the ply and laminate levels. NESSUS (Numerical Evaluation of Stochastic Structures Under Stress) uses information from PICAN to determine the perturbed and probabilistic structural response at global, laminate, and ply levels. PICAN and NESSUS share the FPI (fast probability integrator) module (ref. 8) for the application of fast probability to obtain cumulative distribution functions of the responses for the laminate and the structure.

The probabilistic assessment of composite structures using IPACS begins with the identification of uncertain primitive variables. These variables are then selectively perturbed several times to create a data base for the determination of the relationship between the desired structural response (or the desired material property) and the primitive variables. For every given perturbed primitive variable, micromechanics is applied to determine the corresponding perturbed mechanical properties at the ply and laminate levels. Laminate theory (ref. 3) is then used to determine the perturbed resultant force/moment-strain/curvature relationships. With this relationship at the laminate level, a finite-element perturbation analysis is performed to determine the perturbed structural responses corresponding to the selectively perturbed primitive variables. This process is repeated until enough data are generated and the appropriate relationship between structural responses and primitive variables has been established to use FPI.

If probabilistic distributions of the primitive variables and the relationships between the structural response and the primitive variables are assumed, then for every discrete response value, a corresponding cumulative probability can be computed very quickly by FPI. This process is repeated until the cumulative distribution function can be appropriately represented. The probabilistic material properties at ply and laminate levels are also computed in the same way as that for the structural responses. The output information from FPI for a given structural response includes parameters for a specific probability distribution function and the sensitivity factors of the primitive variables to the structural response for specified probability levels.

SAMPLE CASES AND DISCUSSIONS

A 20- by 10-in. hybrid composite panel with control devices is probabilistically assessed. In each control ply, both control (hybridizing actuation) strips and traditional strips can exist. However, in this report, the control strip is assigned throughout the control ply for computational simplicity. Also, in each control ply, a secondary composite system volume ratio is used to define the percentage of volume for the control device. The percentage of the actuation materials in a secondary composite system is denoted by the control volume ratio. Because actuation materials are much more expensive than traditional materials, the control volume ratio should be determined such that the total cost for an adaptive composite structure will be minimized and subjected to multidesign constraints. The constraints include (1) those typical for traditional composite structures and (2) those for actuation materials based on their particular material characteristics (such as strain, stress, applied voltage requirements, etc.) which have not been studied. For the present analysis, the emphasis was on the demonstration of the probabilistic assessment of adaptive composite structures using intraply hybrid composites with actuation materials.

Uncertainties in traditional material properties are identified at all composite levels as now described. At the constituent level, the material properties for the fiber and matrix are modeled as uncertain variables. Their respective probability distribution type and associated parameters are assumed and are listed in table I. At the ply level, the fabrication variables (fiber volume ratio, void volume ratio, ply orientation and thickness) are also treated as random variables. Their statistics are listed in table II. Also considered in the analysis and presented in table III are the uncertainties associated with the control devices: secondary composite system volume ratio, control volume ratio, control material properties (including strain coefficient), and electric field strength.

Various boundary conditions are assumed for static and buckling analyses. The ply orientations used in this paper are depicted in figure 3. The composite structures are also examined for control devices at different locations as described and discussed in the following. The probabilistic assessment also provides sensitivity factors (ref. 8). 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 the design parameter X_i. This concept is extended to the probabilistic analysis to define the probabilistic sensitivity which measures the change in the probability and/or reliability relative to the change in each random variable. Probabilistic sensitivity factors are products from the probabilistic assessment of smart composite structures. These factors provide quantifiable information about the design parameters that the smart composite structure is most sensitive to. Subsequently, these design parameters can be manufacturing controlled and adjusted to obtain the best benefit with minimum alteration.

STATIC ANALYSIS

In structural design, the displacements at critical locations are tightly monitored. To understand the behavior of the structures with and without control devices, probabilistic static analyses are performed. Two boundary conditions are used: (1) all four sides are simply supported and (2) one side is clamped along the width and the other three sides are free (cantilever plate). To control the displacement, for example, a compressive strain is induced at the upper ply with a given ply orientation. An extension strain is induced at the lower ply with the same orientation as shown in figure 4. By this process, moment is induced to counteract the bending moment caused by the external loads.

Case 1: All Four Sides Simply Supported

A panel with a $[+45/-45/0/90]_s$ composite configuration subjected to a lateral load of 500 lb is shown in figure 5. The control devices are installed at one of two locations: at the 0° ply pair or at the 45° ply pair.

Control using the 0° plies.—A static analysis was performed with control devices installed in the 0° plies. The deterministic ply stresses were investigated and are shown in table IV. The induced stresses had a sign the opposite of the stresses due to the external force in every ply except for the plies with actuation material. Therefore, the maximum ply stresses in the outermost plies are reduced and the ply stresses are only increased in noncritical regions.

The probabilistic displacements at the center of the panel are simulated with and without the actuation strains as shown in figure 6. The displacement without actuation-induced strain is scattered between 0.59 and 0.99 in. When the strain is induced through the control devices, the displacement is reduced and its scatter is shifted to lower values (between 0.43 and 0.78 in.). Therefore, the requisite design tolerance can be satisfied.

Sensitivity factors at a 0.999-probability level for the probabilistic displacement with actuation-induced strain in 0° plies (fig. 7) indicate that the laminate thickness is the most important variable with a sensitivity factor of 0.68, followed by a primary fiber volume ratio of 0.50 and a primary fiber modulus of 0.46. Also shown in figure 7 are the sensitivity factors of the control devices. The sensitivity factors of these devices range from 0.07 to 0.18 and the amount of actuation material (secondary composite system volume ratio) is the most critical one among the control-related variables.

Control using the 45° plies.—The control devices are installed in the 45° plies. The probabilistic displacements with and without the actuation-induced strain are shown in figure 8. The displacement can be reduced from a range of 0.71 to 1.08 in. without actuation-induced strain to a range of –0.39 to +2.4 in. with actuation strain.

The sensitivity factors for the probabilistic displacement are shown in figure 9. For this case, the control-related uncertainties in the 0° plies are the most dominant. The highest is the amount of actuation material (secondary composite system volume ratio, 0.49), followed by the control volume ratio (0.43) in the actuation material, the actuation strain coefficient (0.40), the laminate thickness (0.37), and the electric field strength (0.33). However, it was also found that the deterministic ply stresses at the 45° plies (control plies) are increased as shown in table V. Therefore, if the stress is also a major concern for a design, plies at the outer most locations (45° ply) may not be desirable locations for control devices.

Case 2: One Side Clamped Along the Width and the Other Three Sides Free

The cantilever panel with a $[+45/-45/0/90]_{2s}$ composite configuration is subjected to a lateral load of 50 lb at location A of the free end as shown in figure 10. The control devices are installed at the four locations shown in figure 11. For all cases, the mean actuation strain on the lower half of the panel is –0.005 in./in. (contraction) and the mean actuation strain in the upper half of the panel is +0.005 in./in. (extension).

The probability density functions of the lateral displacement at the free end with and without actuation strain are shown in figure 12. The maximum displacement reduction can be achieved with control devices in the 45° plies. However, the effect with control in the 0° plies is almost the same as that with control in the 45° plies. With respect to lateral displacement at the free end, the effect from the control in –45° plies is only one third the effect from control devices in the 0° or 45° plies. With the control devices in the 90° plies, the displacement actually increases. However, this increase is negligible even if the signs of the actuation strain are changed (contraction in top ply and extension in bottom ply).

The sensitivity factors of the uncertain variables which affect the probabilistic lateral displacement at the 0.999-probability level are shown in table VI. The results indicate that the control devices should be in the 0° plies to minimize both the free-end displacement and the high stresses in the outermost plies.

BUCKLING ANALYSIS

For some types of structures, buckling occurs at low load levels. Therefore, it is important to design a structure with a design load smaller than the buckling load at a high reliability level. To quantify the scatter of the buckling load with and without the actuation strain, probabilistic buckling analyses are performed. Simply supported boundary conditions along the widths and clamped boundary conditions along the lengths are assumed for axial buckling analyses. Two different cases were evaluated: actuation material in (1) the 90° plies and (2) the 0° plies.

Case 1: Control in 90° Plies

The actuation material (control) is in the 90° plies with an actuation strain of –2 percent, as shown in figure 13. The composite structure is stiffened by this arrangement, which results in an in-plane tension in the Y-direction at the laminate level.

Figure 14 shows the probability density functions of the buckling loads with and without the actuation strain. A significant increase in the buckling load is obtained with this arrangement. The scatter of the buckling load before the application of the actuation strain ranges from 6200 to 10 600 lb. With the actuation strain, the scatter of the buckling load is shifted to higher values ranging from 12 300 to 18 800 lb. The corresponding sensitivity factors in figure 15 show that the laminate thickness has the highest effect (0.61), followed by the primary fiber volume ratio (0.47) and the primary fiber modulus (0.42). The uncertainties associated with the control devices tend to increase the scatter in the probabilistic buckling load.

Case 2: Control in 0° Plies

For the case of the control in the 0° plies (fig. 16), positive strains (2 percent) are applied to cause a tension in the Y-direction due to a Poisson effect at the laminate level. The control gain in this case is less than that in the 90° case as shown in figure 17. The sensitivity analysis shows that the sensitivity factors with the control devices in the 0° plies (fig. 18) are similar to those for the 90° case. However, the secondary composite system volume ratio has the least influence on the buckling load.

Investigating the buckling shape shown in figure 19 reveals that the panels without actuation strain buckle at two half sine waves. Panels with actuation strain in the 0° and 90° plies buckle at three and four half sine waves, respectively. This result indicates that the actuation strains activate higher buckling modes and, therefore, increase buckling loads.

SUMMARY

Adaptive composite structures using actuation materials, such as piezoelectric fibers were assessed probabilistically using intraply hybrid composite mechanics in conjunction with probabilistic composite structural analysis. Uncertainties associated with the actuation material as well as the uncertainties in the host composite material properties were quantified and evaluated in the assessment. Static and buckling analyses were performed for rectangular panels with various boundary conditions and various actuation material spatial locations. The probability density function of the structural behavior, such as maximum displacement and critical buckling load, were computationally simulated. The following results of the assessment indicate that the actuation material can be located to obtain designs with improved reliability:

1. The displacement mean and scatter range are reduced by about 30 percent.

2. The mean stresses in the critically stressed plies are reduced by about 30 percent.

3. The actuation material should be placed in the 0° plies for the maximum benefit in end displacements.

4. The actuation material in the 90° plies increases the buckling load by 100 percent and increases its scatter by 30 percent.

5. The actuation material in the 90° plies forces the structure to buckle at higher buckling modes, therefore increasing the buckling load.

6. The displacement and stress are most sensitive to the host composite volume ratio, the host composite fiber modules, and the laminate thickness.

7. The buckling load is most sensitive to laminate thickness, the host composite fiber volume ratio, and the host composite fiber modules.

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TABLE I.—STATISTICS OF CONSTITUENT MATERIAL PROPERTIES (GRAPHITE/EPOXY)

[Assumed distribution type, normal; assumed uncertainty range, ±5 percent.]

Property	Assumed mean
Fiber modulus direction, Mpsi	
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}	.2
Out-of-plane, ν_{23}	.25
Matrix	
Elastic modulus, E_m, Mpsi	.5
Shear modulus, G_m, Mpsi	.185
Poisson's ratio, ν_m	.35

TABLE II.—STATISTICS OF FABRICATION VARIABLES

[Assumed distribution type, normal; assumed uncertainty range, ±5 percent.]

Variable	Assumed mean
Volume ratio	
Fiber	0.60
Void	.02
Ply	
Misorientation, θ_p,[a] deg	0
Thickness, t_p, in.	.015

[a] Assumed coefficient of variation, 0.90 (stdv).

TABLE III.—STATISTICS OF CONTROL-RELATED PARAMETERS

[Assumed distribution type, normal; assumed uncertainty range, ±5 percent.]

Variable	Assumed mean
Secondary composite system volume ratio	0.50
Control	
Volume ratio	.60
Modulus, Mpsi	12.4
Strain coefficient, in./V	2.0×10^{-8}
Electric field strength, V/in.	1.0×10^{6}

TABLE IV.—PREDICTED MEAN PLY STRESSES WITH CONTROL IN 0° PLIES

Source	Ply											
	+45°			−45°			0°			90°		
	Mean ply stress, ksi											
	σ_L	σ_T	σ_S	σ_L	σ_T	σ_S	σ_L	σ_T	σ_S	σ_L	σ_T	σ_S
External force	−61.8	−5.3	−1.1	−49.1	−3.6	0.8	−15.1	−3.1	0.1	−11.6	−0.6	0
Actuation strain	8.2	0.6	0.5	5.7	0.4	−0.4	−76.4	−12.5	0	2.3	0	0
Combined effect	−53.6	−4.7	−0.6	−43.4	−3.2	0.4	−91.5	−15.8	0.1	−9.3	−0.6	0

TABLE V.—PREDICTED MEAN PLY STRESSES WITH CONTROL IN 45° PLIES

Source	Ply											
	+45°			−45°			0°			90°		
	Mean ply stress, ksi											
	σ_L	σ_T	σ_S	σ_L	σ_T	σ_S	σ_L	σ_T	σ_S	σ_L	σ_T	σ_S
External force	−51.7	−7.3	−1.4	−53.8	−4.1	0.9	−23.2	−2.9	0	−13.3	−0.7	0
Actuation strain	−44.6	−8.6	2.1	33.1	2.5	−1.4	6.5	2.1	0	10.8	0.3	0
Combined effect	−96.4	−15.9	0.7	−20.7	−1.6	−0.5	−16.7	−0.8	0	−2.5	−0.4	0

TABLE VI.—SENSITIVITY FACTORS[a] FOR LATERAL DISPLACEMENT AT FREE END[b] WITH AND WITHOUT CONTROL

Variable	Without control	Control location			
		90°	0°	–45°	45°
	Sensitivity factor				
Primary fiber					
Modulus	0.57	0.55	0.12	0.52	0.26
Volume ratio	.65	.65	.16	.59	.28
Ply misorientation	.13	.13	.06	.19	.14
Laminate thickness	.46	.47	.47	.49	.39
Secondary composite system	0	.02	.36	.16	.41
Control					
Volume ratio	.01	.03	.41	.14	.38
Modulus	0	.07	.42	.09	.35
Strain coefficient	0	.07	.39	.09	.36
Electrical field strength	0	.02	.28	.10	.27

[a] These factors are nondimensional and denote relative significance.

[b] Location A in figure 10.

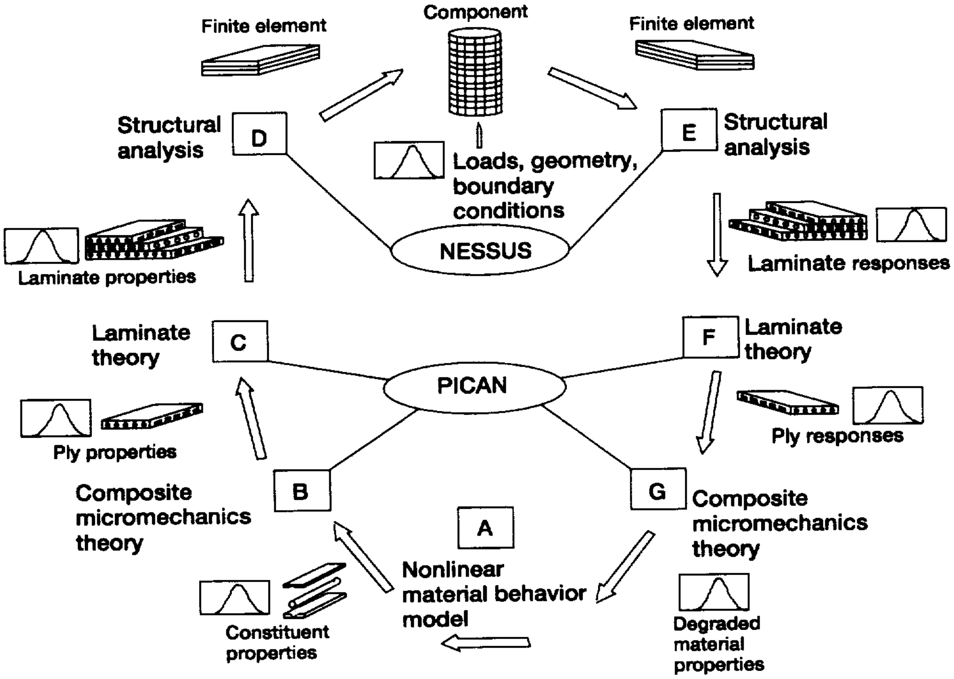

Figure 1.—Concept of probabilistic assessment of composite structures.

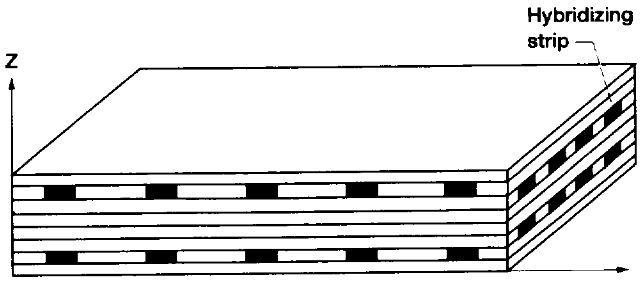

Figure 2.—Intraply hybrid composite system.

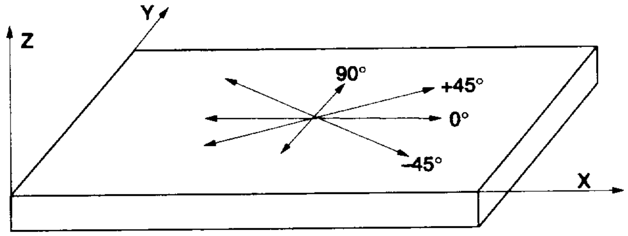

Figure 3.—Ply orientations.

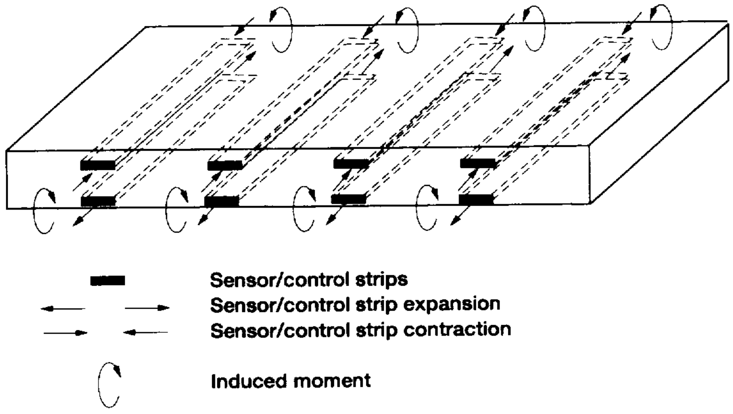

Figure 4.—Structural control using sensor/control materials.

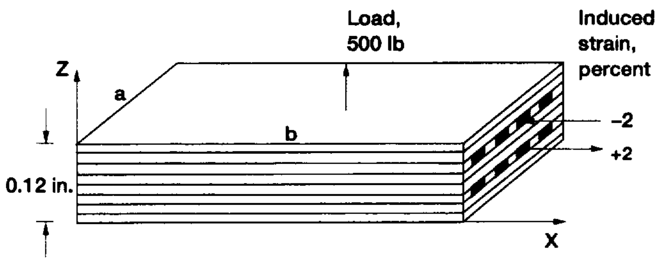

Figure 5.—Composite configuration ([45/−45/0/90]$_S$) and loading conditions for simply supported panel with induced strain in 0° plies; a = 10 in.; b = 20 in.

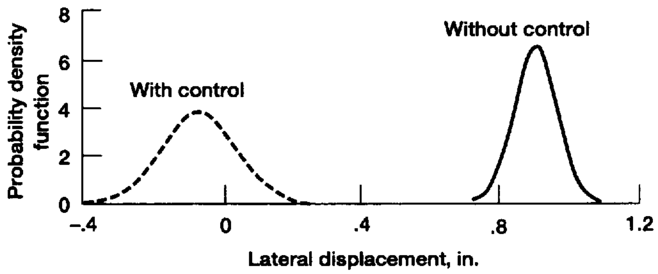

Figure 8.—Lateral displacement at center of panel with and without induced strains in 45° plies.

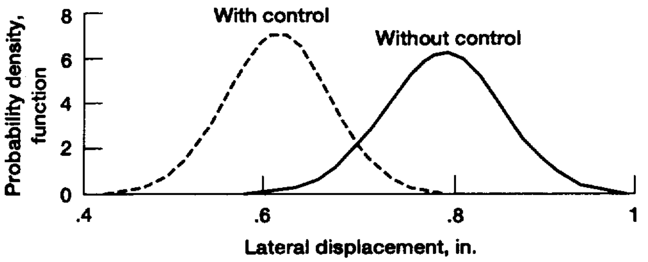

Figure 6.—Lateral displacement at center of panel with and without induced strains in 0° plies.

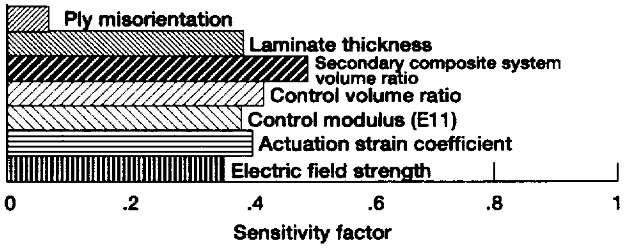

Figure 9.—Sensitivity factors for probabilistic displacement at center of panel with induced strains in 45° plies.

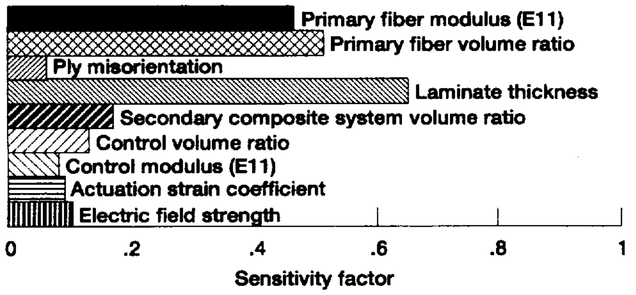

Figure 7.—Sensitivity factors for probabilistic displacement at center of panel with induced strains in 0° plies.

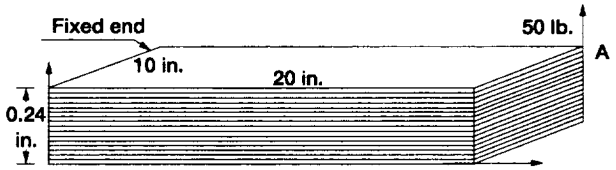

Figure 10.—Geometry and composite configuration ([[+45/−45/0/90]$_S$]$_S$) of cantilevel panel.

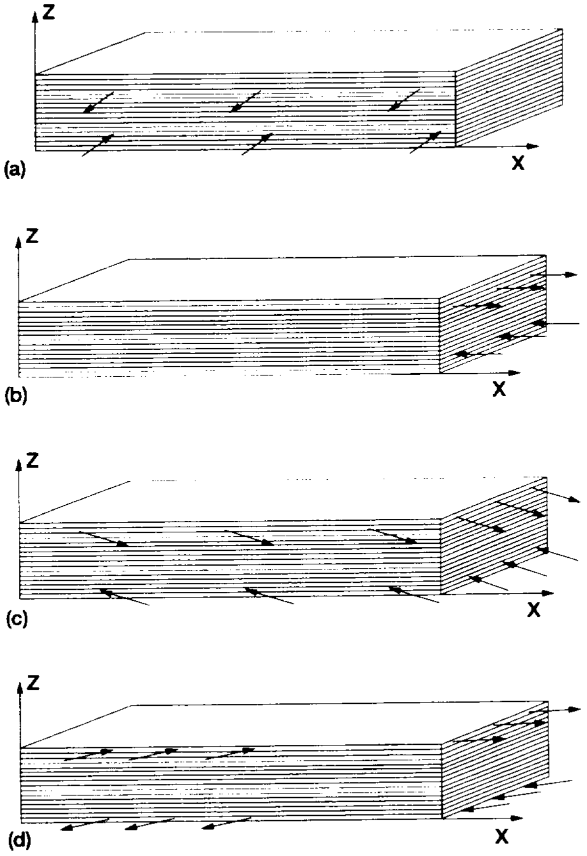

Figure 11.—Cantilever composite panel with induced strains in (a) 90° plies, (b) 0° plies, (c) –45° plies, (d) 45° plies.

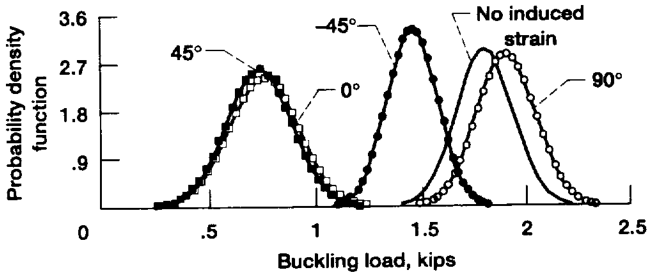

Figure 12.—Lateral displacement at free end (location A of fig.11) for structures with induced strains in 45°, –45°, 0° and 90° plies.

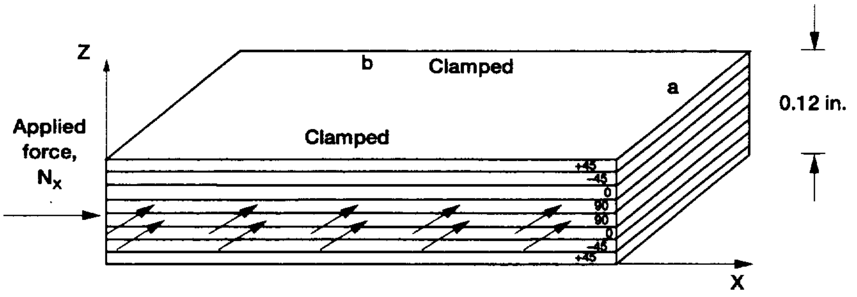

Figure 13.—Boundary conditions and sensor/control locations (in 90° plies) for buckling analysis. Actuation strain, –2 percent; a = 10 in.; b = 20 in.

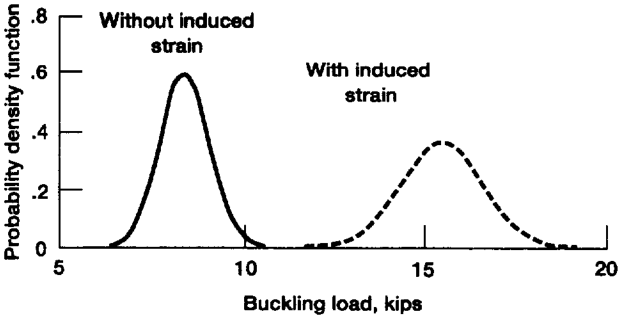

Figure 14.—Probabilistic buckling load of plate with and without induced strain in 90° plies.

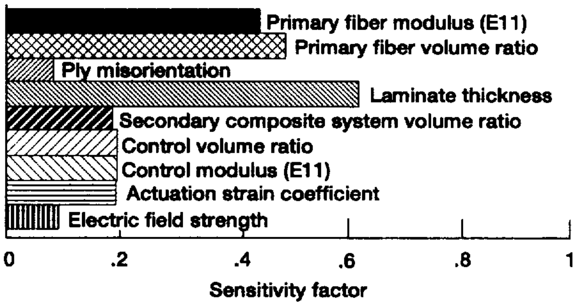

Figure 15.—Sensitivity factors for probabilistic buckling load with induced strain in 90° plies.

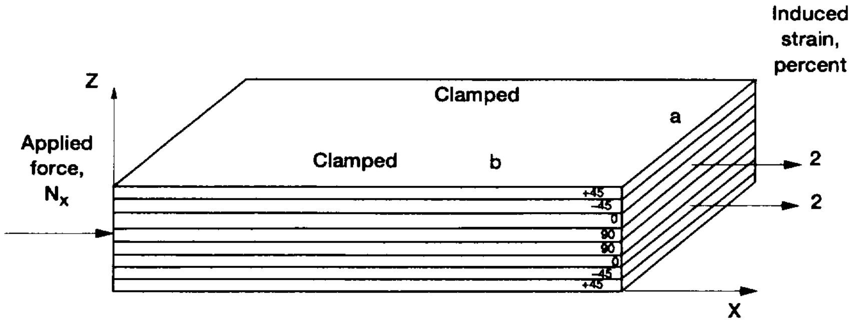

Figure 16.—Boundary conditions and sensor/control locations (in 0° plies) for buckling analysis; a = 10 in.; b = 20 in.

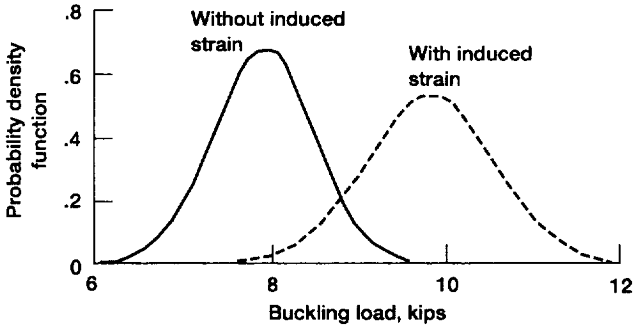

Figure 17.—Probability buckling load of panel with and without induced strains in 0° plies.

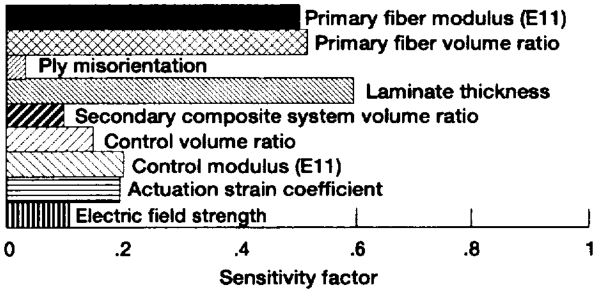

Figure 18.—Sensitivity factors for probabilistic buckling load with induced strains in 0° plies.

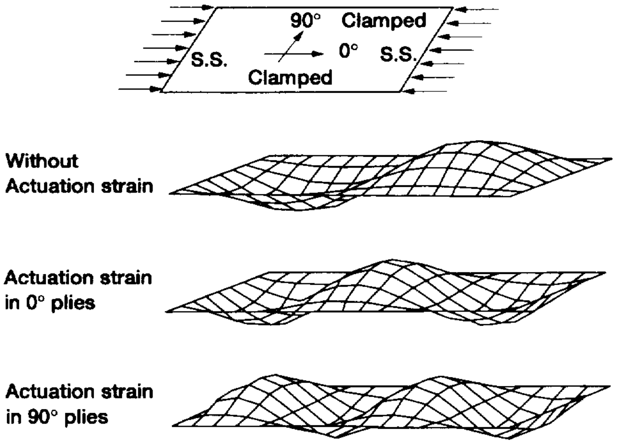

Figure 19.—Buckling mode shapes with and without actuation strains.

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

Adaptive composite structures using actuation materials, such as piezoelectric fibers were assessed probabilistically utilizing intraply hybrid composite mechanics in conjunction with probabilistic composite structural analysis. Uncertainties associated with the actuation material as well as the uncertainties in the regular (traditional) composite material properties were quantified and considered in the assessment. Static and buckling analyses were performed for rectangular panels with various boundary conditions and different control arrangements. The probability density functions of the structural behavior, such as maximum displacement and critical buckling load, were computationally simulated. The results of the assessment indicate that improved design and reliability can be achieved with actuation material.

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National Aeronautics and
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Lewis Research Center
21000 Brookpark Rd.
Cleveland, OH 44135-3191