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PROBABILISTIC EVALUATION OF FUSELAGE-TYPE COMPOSITE STRUCTURES

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SUMMARY

A methodology is developed to computationally simulate the uncertain behavior of composite structures. The uncertain behavior includes buckling loads, natural frequencies, displacements, stress/strain etc., which are the consequences of the random variation (scatter) of the primitive (independent random) variables in the constituent, ply, laminate and structural levels. This methodology is implemented in the IPACS (Integrated Probabilistic Assessment of Composite Structures) computer code. A fuselage-type composite structure is analyzed to demonstrate the code's capability. The probability distribution functions of the buckling loads, natural frequency, displacement, strain and stress are computed. The sensitivity of each primitive (independent random) variable to a given structural response is also identified from the analyses.

INTRODUCTION

Composites are becoming an important class of engineering material in aerospace design. Their outstanding mechanical properties are very attractive to the aerospace industry especially the high strength to low density ratio. They also posses excellent fatigue strength and the ability to resist corrosion and impact. The mechanical properties of composites are derived from a wide variety of variables. The variables are, for example, fiber and matrix material properties at the constituent level and fabrication variables at the ply level such as fiber volume ratio, void volume ratio, ply orientation, ply thickness etc. These primitive variables are statistical in nature, therefore, the mechanical properties of a composite material can not be quantified deterministically. As a consequence, the behavior of composite structures shows a scatter from its average value. Traditionally, a "safety factor" is used to account for those unpredictable behavior. However, this concept results in either an overconservative design or a design of a structure with a high probability of failure. Because of the void in design for a probabilistic assessment of composite structures, a methodology was developed at NASA Lewis Research Center. The methodology is based upon the identification of uncertain variables at every structural level such as at the constituent, ply, or laminate level. The uncertain variables are then filtered through an analyzer which combines the composite mechanics, structural mechanics and probability theory. The output of the analyzer is the desired structural response such as displacement, stress/strain, buckling load, natural frequency, etc. These types of problems can normally be solved by the Monte Carlo simulation method. But, it is computationally expensive. In order to save computational time, the newly developed methodology integrates composite mechanics, finite element methods and probability algorithms to provide an efficient and affordable way for the probabilistic assessment of uncertain composite structures. The methodology is implemented in the computer code IPACS (Integrated Probabilistic Assessment of Composite Structures) and is described in the following sections. A fuselage-type composite structure is analyzed to demonstrate the code's capability. Buckling, natural frequency and static analyses are performed. The probability distributions for buckling load, natural frequency, nodal displacement, nodal strain and stress are computed. The sensitivity of each primitive (independent random) variable to a given structural response is also identified.

SYMBOLS

E_{f11} : fiber modulus in longitudinal direction
E_{f22} : fiber modulus in transverse direction
G_{f12} : in-plane fiber shear modulus
G_{f23} : out-of-plane fiber shear modulus
ν_{f12} : in-plane fiber Poisson's ratio
ν_{f23} : out-of-plane fiber Poisson's ratio
α_{f11} : fiber thermal expansion coefficient in longitudinal direction
α_{f22} : fiber thermal expansion coefficient in transverse direction
ρ_f : fiber mass density
N_f : number of fiber per end
d_f : filament equivalent diameter
C_f : fiber heat capacity
K_{f11} : fiber heat conductivity in longitudinal direction
K_{f22} : fiber heat conductivity in in-plane transverse direction
K_{f33} : fiber heat conductivity in out-of-plane transverse direction
S_{fT} : fiber tensile strength
S_{fC} : fiber compressive strength
E_m : matrix elastic modulus
G_m : matrix shear modulus
ν_m : matrix Poisson's ratio
α_m : matrix thermal expansion coefficient
ρ_m : matrix mass density

C_m : matrix heat capacity
K_m : matrix hear conductivity
S_{mT} : matrix tensile strength
S_{mC} : matrix compressive strength
S_{mS} : matrix shear strength
β_m : matrix moisture coefficient
D_m : matrix diffusivity
fvr : fiber volume ratio
vvr : void volume ratio
θ_p : ply misalignment
t_{psk} : ply thickness of skin
t_{pst} : ply thickness of stringer
K_{cTR} : translational spring constant
K_{cTO} : torsional spring constant
C_z : out-of-plane nodal uncertainties on stringers at free edges
stdv : standard deviation
M_p : material properties
R : structural response
V_i : independent random variable
ϵ : strains
κ : curvatures
N : resultant in-plane forces
M : resultant moments

CONCEPT OF PROBABILISTIC ASSESSMENT OF COMPOSITE STRUCTURES

To start a probabilistic assessment of a composite structure, the uncertainties within the model should be identified at micro and macro levels. For example, at constituent level, the uncertain constituent primitive variables are the fiber and matrix material properties. At the ply level, they are fiber volume ratio, void volume ratio, ply orientation and ply thickness, etc. At the structural level, uncertain loads, temperatures, geometry or the boundary condition may also be included. All the uncertain sources are characterized by their own probability distribution functions. The uncertain sources are then fed into an analyzer of composite mechanics, structural mechanics and probability theory. From the analysis, structural responses and degraded material properties are obtained which can only be properly represented by a probability distribution function. The detail is illustrated in figure 1. PICAN and NESSUS in figure 1 are probabilistic analyzers for both composite and structural mechanics which will be described next.

PROBABILISTIC COMPUTER CODE IPACS

IPACS is a computer code for probabilistic analysis of composite structures. It integrates several NASA in-house computer programs developed in recent years such as COBSTRAN, PICAN and NESSUS. COBSTRAN is a model generator for composite structures which generates finite element models for structural analyses. PICAN (Probabilistic Integrated Composite Analyzer) used to determine the perturbed and probabilistic composite material properties at the ply and laminate level. NESSUS (Numerical Evaluation of Stochastic Structures Under Stress) is used to determine the perturbed and probabilistic structural response at structural, laminate and ply levels. PICAN and NESSUS share the same sub-module, FPI (Fast Probability Integrator), for the probabilistic method. The architecture of IPACS software system is depicted in figure 2. The details of PICAN, NESSUS and FPI are explained in the following.

PICAN has evolved from the deterministic composite mechanics code ICAN (Integrated Composite Analyzer) (ref. 1). This module performs a comprehensive multi-level perturbation and probabilistic analysis of composite material properties based on the primitive (independent random) variables occurring at the constituent (fiber and matrix material properties) and at ply level (fiber volume ratio, void volume ratio, ply orientation and ply thickness). Perturbed material properties at every level corresponding to all the perturbed primitive variables are computed. With this information, mathematical functions to represent the relationships between the material properties and the primitive variables can be determined numerically. The functions can be expressed by equation 1 for a linear relationship or equation 2 for a nonlinear relationship.

$$M_p = a_0 + \Sigma a_i V_i \tag{1}$$

$$M_p = a_0 + \Sigma a_i V_i + \Sigma b_i V_i^2 \tag{2}$$

where M_p is any material property; V_i are primitive variables; and a_0, a_i, b_i are constants. Using equation 1 or 2 and the probability distributions of the primitive variables, probabilistic methods can then be applied to find the probability distribution function of any material property.

NESSUS is a finite element module for the perturbation and probabilistic structural analysis, which is developed by South West Research Institute under NASA contract. This module is being modified to include the capability for structural analysis with uncertain composite material properties. For a given perturbation on any coefficient in the matrices $\boldsymbol{A}$, $\boldsymbol{C}$ and $\boldsymbol{D}$ as defined in equation (3), the corresponding structural responses will be computed by this module. The $\boldsymbol{A}$, $\boldsymbol{C}$ and $\boldsymbol{D}$ matrices are the relationship between resultant force/moment and strain/curvature from laminate theory.

$$\begin{Bmatrix} N \\ M \end{Bmatrix} = \begin{bmatrix} A & C \\ C & D \end{bmatrix} \begin{Bmatrix} \varepsilon \\ \kappa \end{Bmatrix} \tag{3}$$

where N are the resultant forces and M are the resultant moments; ε are the in-plane strains and κ are the curvatures. Because the perturbed coefficients in matrices A, C and D are computed using composite mechanics with a perturbed primitive variable, and the perturbed structural response is computed using the perturbed coefficients in matrices A, C and D, structural responses can be related to the primitive variables and the relationship between the structural response and the primitive (independent random) variables can be developed numerically. This relationship can also be expressed by equation 1 or 2 but replacing the material properties M_p with the structural response R as shown in equations 4 and 5.

$$R = a_0 + \Sigma a_i V_i \tag{4}$$

$$R = a_0 + \Sigma a_i V_i + \Sigma b_i V_i^2 \tag{5}$$

Similarly, the probability distribution functions of structural responses will be determined by probabilistic methods.

The FPI module evolved from the probability algorithm FORM (First Order Second Moment Reliability Method) with Wu's version (refs. 2,3). After the perturbation study, a database is created. The relationship between the structural responses and the primitive variables can be determined numerically by FPI. If the perturbed variables are independent of each other with known probability distribution functions, FPI can be used to compute the discrete cumulative distribution function (cdf). An analytical probability distribution function of a structural response is then determined using this discrete cdf value.

Using IPACS for probabilistic assessment of composite structures, the uncertain primitive variables at constituent and ply levels are identified. These variables are then selectively perturbed several times in order to create a database 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, micro mechanics are applied to determine the corresponding perturbed mechanical properties at the ply and laminate level. Laminate theory is then used to determine the perturbed resultant force/moment-strain/curvature relationship. 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 is generated and the proper relationship between structural responses and primitive variables can be determined through a numerical procedure. With the known probabilistic distributions of the primitive variables and a numerically determined relationship between the structural response and the primitive variables, fast probability integration is applied. For every discrete response value, a corresponding cumulative probability can be computed 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 for the structural responses. The output information from FPI for a given structural response includes its discrete cdf values, the coefficients for a special type of probability distribution function, and the sensitivity factors of the primitive variables to the structural response.

NUMERICAL EXAMPLES AND DISCUSSIONS

A cylindrical shell with 10 ft. in diameter and 50 ft. in length is analyzed by IPACS. Four vertical stringers and three ring stringers shown in figure 3(a) are used to strengthen the shell-skin structure shown in figure 3(b). Three hundred and twelve nodes including ninety six duplicate nodes are used to model the structure for the finite element analysis. The structure is fixed at one end by translational and torsional springs and is free at the other end as shown in figure 4(a) and 4(b). The composite structure is made of graphite fiber and epoxy matrix. The average ply thickness for the shell skin is 0.005 inches with a $[0,-45,45,90]_s$ ply lamination. The average ply thickness for the stringers are 0.05 inches with 10 zero degree plies. The primitive variables identified at constituent level are: (1) 17 material properties for fiber, (2) 12 material properties for matrix. The identification and statistics of these twenty nine primitive variables are listed in Table 1. At ply level, the fabrication variables are: (1) fiber volume ratio, (2) void volume ratio, (3) ply orientation and (4) ply thickness. Their statistical data are listed in Table 2. At structural level, translational and torsional spring constants for boundary rigidity are modeled as uncertain parameters. Uncertainties are also assigned to those nodes on the free edge of the vertical stringers in their out of plane directions. Their statistics are shown in Table 3. Three analyses are performed: (1) buckling analysis, (2) static analysis and (3) natural frequency analysis. Ninety three uncertain primitive variables are considered including sixty six variables from stringer and skin in the constituent and ply levels, three variables for the uncertain boundary conditions and twenty four out-of-plane nodal uncertainties in the vertical stringers.

From the buckling analysis, the probabilistic buckling load of the first buckling mode is computed. The cumulative distribution function (cdf) of the buckling load is plotted in figure 5. The sensitivity factors of six most important primitive variables are plotted in figure 6. It shows that the probabilistic buckling load is highly sensitive to the ply thickness, fiber volume ratio and fiber modulus of the skin and the stringer ply thickness. The uncertain torsional springs also show some effect on the scatter of the probabilistic buckling load. In this analysis, the distance between the ring stringers is assumed to be constant. However, the distance should be included in the probabilistic analysis even if the distance shows a small scatter, because the first buckling mode shape is very sensitive to the distance between the rings.

Modal analysis is also conducted. The deterministic first vibration frequency is 1.1 rad/sec. The cdf of this frequency is plotted in figure 7. The sensitivity factor of each primitive variable to the scatter of the vibration frequency is shown is figure 8. Again, it is found that skin ply thickness is the most important variable with a sensitivity factor equal to 0.88.

Static analysis is performed using an equivalent load to the first buckling load. The displacement at the free end in the longitudinal direction is analyzed. Its cdf is plotted in figure 9. The sensitivity analysis shows that the fiber modulus, fiber volume ratio and ply thickness of both skin and stringer have approximately the same contribution to the scatter of the displacement. The sensitivity factors are plotted in figure 10. Also studied are the strain and stress of the node at the fixed end in the vertical stringer. The cdf of the strain and its sensitivity factors are plotted in figures 11 and 12 respectively. The cdf of stress and its sensitivity factors are plotted in figures 13 and 14 respectively. The sensitivity analysis again shows that the scatter of the strain and stress all are strongly dominated by the ply thickness, fiber volume ratio and fiber normal modulus of both skin and stringers. The sensitivity results for strain and stress are similar to those for displacement because of the fact that stress/strain analyses are highly dependent on displacement analysis.

Once the probability distribution functions are determined, reliability assessments of the entire structures can be assessed as proposed by Shiao and Chamis (refs. 4, 5, 6, 7).

CONCLUDING REMARKS

A methodology is developed to computationally simulate the uncertainties in the composite structural analysis. The methodology is implemented into the computer code IPACS which can efficiently and effectively simulate the uncertain structural responses. The code is capable of handling the uncertainties in the constituent, ply and laminate levels of composite structures. A large amount of useful information such as the probability distributions of desired structural responses and the sensitivity of each independent primitive variable to the probabilistic structural response can be obtained through the analysis. A reliability assessment can be performed once this information is available.

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Table 1. Material Properties at Constituent Level for both Skin and Stringers

	unit	Distribution type	Mean	coefficient of variation
E_{f11}	Msi	Normal	31.0	0.05
E_{f22}	Msi	Normal	2.0	0.05
G_{f12}	Msi	Normal	2.0	0.05
G_{f23}	Msi	Normal	1.0	0.05
ν_{f12}	---	Normal	0.2	0.05
ν_{f23}	---	Normal	0.25	0.05
α_{f11}	ppm/°F	Normal	-0.55	0.05
α_{f22}	ppm/°F	Normal	5.6	0.05
ρ_f	lb/in^3	Normal	0.063	0.05
N_f	---	constant	10,000	0.00
d_f	in	Normal	0.0003	0.05
C_f	BTU/in/°F	Normal	0.17	0.05
K_{f11}	BTU.in/hr/in^2/°F	Normal	580	0.05
K_{f22}	BTU.in/hr/in^2/°F	Normal	58	0.05
K_{f33}	BTU.in/hr/in^2/°F	Normal	58	0.05
S_{fT}	Ksi	Weibull	400	0.05
S_{fC}	Ksi	Weibull	400	0.05
E_m	Msi	Normal	0.5	0.05
G_m	Msi	Normal	0.185	0.05
ν_m	---	Normal	0.35	0.05
α_m	ppm/°F	Normal	42.8	0.05
ρ_m	lb/in^3	Normal	0.0443	0.05
C_m	BTU/in/°F	Normal	0.25	0.05
K_m	BTU.in/hr/in^2/°F	Normal	1.25	0.05
S_{mT}	Ksi	Weibull	15	0.05
S_{mC}	Ksi	Weibull	35	0.05
S_{mS}	Ksi	Weibull	13	0.05
β_m	in/in/1%moist	Normal	0.004	0.05
D_m	in^3/sec	Normal	0.002	0.05

Table 2. Fabrication variables at ply level

	unit	Distribution type	mean	Coefficient of variation
fvr	---	Normal	0.60	0.05
vvr	---	Normal	0.02	0.05
θ_p	degree	Normal	0.00	0.9 (stdv)
t_{psk}	in	Normal	0.005	0.05
t_{pst}	in	Normal	0.02	0.05

Table 3. Uncertainties in the structural level

	unit	Distribution type	mean	coefficient of variation
K_{cTR}	lb/in	Normal	30E+06	0.30
K_{cTO}	lb-in/rad.	Normal	12E+02	0.30
C_z	in	Normal	0.0	0.01 (stdv)

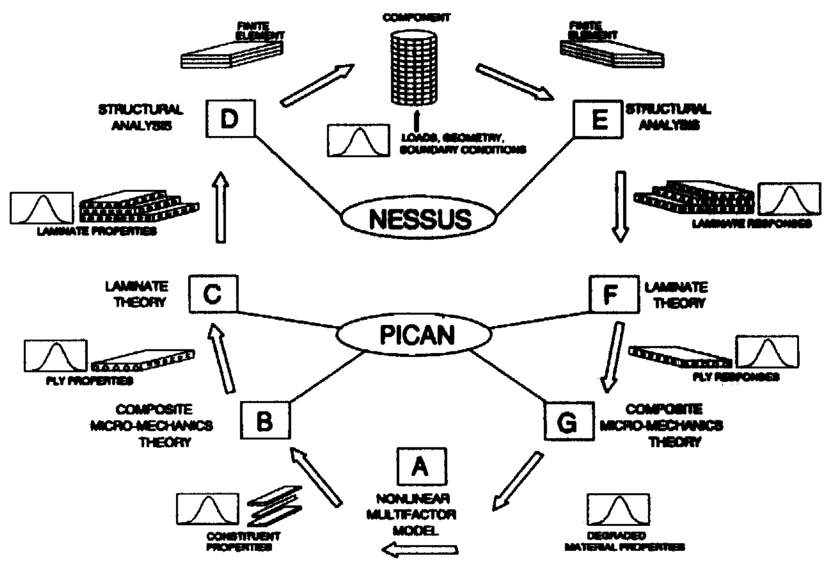


Figure 1. Concept of Probabilistic Assessment of Composite Structures

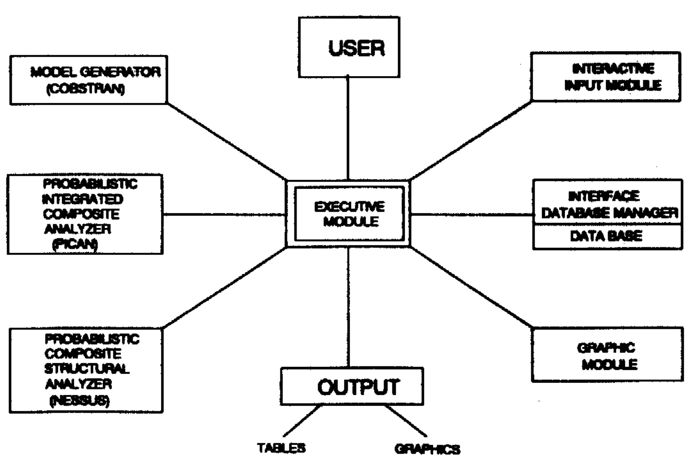
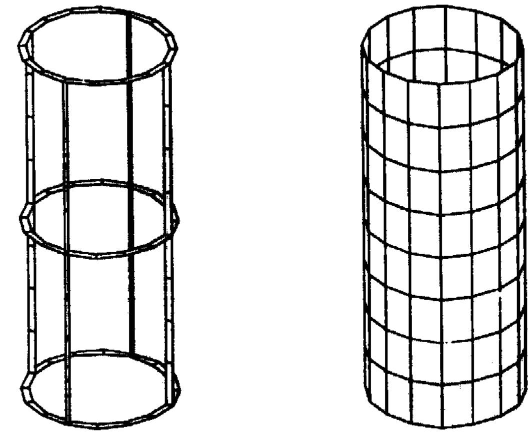


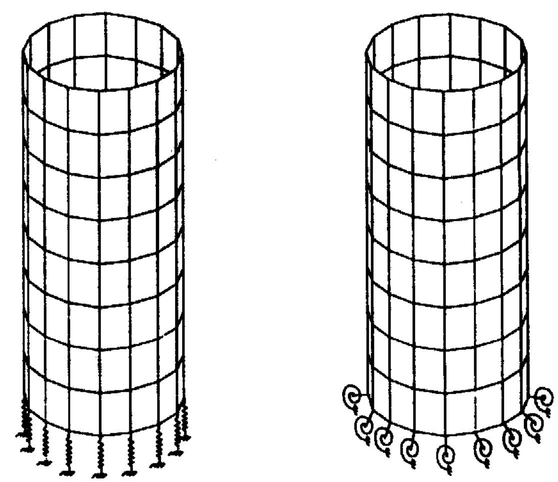
Figure 2. Architecture of IPACS Software System

(IPACS: Intergrated Probabilistic Assessment of Composite Structures)



(a) frames/stringers (b) skin

Figure 3. Finite Element Model of a Composite Cylindrical Shell



(a) translational springs (b) torsional springs

Figure 4. Boundary Conditions of a Composite Cylindrical Shell

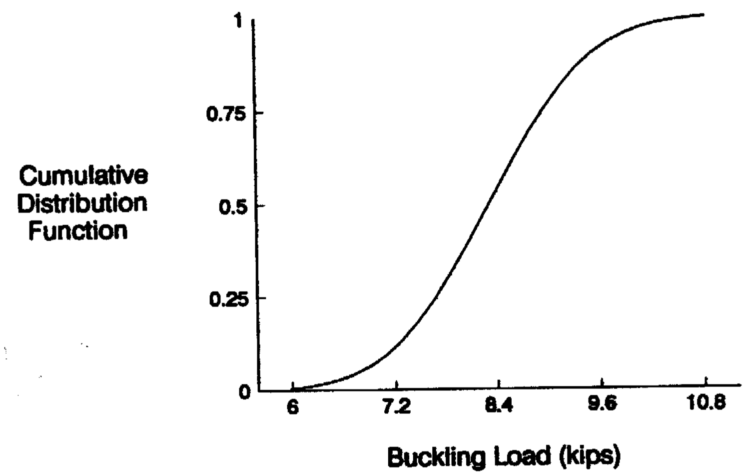


Figure 5. Cumulative Distribution function of first buckling load

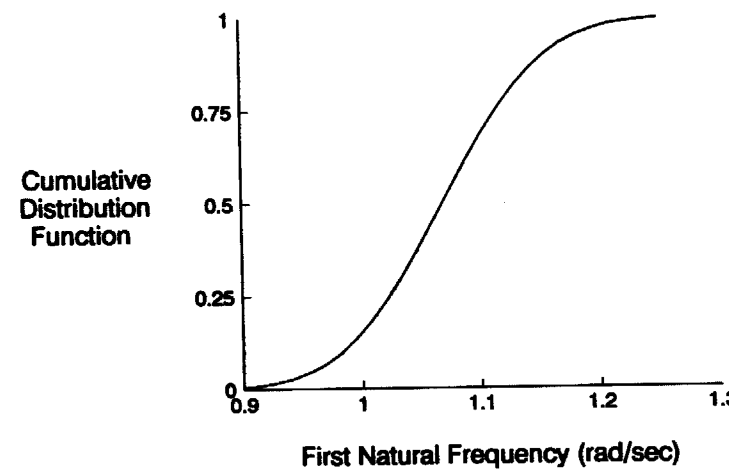


Figure 7. Cumulative Distribution function of first natural frequency

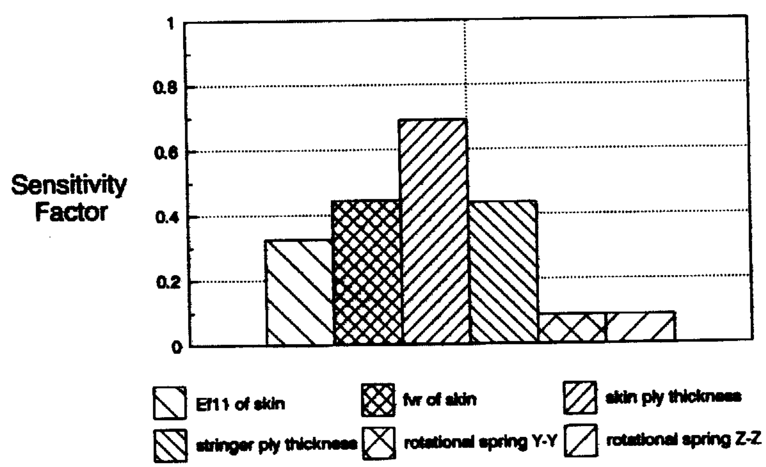


Figure 6. Sensitivity factors of six most important primitive variables to the first buckling load at probability level 0.005

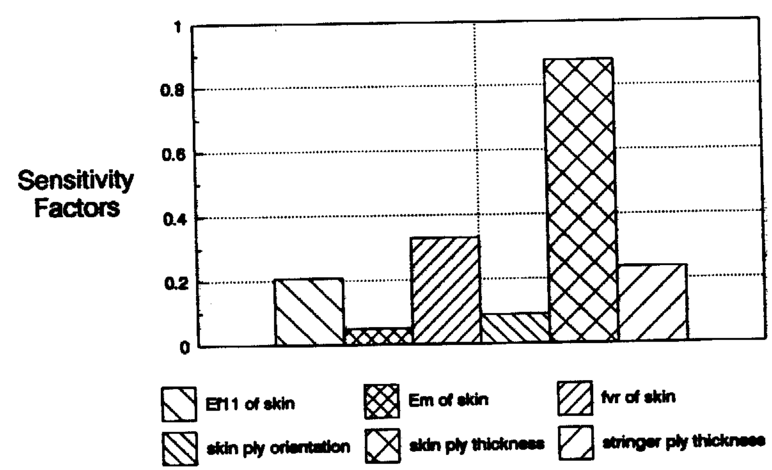


Figure 8. Sensitivity factors of six most important primitive variables to the first natural frequence at probability level 0.005

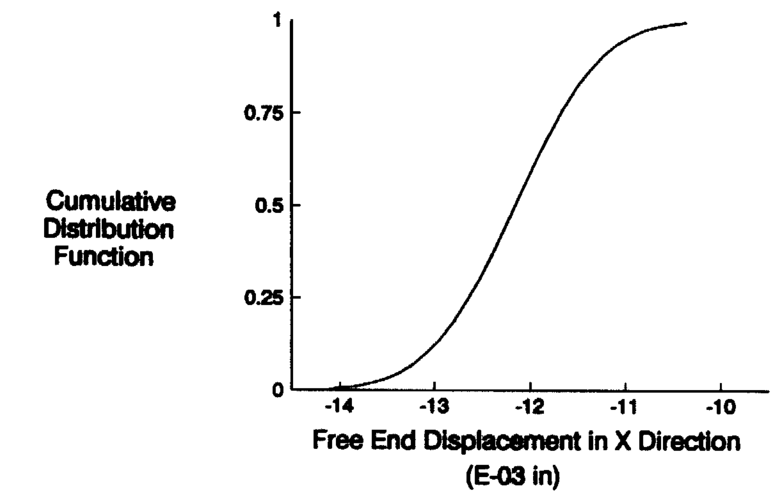


Figure 9. Cumulative Distribution function of free end displacement in X direction

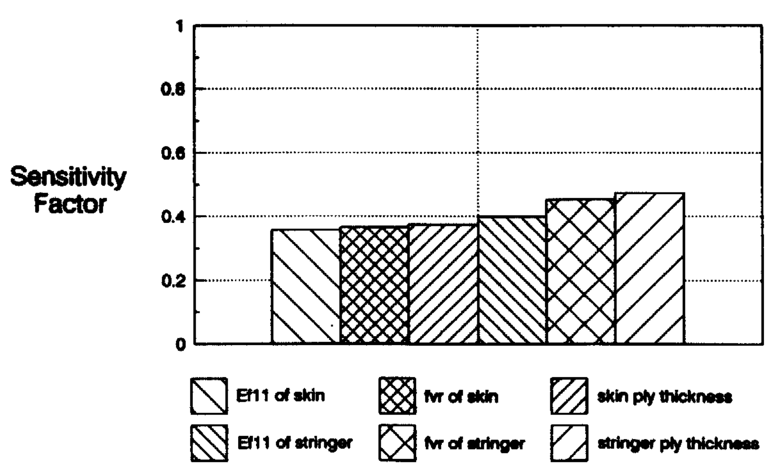


Figure 10. Sensitivity factors of six most important primitive variables to free end displacement in x direction at probability level 0.005

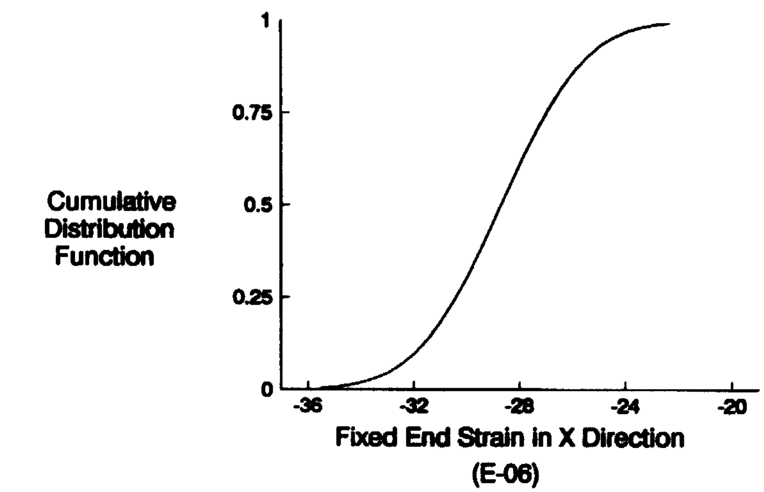


Figure 11. Cumulative Distribution function of fixed end strain in X direction

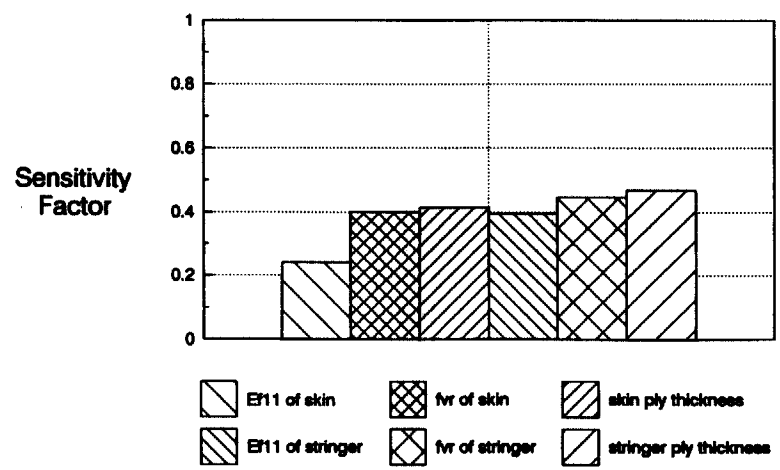


Figure 12. Sensitivity factors of six most important primitive variables to fixed end strain in x direction at probability level 0.005

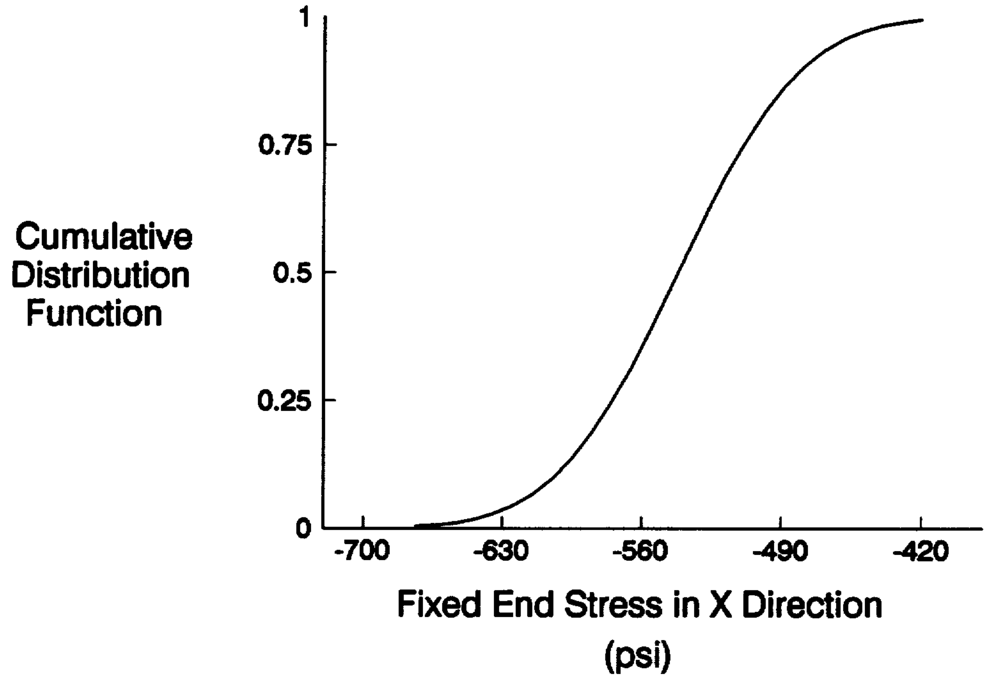


Figure 13. Cumulative Distribution function of fixed end stress in X direction

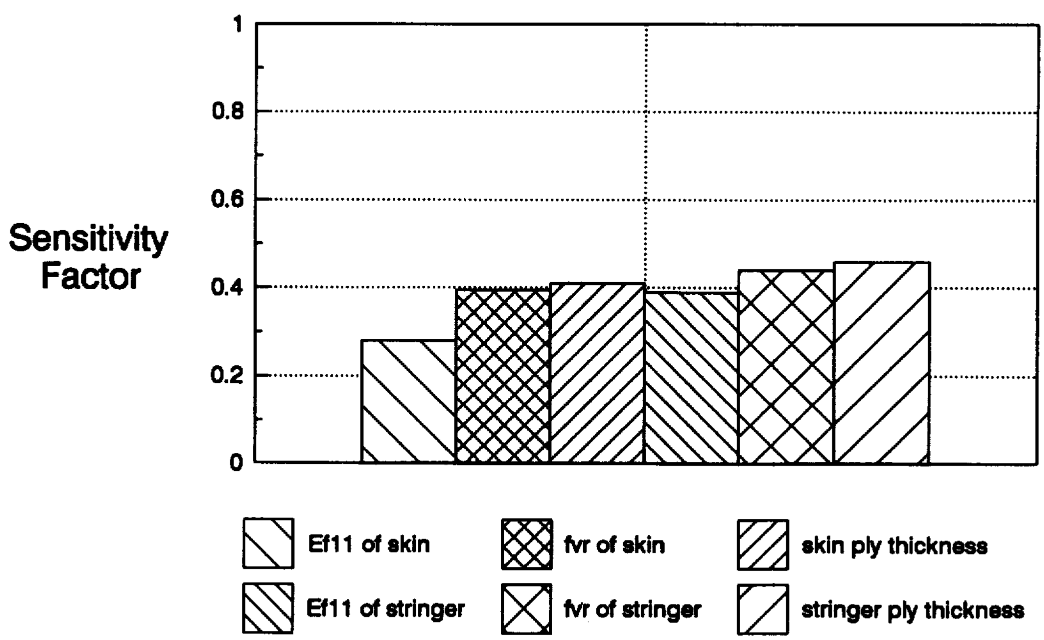


Figure 14. Sensitivity factors of six most important primitive variables to fixed end stress in x direction at probability level 0.005

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