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Probabilistic Assessment of Space Trusses Subjected to Combined Mechanical and Thermal Loads

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PROBABILISTIC ASSESSMENT OF SPACE TRUSSES SUBJECTED TO COMBINED MECHANICAL AND THERMAL LOADS

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SUMMARY

A three-bay, space, cantilever truss is probabilistically evaluated to quantify the range of uncertainties of buckling loads and member forces due to nonuniform thermal loads, applied loads and moments (mechanical loads), and combination of both. The truss members are assumed to be made from (1) Aluminum tubes or (2) high modulus graphite-fiber/intermediate modulus epoxy-matrix composite tubes. Cumulative distribution function results show that certain combinations of thermal loads with mechanical loads reduce the probabilistic buckling loads and increase the magnitude of the member axial forces for aluminum truss. The same trend is observed for composite truss as well, however, the thermal effects on the probabilistic buckling loads and member axial forces are not as substantial as that for an aluminum truss. This can be attributed to the large differences in the values of coefficient of thermal expansion. Finally, the sensitivities associated with the uncertainties in the structural, material and load variables (primitive variables) are investigated. They show that buckling loads and member axial forces are most sensitive to the uncertainties in spacial (geometry) variables.

INTRODUCTION

Aerospace structures and spacecraft are a complex assemblage of structural components that are subjected to a variety of complex thermal and mechanical loading conditions. All of these introduce significant uncertainties. The inherent randomness of material properties and the fabrication processes introduce additional uncertainties. Therefore, it is becoming increasingly evident that to assure the structural performance/reliability of these structures, all these uncertainties have to be quantified in order to ascertain that the structural response will be within the acceptable ranges during the life of the structure. Probabilistic structural analysis provides a formal way to properly account for all these uncertainties.

A Probabilistic Structural Analysis Method (PSAM) is being developed at NASA Lewis Research Center (ref. 1) which uses different distributions such as the Weibull, normal, log-normal, etc. to describe the uncertainties in the structural and load parameters, herein referred to as primitive variables. PSAM assesses the effects of these uncertainties on the scatter of structural responses (buckling loads, frequencies, member forces). Thus, PSAM provides a formal and systematic way to reliably evaluate structural performance and durability. PSAM is embedded in a computer code NESSUS (Numerical Evaluation of Stochastic Structures Under Stress) (refs. 2 and 3).

In the recent past, NESSUS has been used to computationally simulate and probabilistically evaluate a three-dimensional, three-bay cantilever truss (fig. 1) typical for space type structures and quantify the uncertainties in the structural responses (displacements, member axial forces, and vibration frequencies) (ref. 4). Furthermore, a methodology has been developed to perform probabilistic progressive buckling assessment of space type trusses using the NESSUS computer code (ref. 5). In this methodology, the initial deterministic analysis indicated that axial forces in some members were sufficiently high to cause local buckling in these member(s). The subsequent probabilistic analysis showed that the scatter in the spacial geometry (variations in the nodal coordinates) has very significant impact on the probabilistic buckling load. In addition, criteria have been established to probabilistically scope the structural requirements of truss-type space structures in order to ascertain that the in-service performance requirements are maintained by the use of adaptive/smart/intelligent structural concepts (ref. 6). Recently, PSAM has been extended to include the effects of thermal loads and their respective uncertainties on the truss structural performance.

The objective of this paper to describe the feasibility of using NESSUS to evaluate the probabilistic buckling loads (when the first member buckles) and member axial forces for the three-bay cantilever truss for: (1) thermal loads only such that, either only top surface of the truss or bottom surface of the truss is exposed to Sun rays, (2) applied vertical and longitudinal loads and twisting moments, (3) applied loads and moments combined with each of the two above thermal loading conditions, and (4) the effects of replacing the aluminum tube members with tubes made from high modulus graphite-fiber/intermediate modulus epoxy-matrix composites with each of the above loading cases.

FUNDAMENTAL APPROACH AND CONSIDERATIONS

One of the major problems encountered in the design analysis of space type trusses is to assure their structural performance for their design life in uncertain space environment loading conditions. In addition, these trusses may be exposed to nonuniform thermal loads in situations where, only the top surface members of the truss are exposed to the Sun rays while the bottom surface members will radiate to cold space. The reverse situation is also probable as the Earth rotates about its axis and the space structure spins and orbits around the Earth. The presently available methods/computer programs do not easily allow us to identify and quantify the sensitivities associated with uncertainties in primitive variables. For a space truss the primitive variables such as spacial truss geometry, stiffness parameters, strength parameters, thermal loads, and applied loads and moments continuously vary due to changes in orbital environments. With the aid of the NESSUS code, methodologies for the probabilistic structural analysis of the truss with the aim to evaluate the probabilistic buckling loads and member axial forces are developed and are described hereafter.

FINITE ELEMENT MODEL

A three-dimensional, three-bay cantilever truss (see fig. 1) is computationally simulated using a linear isoparametric beam element based on the Timoshenko beam equations. The element is idealized as a two-noded line segment in three-dimensional space. The cantilever truss is assumed to be made from hollow circular pipe members. The members are made up of wrought Aluminum alloy (616-w) with modulus of elasticity (E) equal to 10 Mpsi and the coefficient of thermal expansion (α) equal to 13.1 ppm/°F. However, when the truss members are replaced with high modulus grafite-fiber/intermediate modulus epoxy-matrix composite tubes with 60 percent fiber-volume ratio, the E and α are, respectively, 36 Mpsi and 0.1 ppm/°F. The outer and inner radii (r_o and r_i) of the tube, are 0.5 and 0.4375 in., respectively. All six degrees of freedom are restrained at the fixed end (left side) nodes. Each bay of the truss is 5 ft wide, 8 ft long, and 6 ft high. The overall length of the truss is 24 ft.

Six vertical and two longitudinal loads are applied. In addition, twisting moments are applied at the truss-end nodes. The directions of the forces and moments are shown in figure 1. The applied loads and moments are selected to represent anticipated loading conditions for a typical space truss. Finally, when the top surface of the truss is exposed to the Sun rays, all the top members will be hot with temperature equal to 212 °F and all the bottom members will be cold with temperature equal to -4° F. For the reverse case, the top members will be cold and the bottom members will be hot and the temperature profile will be reversed. Furthermore, the thermal load profile induces nonuniform thermal environmental effects on the truss buckling loads and member axial forces. This is also true for an actual space truss. It is important to note that, for the analyses considered in this paper the temperature range was assumed to have negligible effect on E, α, and ν (Poisson's ratio) and, therefore, these properties are assumed to be constant in this range.

PROBABILISTIC MODEL

The following primitive variables are considered in the probabilistic analysis:

1. Nodal coordinates (X, Y, Z)
2. Modulus of elasticity (E)
3. Outer radius of the tube (r_o)
4. Inner radius of the tube (r_i)
5. Vertical loads (V)
6. Longitudinal loads (H)
7. Twisting moments (M)
8. Truss Panel Point Temperature (T)

It is possible that the above primitive variables will vary continuously and simultaneously due to extreme changes in the environment when such trusses are used in upper Earth orbit for space-station-type structures. The normal distribution is used to represent the uncertainties in E, r_o, r_i, and X,Y,Z coordinates. The applied loads and moments are selected to represent an anticipated loading for a typical space truss. The scatter in these are represented by log-normal distributions. Finally, the thermal load variations at each of the truss panel points are also represented by the log-normal distributions. Initially, the NESSUS/FEM (Finite Element Methods) module is used to deterministically analyze the truss for mean values of each of these primitive variables. In the subsequent probabilistic analyses, each primitive variable is perturbed independently and by a different amount. Usually, the perturbed value of the primitive variable is obtained by certain factor of the standard deviation on either side of the mean value.

In, general, the finite element equation for motion is written as:

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = F(t) \tag{1}$$

where [M], [C], and [K] denote the mass, damping, and stiffness matrices, respectively. It is important to note that these matrices are evaluated probabilistically in the NESSUS code. Furthermore, $\{\ddot{u}\}$, $\{\dot{u}\}$, and $\{u\}$ are the acceleration, velocity, and displacement vectors at each node, respectively. The forcing function vector, $\{F(t)\}$, is time independent at each node.

In this paper, the static case is considered by setting the mass and damping matrices to zero and considering the forcing function being independent of time in equation (1) such that

$$[K]\{u\} = \{F\} \tag{2}$$

It is important to note that, in the NESSUS code a linear buckling analysis is carried out by making use of the subspace iteration technique to evaluate the probabilistic buckling load. The matrix equation for the buckling (eigenvalue) analysis for a linear elastic structure is as follows:

$$\{[K] - \lambda \ [K_g]\} \{\phi\} = 0 \tag{3}$$

In the above equation, [K] is the standard stiffness matrix, $[K_g]$ is the geometric stiffness matrix, λ is the eigenvalue, and ϕ are the eigenvectors.

For the case of the truss being exposed to purely thermal loads (in our case nonuniform thermal loads), thermal strains account for the thermal deformation of truss members, mainly the first and second bay front and rear diagonals as well as the two ends of the vertical members (see fig. 1).

Finally, the NESSUS/FPI (Fast Probability Integration) module extracts the response variables (buckling loads, and member axial forces) to calculate respective probabilistic distributions and respective sensitivities associated with the corresponding uncertainties in the primitive variables. The mean, distribution type and scatter, in terms of percentage variation, for each primitive variables are given in table I.

RESULTS AND DISCUSSION

Hollow Aluminum Tube Members

Initially, the three-bay truss was probabilistically analyzed assuming thermal loads such that the top surface members were hot (212 °F) and the bottom surface members were cold (-4 °F). These temperatures are representative of exposed surface and cold surface in space. The results of the analyses indicated that the induced thermal stresses were not sufficiently high enough to cause any over all buckling of the truss. Furthermore, the thermal load was combined with the applied loads and moments and subsequent probabilistic eigenvalue analyses also did not indicate any buckling of the truss. This suggests that the scatter in the applied loads and moments did not counteract the uncertainties in the thermal loads. However, when the purely thermal load profile was reversed the cumulative distribution function (CDF) of the probabilistic buckling loads as shown in figure 2 suggest that the induced thermal stresses were effective so as to cause the buckling of the truss. According to figure 2 , the probabilistic buck-ling loads were sufficiently higher when only applied loads and moments and were considered in the probabilistic analyses. When the thermal loads with the bottom surface exposed to the Sun rays and the top surface in the shadow were combined with the applied loads and moments, the probabilistic buckling loads were much lower in magnitude (see fig. 2). In addition for this case, from the sensitivity factors from figure 3, the scatter in the bay height (Z-coordinate) has the highest impact on the probabilistic buckling load followed by the bay length (Y-coordinate), the outer radius, the inner radius and finally the bay width (X-coordinate). For the above discussed three loading cases, the CDF of the probabilistic member axial force in the first bay rear diagonal are shown in figure 4. The thermal load combined with the applied loads and moments increase significantly the magnitude of the probabilistic member axial forces. According to the sensitivity factors shown in figure 5, the uncertainties in the bay length and bay height had equally significant impact on the probabilistic member axial forces followed by member radii.

Composite Tube Members-Alternatively, the truss was probabilistically evaluated using high modulus graphite-fiber/intermediate modulus epoxy-matrix composite tubes. The probabilistic eigenvalue analysis with top surface members hot and bottom surface members cold showed that the induced thermal stresses were not sufficiently high to cause buckling. However when the thermal loads were reversed, the induced thermal stresses were effective so as to cause the buckling of the truss (see fig. 6). The CDF of the probabilistic buckling loads for applied loads and moments only and combination of these with either of the thermal load profiles is shown in figure 7. It is interesting to note that the probabilistic buckling loads were sufficiently higher compared to aluminum tubes case (see fig. 2) even though the thermal loads were combined with mechanical loads. The reason is that α for the composite tubes was very low. According to figures 8 and 9, the sensitivity factors suggest that the uncertainties in spacial (geometry) variables and applied vertical loads had significant impact on the probabilistic buckling loads when the thermal loads were combined with other loads. Figure 10 shows the magnitude of the probabilistic member axial forces in the first bay rear diagonal for purely thermal loads are significantly lower compared to other load cases due to very low value of α for the composite tubes. Finally, the uncertainties in spacial (geometry) variables had significant impact on the probabilistic member axial forces followed by vertical load (see figs. 11 and 12).

It is important to note that even comparatively large variations in modulus (E) for all load cases and in area (r_o and r_i) for majority of load cases had very neglible impact on the probabilistic buckling loads and member axial forces. Furthermore, the CDF of the probabilistic member axial forces was evaluated for the first bay rear diagonal due to the fact that the initial static buckling analysis indicated that this member will buckle first. Howver, similar probabilistic analysis can also be applied for other members to obtain the CDF of the probabilistic member axial forces.

CONCLUSIONS

Probabilistic evaluation of the buckling of truss structures for non-uniform thermal loads, other loads and moments, and combination of both is demonstrated using the NESSUS computer code and step-by-step procedures are outlined. Scatter of the probabilistic buckling loads and member axial forces are evaluated and the sensitivities associated with the uncertainties in the primitive variables are determined. The results indicate that (1) for the combination of thermal loads with the other loads , the probabilistic buckling loads reduce and the magnitude of the probabilistic member axial forces increase when hollow aluminum tube members are used. However, when high modulus graphite-fiber/intermediate modulus epoxy-matrix composite tubes are used in lieu of aluminum, the thermal effects on the buckling loads and member axial forces are not as pronounced; (2) the scatter in the spacial (geometry) variables has a very significant impact on the probabilistic buckling loads and member forces; (3) in the case of the aluminum truss, the scatter in member radii has a nonneglible impact on the probabilistic buckling loads and member axial forces when the thermal loads are combined with the other loads. Finally, the composite tubes are recommended for controlling the buckling loads and member axial forces.

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TABLE I. - PRIMITIVE VARIABLES AND UNCERTAINTIES FOR

PROBABILISTIC STRUCTURAL ANALYSIS OF A SPACE TRUSS

[Assumed scatter in input data.]

Primitive variables		Distribution type	Mean value	Scatter ±percentage
Geometry	Width	Normal	60 in.	0.5
	Length	Normal	96 in. 192 in. 288 in.	0.1 .1 .1
	Height	Normal	72 in.	0.2
Loads	Vertical Longitudinal Twisting moment Thermal	Lognormal Lognormal Lognormal Lognormal	20 lb 20 lb 50 lb. in. 212 °F; -4 °F	6.3 2.5 6.3 6.3
Material property	Modulus	Normal	10 Mpsi	7.5
Tube radii	Outer radius Inner radius	Normal Normal	0.5 in. 0.44 in.	7.5 7.5

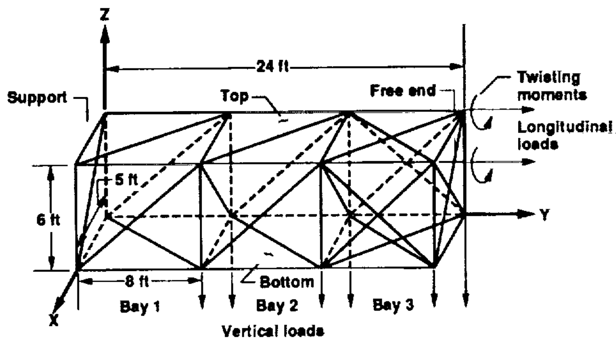

Figure 1.—Solar Array Panels Mast – Typical Truss.

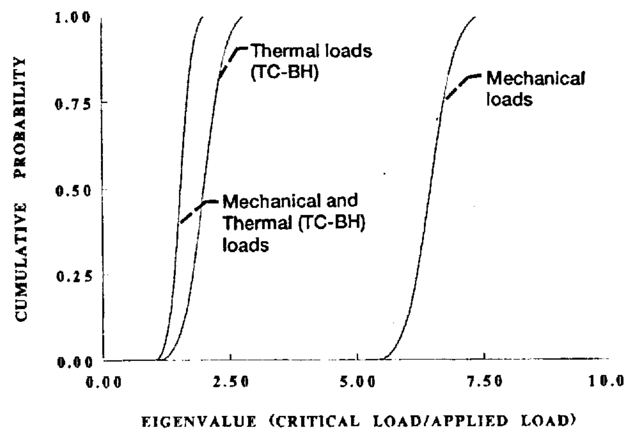

Figure 2.—Probabilistic buckling load (aluminum truss — mechanical and thermal loads; (TC-BH) = top cold-bottom hot).

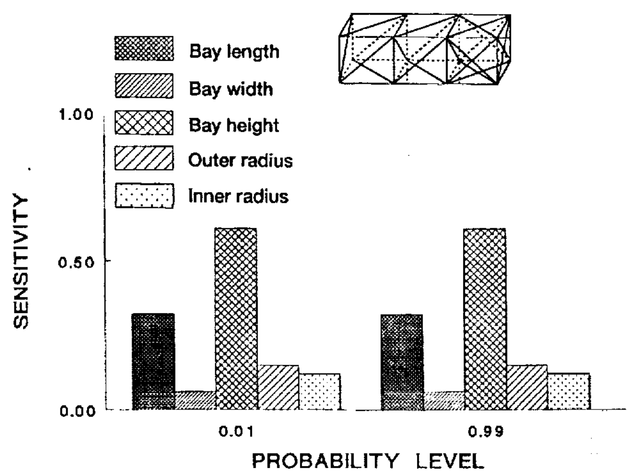

Figure 3.—Probabilistic buckling load sensitivities (aluminum truss — mechanical and thermal (top cold-bottom hot) loads).

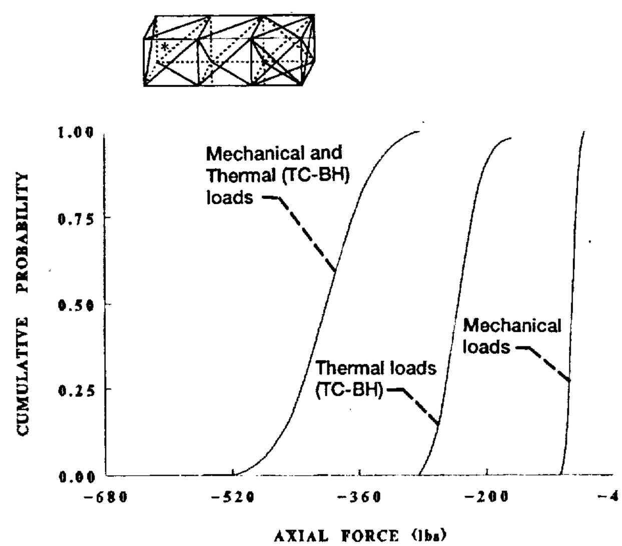

Figure 4.—Probabilistic member force (aluminum truss — mechanical and thermal loads; (TC-BH) = top cold-bottom hot; first-bay rear diagonal).

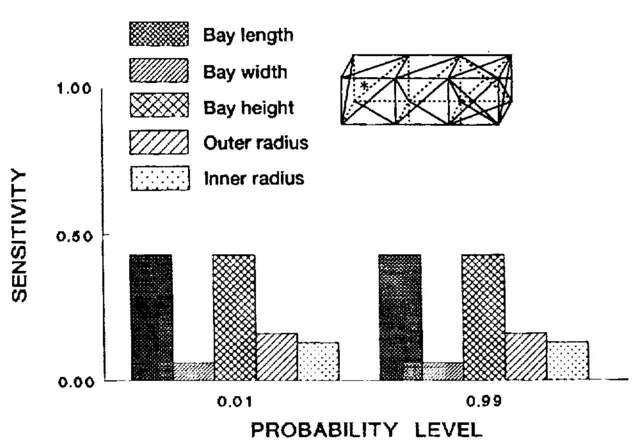

Figure 5.—Probabilistic member force sensitivities (aluminum truss —mechanical and thermal (top cold-bottom hot) loads; first-bay rear diagonal).

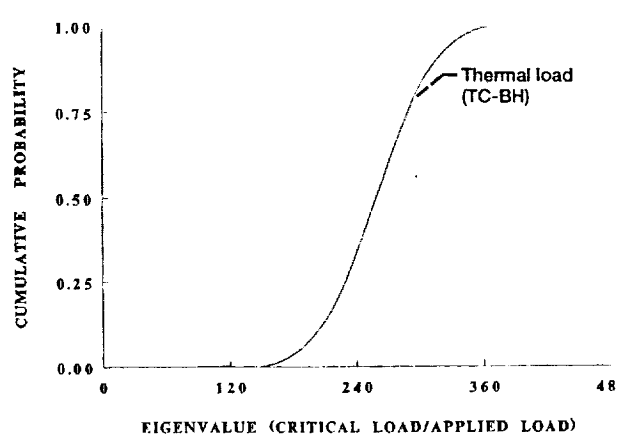

Figure 6.—Probabilistic buckling load (composite truss — thermal load; (TC-BH) = top cold-bottom hot).

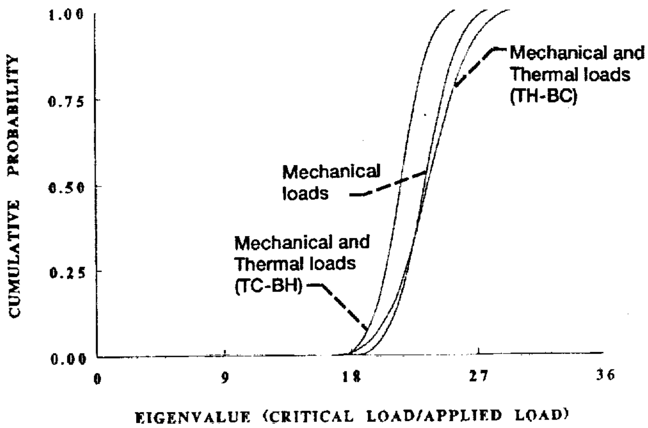

Figure 7.—Probabilistic buckling load (composite truss — mechanical and thermal loads (TC-BH) = top cold-bottom hot; (TH-BC) = top hot-bottom cold).

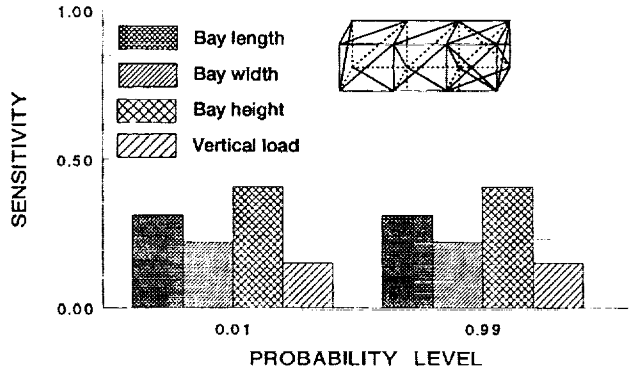

Figure 8.—Probabilistic buckling load sensitivities (composite truss - (mechanical and thermal loads; (top cold bottom hot).

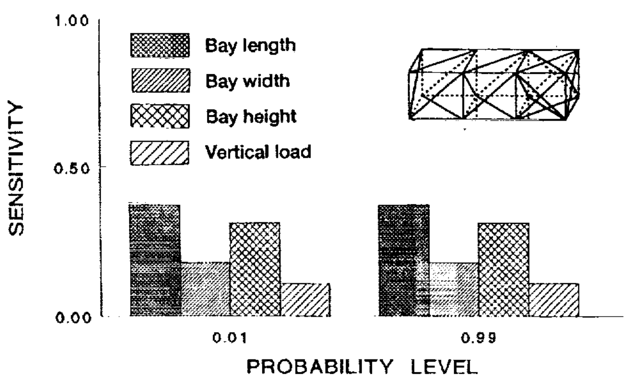

Figure 9.—Probabilistic buckling load sensitivities (composite truss — mechanical and thermal loads; (top hot-bottom cold)).

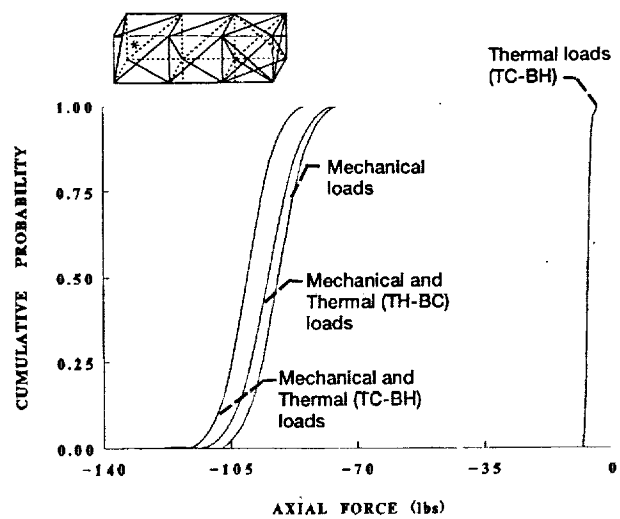

Figure 10.—Probabilistic member force (composite truss—mechanical and thermal loads; (TH-BC) = top hot-bottom cold; (TC-BH) = top cold-bottom hot).

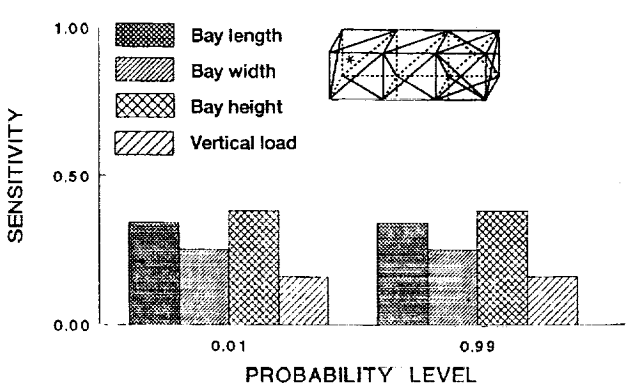

Figure 11.—Probabilistic member force sensitivities (composite truss —mechanical and thermal (top cold-bottom hot) loads; first-bay rear diagonal).

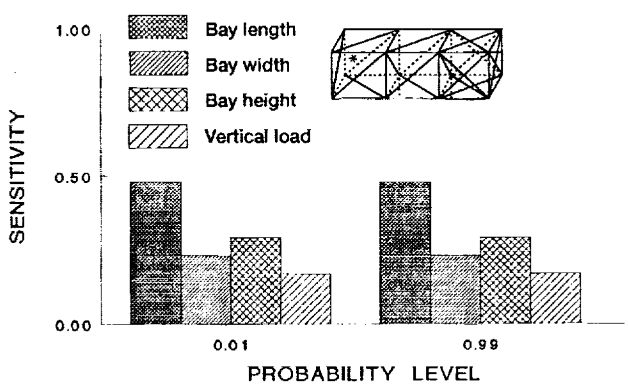

Figure 12.—Probabilistic member force sensitivities (composite truss —mechanical and thermal (top hot-bottom cold) loads; first-bay rear diagonal).

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

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