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Probabilistic Response of Truss-Type Space Structure with Joint and Member Imperfections

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A truss-type space structure having a special type of joint defect and member initial imperfection is analyzed to determine its deterministic and probabilistic response. The joint defect is created by considering only the global translation (but not the rotation) degrees of freedom of selected member end nodes—the same as those of the joint at which the member ends meet. The initial member imperfection is considered in terms of some members being initially bent or crooked into a sinusoidal shape. A finite element computational code, "Numerical Evaluation of Stochastic Structures under Stresses," of the NASA Lewis Research Center is used for the determination of the structural response. Results from the study include deterministic and probabilistic vibration frequencies, displacements, and buckling loads. Cumulative probability levels and sensitivity factors are obtained for these responses to delineate the effects on them of random changes in certain geometric, loading, and material design parameters. Results from both the deterministic and probabilistic studies show that the member-end connection defect has significant effects on vibration frequencies, especially the first mode. However, the deterministic results indicate that effects on displacements and buckling loads due to one end-connection defect are small. Larger numbers of member end connection (joint) defects, however, can have appreciable influence on the displacement. Initial member imperfections are observed to have small effects on the structural response. Results from the probabilistic analysis indicate that although overall cumulative probabilities of displacements and buckling loads change very slightly as a result of initial member imperfection, different sets of design variables show greater sensitivity than in the case of the joint defect.

Nomenclature

E_1	= modulus of elasticity of tubular members
F	= applied joint force vector
$F_Z(Z_0)$	= cumulative distribution function
$f_X(X)$	= joint probability density
$g, g(X)$	= limit state function [$g = Z(X) - Z_0 = 0$]
H1	= connection defect at node 39, member initial imperfection (out-of-straightness) with mean $\delta_0 = 0.00$
H2	= connection defect at node 39, member initial imperfection (out-of straightness) with mean $\delta_0 = 0.003L$
H28	= connection defect at node 28
H39	= connection defect at node 39
IR_1	= inner radius of tubular member
$[K]$	= stiffness matrix
$[K_g]$	= geometric stiffness matrix
L	= length of a member
$[M]$	= mass matrix
O0	= no connection defect; no member initial imperfection (perfectly straight members)
O1	= no connection defect; member initial imperfection with mean $\delta_0 = 0.00$
O2	= no connection defect; member initial imperfection with mean $\delta_0 = 0.003L$
O/I	= no connection defect; imperfect members (initially bent, $\delta_0 = 0.003L$)
O/P	= no connection defect; perfectly straight members
OR_1	= outer radius of tubular members
P_{28}	= load at joint 10 in X (vertical) direction
p_f	= probability of failure
U_{in}, U_{jn}	= translation degrees of freedom of master node i and slave node j along global direction n (X, Y, or Z)
u	= displacement vector (global degrees of freedom)
$\ddot{u}$	= acceleration vector
X, Y, Z	= global coordinate axes
X_i	= random design variables ($i = 1, \dots, n$)
$X1$	= X coordinate of the midpoint of member 1 (between joints 1 and 2)
$X4$	= X coordinate of the midpoint of member 4 (between joints 1 and 10)
$X17$	= X coordinate of the midpoint of member 17 (between joints 4 and 14)
$X18$	= X coordinate of the midpoint of member 18 (between joints 4 and 6)
$X29$	= X coordinate of the mid-point of member 29 (between joints 9 and 10)
X/I	= X displacement, imperfect members ($\delta_0 = 0.003L$)
X/P	= X displacement, perfect members (initially straight members)
Y/I	= Y displacement, imperfect members ($\delta_0 = 0.003L$)
Y/P	= Y displacement, perfect members (initially straight)
Z/I	= Z displacement, imperfect members ($\delta_0 = 0.003L$)
Z/P	= Z displacement, perfect members (initially straight)
Z_0	= value of random performance/response function $Z(x)$
$Z(X)$	= performance or response function in probabilistic analysis
α_i	= probability/reliability sensitivity factors
δ	= initial displacement of a point in a member at a distance x measured along the length from one end of the member
δ_0	= initial displacement of the midpoint of a member
Θ_{in}, Θ_{jn}	= rotation degrees of freedom of master node i and slave node j about global coordinate axis n (X, Y, or Z)

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λ = buckling eigenvalue
μ_i = mean value of random variable X_i
σ_i = normal standard deviation of random variable X_i
ϕ = mode shape vector
Ω = failure region
ω = circular vibration frequency

Introduction

SPACE environments, in which a space structure must function, are not yet completely understood. In addition, a space structure may be subjected to changes in its original design parameters due to several unanticipated causes. These factors may include fabrication and construction errors, transportation and storage environments, differences between construction (field) and fabrication (shop) environments, material defects, liftoff forces, and extreme temperature changes. These factors may create defects in joints and change the geometric configuration of the members. These defects can cause sudden member failure of a truss-type structure and may give rise to progressive failure of members. The member failure in turn can greatly influence the response of the structure.[1,2] Therefore, a design based on the deterministic approach alone cannot be completely justified for structures to be built or deployed in space. Usually such a design is overly conservative. Considering the high cost of material transportation to space, such design practice may not be justified in terms of economy, especially for large-scale construction as envisioned for the future. At the same time, the safety of the structure under unforeseen variations of loadings and other space environmental factors must not be sacrificed. For these reasons, probability-based structural analysis is desirable.

This paper presents results obtained from deterministic and probabilistic studies of a truss-like (frame) space structure having member-end connection (joint) defects and initial member imperfections (crookedness). The analyses were performed using the NASA Lewis Research Center (LeRC) special finite element code, Numerical Evaluation of Stochastic Structures under Stresses (NESSUS). Variations in joint loads, material properties, and member dimensions are considered. However, the major contribution of this paper is the inclusion of the joint defects and initial member imperfections in the probabilistic analysis. The structural responses of main interest include natural vibration frequencies, static displacements, member forces, and buckling eigenvalues. Cumulative probability levels and sensitivity factors are obtained for these responses.

Analysis Methodology

The NESSUS finite element code is designed initially for probabilistic analysis of complex engine components using continuum-type finite elements, such as beams and plates.[3] An overview of the code can be found in Ref. 4. The NESSUS code uses a three-field mixed formulation and uses iterative perturbation algorithms in probabilistic finite element analysis.[5,6] The probabilistic analysis capability of the code has been enhanced with the addition of modern techniques and the demonstration of the use of the code for various complex structures.[7–10] In recent years, the use of the code has been demonstrated on discrete (i.e., truss-type) space structures.[11,12] The code also has provision for the traditional displacement (stiffness) method. That method was selected for this study. Response parameters, such as displacements, stresses, and forces, are computed at each nodal point. The displacements are determined in the global coordinates, whereas the forces and moments are given in the local coordinates. A linear isoparametric tapered beam element based on the Timoshenko beam equation, which includes shear deformation, is used to model the members of the space frame structure. The code uses a linear interpolation function in the finite element formulation.

For a static analysis, the equation of equilibrium in matrix form can be expressed as

$$[K]\boldsymbol{u} = \boldsymbol{F} \tag{1}$$

Solution of this equation gives the nodal displacements, from which the stresses and member forces are computed.

For a linear elastic structure, the buckling eigenvalues can be determined by solving the following equation:

$$([K] - \lambda[K_g])\boldsymbol{\phi} = \boldsymbol{0} \tag{2}$$

Natural frequencies of vibration of a structure are determined from the equation of motion of undamped free vibration:

$$[M]\ddot{\boldsymbol{u}} + [K]\boldsymbol{u} = \boldsymbol{0} \tag{3}$$

Considering the response to be sinusoidal in nature, the above equation of motion can be reduced to

$$([K] - \omega^2[M])\boldsymbol{\phi} = \boldsymbol{0} \tag{4}$$

In the NESSUS finite element code the eigenvalue problem [Eqs. (2) and (4)] is solved using the subspace iteration procedure.

Special Member-Connection (Joint) Defects

In the present study, a perfect joint is one that has full moment-carrying and -transmitting capability. If at a connection (joint) several nodes meet and if all of them are to share the same global displacement (translation and rotational) degrees of freedom, they are constrained using the "duplicate" node option. In this option one node is considered the "master" (main) node, and all other nodes meeting at the joint are considered duplicate to this node ("slave" nodes). Duplicate nodes resolve ambiguities resulting from the geometric or material discontinuities and do not increase the size of the stiffness matrix. In the present study, a special connection defect is created at selected joints by considering a node to have only the global translation degrees of freedom tied to the corresponding degrees of freedom of the master node of the joint using the "tying" option (Fig. 1a). That is,

$$U_{jn} = U_{in}, \qquad \Theta_{jn} \neq \Theta_{in} \tag{5}$$

All other member ends (nodes) meeting at the particular joint are connected with the master node by the "duplicate" option. The constraint equation (5) ensures that the member-end node that is defective has the same value of the translation in a particular global direction as that of the corresponding translation of the joint (or of other nodes that meet at the joint). However, the rotation degrees of freedom of the defective node do not have the same value as the corresponding rotation of the joint. Effectively, a hinge is created. Thus, this process results in additional kinematic degrees of freedom. Causes for such joint defects may include fabrication and construction errors, material defects, and accidents.

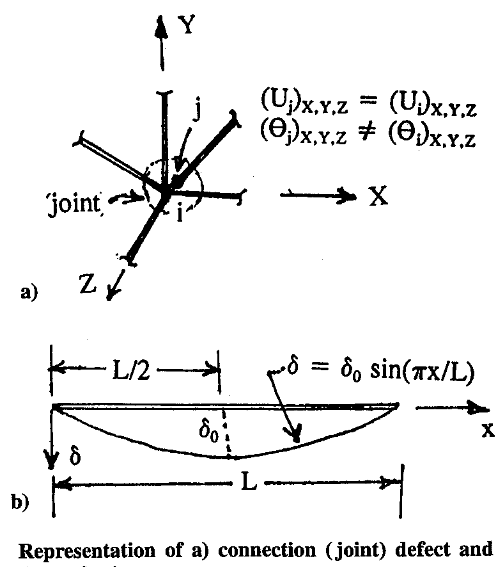

Fig. 1 Representation of a) connection (joint) defect and b) initial member imperfection.

Initial Member Imperfection

The initial member imperfection is considered in terms of some members being initially bent or crooked. The initial bent shape of members is taken to be sinusoidal (Fig. 1b):

$$\delta = \delta_0 \sin(\pi x/L) \tag{6}$$

In practice, initial crookedness can arise for numerous reasons, including fabrication and construction errors, poor workmanship, and less than ideal transportation and storage facilities.

Probabilistic Concepts

The basic probabilistic concept as utilized in the NESSUS finite element code is presented below in brief. A detailed description of this material can be found elsewhere.[6–10,13]

Performance and Limit State Functions

A performance or response function (Z function)—e.g., for displacements, stresses, or frequencies—of a structural system with random variables is written as

$$Z(X) = Z(X_1, X_2, X_3, \ldots, X_n) \tag{7}$$

where $Z(X)$ is the performance or response function, and X_i ($i = 1, \ldots, n$) are random design/input variables. The limit state function g is defined as

$$g = Z(X) - Z_0 = 0 \tag{8}$$

where Z_0 is a value of random variable $Z(X)$. In structural reliability analysis, $[g < 0]$ defines the failure region and $[g \geq 0]$ defines the safe region. The probability of failure, p_f, is given by

$$p_f = \text{Prob}[g \leq 0] = \int \cdots \int_{\Omega} f_X(X)\, \mathrm{d}X \tag{9}$$

Cumulative Distribution Function

The cumulative distribution function (CDF) of $Z(X)$ can be defined by[13–16]

$$\text{Prob}[Z(X) < z_0] = F_Z(z_0) = \int_{Z<z_0} f_x(x)\, \mathrm{d}x \tag{10}$$

where z_0 is a value of the random performance (response) function $Z(X)$. Thus, the CDF of Z at Z_0 is equal to the probability that $g < 0$ [i.e., the probability of failure, p_f, Eq. (9)]. The multiple integral equation (9) or (10) is extremely difficult to evaluate in general. The method of the fast probability integration (FPI), available in NESSUS, is used for the present analysis.

Mean-Based Method

The option based on the mean-value first-order method of the NESSUS code is utilized for the probabilistic structural analysis. For a smooth Z function, the Taylor's series expansion at the mean value μ gives (ignoring the higher-order terms)

$$\begin{aligned} Z(X) &= Z(\mu) + \sum \frac{\partial Z(X)}{\partial X_i}(X_i - \mu_i) \\ &= a_0 + \sum a_i X_i \end{aligned} \tag{11}$$

Several methods are available[16] to obtain a_i. The NESSUS code makes use of iterative perturbation algorithms to compute the Z function around an X and uses the solution to determine a_i using the least-squares procedure.[5]

In the mean-value first-order method, the mean and standard deviation of the performance function Z are approximated by

$$\mu_Z = a_0 + \sum a_i \mu_i \tag{12}$$

$$\sigma_z^2 = \sum a_i^2 \sigma_i^2 \tag{13}$$

Knowing the coefficients a_i, these two statistical moments can be readily computed.

Sensitivity Analysis

The commonly used sensitivity in deterministic engineering analysis is the performance sensitivity, which measures the change in the performance $Z(X)$ due to the change in a design parameter X_i, i.e., $\partial Z(X)/\partial X_i$. In probabilistic analysis, a more direct sensitivity measure is the probability (reliability) sensitivity, which measures the change in the probability (reliability) relative to the distribution parameters such as the mean and the standard deviation. A more important probability (reliability) sensitivity analysis is the determination of the relative importance of the random variables. The probabilistic sensitivity factors are dependent[13–16] on both the deterministic performance sensitivity $\partial Z(X)/\partial X_i$ and the uncertainty characterized by the normal standard deviation σ_i. That is,

$$|\alpha_i| \propto \left(\frac{\partial g(X)}{\partial X_i}\right)_{x^*} \sigma_i \tag{14}$$

where x^* is the value of the design variables X at the most probable point.

Having presented some basic parameters and terminologies involved in the NESSUS code, an outline of the probabilistic analysis solution procedure pertinent to this work is now presented:

1) First, the limit state (performance) function is approximated using a small number of response functions evaluated at and around the mean values of random variables. For each perturbation, the random variables and the corresponding response values are input to the FPI technique. The response sensitivities $\partial Z(X)/\partial X_i$ of each random variable with respect to the mean values are computed. The finite element method available in NESSUS is used. Nessus uses perturbation algorithms to determine sensitivities efficiently.[5]

2) A first-order fit to the response surface about the mean values [Eq. (11)] is established, using the sensitivities determined above.

3) The mean-value solution is obtained. The design points, or most probable points (MPPs), of the random variables at any desired probability or response level are evaluated using the FPI algorithm.[6,13] The FPI algorithm begins by using the first-order reliability method to identify the approximate location of the MPP, which is defined as the minimum distance between the origin of the joint probability density function and the failure surface in the transformed standard normal coordinate system (u space). The failure surface is next approximated using a quadratic polynomial and then transformed to linear. All nonnormal random variables are estimated as three-parameter normals. The integration (10) is now carried out readily, and thus the CDF is determined.

4) The FPI analysis also produces the probability sensitivity factors (14), which express the relative importance of the random variables at each point at which the CDF is computed. This is a useful feature of FPI.

Application

Structural Model

A preliminary design configuration of the NASA LeRC short-spacer truss is shown in Fig. 2. Except for the three end support members that meet at joints 3, 8, and 13, all members of the structure are circular tubes with outer radius equal to 1.25 in. and inner radius equal to 1.05 in. The members are made of aluminum (modulus of elasticity, $E = 9.90 \times 10^3$ ksi; Poisson's ratio, $\nu = 0.3$). The three support members are solid-rod steel ($E = 29.4 \times 10^3$ ksi; $\nu = 0.29$). Two of the end rods (members between nodes 3 and 83 and between nodes 13 and 85) have radii equal to 1.62 in. each, and the third one (member between nodes 8 and 87) has a radius equal to 1.498 in. Direct forces are applied at all joints and at three intermediate nodes in each of the tubular members. Loads are applied in all three directions. Their magnitudes vary from 1.334 to 307.8 lb. Additional concentrated masses are applied at each joint. Joints 1 through 14 have additional concentrated masses equal to 0.017024 lbf · s²/in. on each. End-support nodes 83, 85, and 87 have masses 0.023848, 0.02348, and 0.018985 lbf · s²/in., respectively. Intermediate nodes 335 (between joint 3 and node 85) and 337 (between joint 13 and 85) have an additional mass of 0.087124 lbf · s²/in., each. The structure is pin-supported at nodes 83, 85,

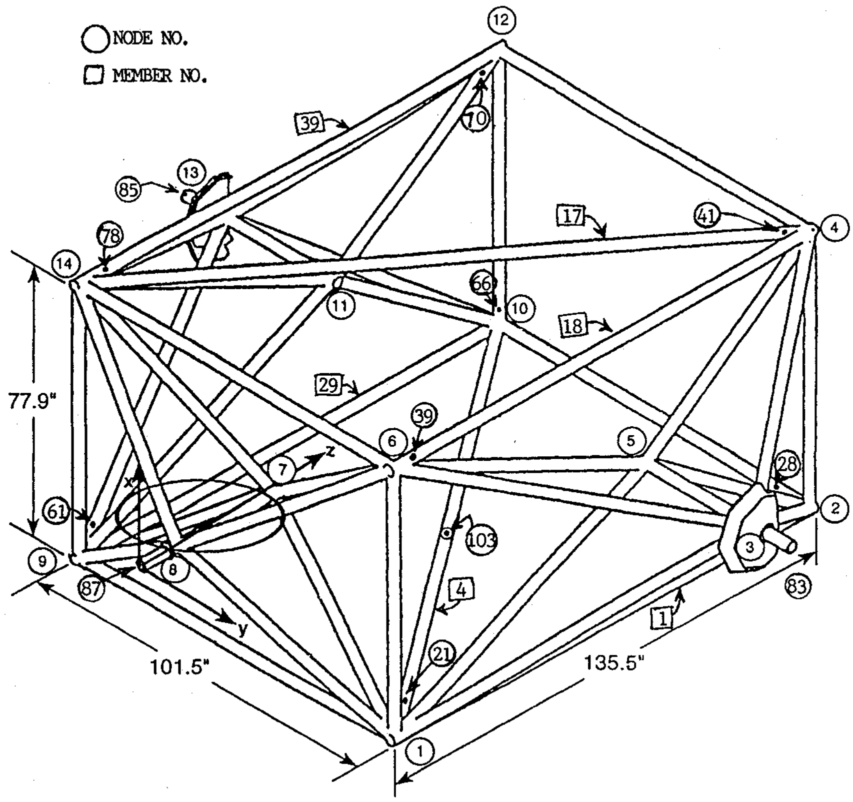

Fig. 2 Preliminary configuration of short-spacer truss.

and 87, in such a way that these nodes are free to translate along the Y direction at nodes 83 and 85 and along the Z direction at node 87.

Joint Defects

The special joint defect is created by making the rotation degrees of freedom of some slave nodes (ends of some members) independent of the master node at a joint. For such nodes, the translation degrees of freedom are tied one-to-one with those of the master node of the joint according to the constraint relation (5). The number of nodes where the end-connection defects are created varies from 1 to 8 (nodes 21, 28, 39, 41, 61, 66, 70, and 78) for the deterministic analysis. These nodes are shown in Fig. 2. For the probabilistic analysis results were obtained only for the connection defect at node 39, the end of member 18 connected to joint 6.

Member Imperfection

Six members (the members between joints 1 and 2, 1 and 10, 9 and 10, 4 and 6, 4 and 14, and 12 and 14; Fig. 2) are considered to have initial crookedness in the X direction (direction of maximum static-deterministic displacement) with a sinusoidal form. Some members are curved up ($+X$ direction) and some down ($-X$ direction), to get the lowest first vibration frequency. The initial stress-free deformed shape is taken to be a sinusoidal curve. The initial displacement δ_0 of the midlength point of each member measured from the straight position is taken to be 0.3% of the length of the corresponding member. For the probabilistic analysis, this value is taken as the mean value. A mean value of zero for the initial member midpoint displacement δ_0 is also considered for the probabilistic analysis.

Random Input Variables

For the probabilistic analysis, 54 random primitive variables are selected: 1) moduli of elasticity of the tubular aluminum and solid steel members (2 variables); 2) inner and outer radii of the tubular members (2 variables); 3) radii of the solid rods (2 variables); 4) X, Y, and Z loads at the fourteen joints (42 variables); and 5) member initial imperfections (6 variables). All variables are considered to have normal distributions. The mean values, standard deviations, and perturbations provided for these random variables for the probabilistic analysis are shown in Table 1.

Results

The response of the structure in terms of deterministic and probabilistic vibration frequencies, static displacements, member forces, and buckling eigenvalues was obtained. Some representative results are presented and discussed below.

Deterministic Response

Some deterministic results are presented in Figs. 3–5. Figures 3a and 3b show the effects of the special connection defects and initial member imperfections on the deterministic natural frequencies of the structure. It is observed that the first frequency is drastically affected by a single member connection defect (though this is a local-mode effect). It can also be seen that the same defect on different nodes (28 or 39) can have different amounts of effect on the frequency (Fig. 3a). The effect of the initial member imperfection on the vibration frequency is observed to be negligible. Figure 3b shows the effects of one member-end connection defect on the first ten natural vibration frequencies.

Figures 4a and 4b show that the X, Y, and Z displacements of node 103 (midpoint of member between joints 1 and 10) increase significantly as the number of member-end connection defects reaches five for a structure with perfectly straight members (curve X/P). The same is true for the structure with the six members initially bent with midpoint displacement $0.003L$ (curve X/I). There is only a slight effect due to the member imperfections. Figure 5 shows that formation of the special connection defect at node 39 results in some decrease in the first buckling eigenvalue. The effect on the buckling load of a joint defect at node 28 is negligible. The effect of the initial member imperfections on the buckling eigenvalue is observed to be small.

Probabilistic Response

Some representative results from the probabilistic analysis are presented in Figs. 6–8. Figures 6a–6d present the first vibration frequency, Figs. 7a–7d the vertical (X) displacement of node 103, and Figs. 8a–8d the first buckling eigenvalue. These results include

Table 1 Mean values, standard deviations, and perturbations for random input variables

Random variables X_i		Distribution type	Mean value μ_i	Standard deviation σ_i	Perturbation[a] coefficient (+), C_{pert}
a) Material properties					
E_1 (tube)		Normal	9.9E06 psi	0.495E06 psi	0.50
E_2 (rod)		Normal	29.4E06 psi	1.470E06 psi	0.40
b) Member radii					
Tube:					
OR_1 (outer radius)		Normal	1.25 in.	0.0625 in.	0.75
IR_1 (inner radius)		Normal	1.05 in.	0.0525 in.	1.25
Solid rod:					
R_1 (rod 1)		Normal	1.498 in.	0.0749 in.	0.85
R_2 (rod 2)		Normal	1.620 in.	0.0810 in.	1.20
c) Member initial deflection (X coordinate)					
i) For mean value of $\delta_0 = 0.0$					
Node no.	Member no.				
89	1	Normal	−38.950 in.	3.895 in.	0.10
103	4	Normal	−38.950 in.	3.895 in.	0.10
143	29	Normal	−38.950 in.	3.895 in.	0.10
121	18	Normal	38.950 in.	3.895 in.	0.10
125	17	Normal	38.950 in.	3.895 in.	0.10
165	39	Normal	38.950 in.	3.895 in.	0.10
ii) For mean value of $\delta_0 = 0.003$ (member length)					
Node no.	Member no.				
89	1	Normal	−39.3565 in.	3.895 in.	0.10
103	4	Normal	−38.4420 in.	3.895 in.	0.10
143	29	Normal	−39.3565 in.	3.895 in.	0.10
121	18	Normal	38.3565 in.	3.895 in.	0.10
125	17	Normal	38.4420 in.	3.895 in.	0.10
165	39	Normal	39.3565 in.	3.895 in.	0.10
d) Applied joint loads					
Node no.	Direction				
1	X	Normal	140.60 lb	7.0300 lb	0.80
	Y	Normal	46.88 lb	2.3440 lb	1.30
	Z	Normal	140.60 lb	7.0300 lb	1.50
2	X	Normal	98.51 lb	4.9250 lb	1.00
	Y	Normal	32.84 lb	8.2100 lb	0.50
	Z	Normal	98.51 lb	4.9255 lb	0.40
3	X	Normal	129.60 lb	6.4800 lb	0.75
	Y	Normal	43.20 lb	10.8025 lb	1.25
	Z	Normal	129.60 lb	6.4800 lb	0.85
4	X	Normal	118.70 lb	5.9350 lb	1.20
	Y	Normal	39.58 lb	1.9790 lb	0.80
	Z	Normal	118.70 lb	5.9350 lb	1.30
5	X	Normal	85.85 lb	4.2924 lb	1.50
	Y	Normal	28.62 lb	1.4310 lb	1.00
	Z	Normal	85.85 lb	4.2925 lb	0.50
6	X	Normal	120.40 lb	6.0200 lb	0.40
	Y	Normal	40.14 lb	2.0070 lb	0.75
	Z	Normal	120.40 lb	6.0200 lb	1.25
7	X	Normal	79.27 lb	3.9635 lb	0.85
	Y	Normal	26.42 lb	1.3210 lb	1.20
	Z	Normal	79.27 lb	3.9635 lb	0.80
8	X	Normal	105.80 lb	5.2900 lb	1.30
	Y	Normal	35.27 lb	1.7635 lb	1.50
	Z	Normal	105.80 lb	5.2900 lb	1.00
9	X	Normal	120.40 lb	6.0200 lb	0.50
	Y	Normal	40.14 lb	2.0070 lb	0.40
	Z	Normal	120.40 lb	6.0200 lb	0.75
10	X	Normal	118.70 lb	5.9350 lb	1.25
	Y	Normal	39.58 lb	1.9790 lb	0.85
	Z	Normal	118.70 lb	5.9350 lb	1.20
11	X	Normal	85.85 lb	4.2925 lb	0.80
	Y	Normal	28.62 lb	1.4310 lb	1.30
	Z	Normal	85.85 lb	4.2925 lb	1.50
12	X	Normal	98.51 lb	4.4925 lb	1.00
	Y	Normal	32.84 lb	1.6400 lb	0.50
	Z	Normal	98.51 lb	4.9255 lb	0.40
13	X	Normal	134.40 lb	6.7200 lb	0.75
	Y	Normal	44.79 lb	2.2395 lb	1.25
	Z	Normal	134.40 lb	6.7200 lb	0.85
14	X	Normal	140.60 lb	7.0300 lb	1.20
	Y	Normal	46.88 lb	2.3440 lb	0.80
	Z	Normal	140.60 lb	7.0300 lb	1.30

[a] $X_{i(\text{perturbed})} = \mu_i + C_{pert}\sigma_i$.

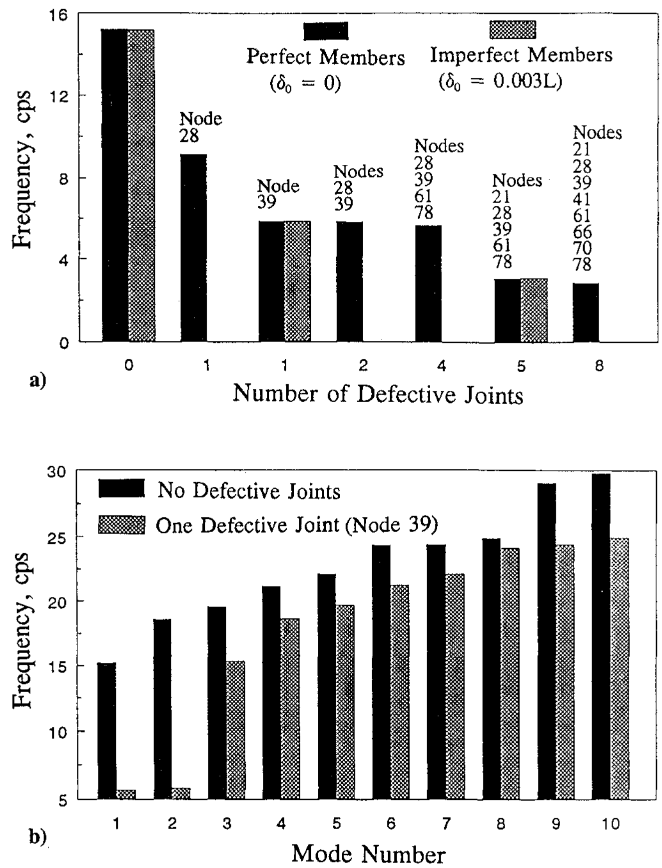

Fig. 3 Deterministic structural vibration frequencies: a) first structural frequency and b) first ten structural frequencies.

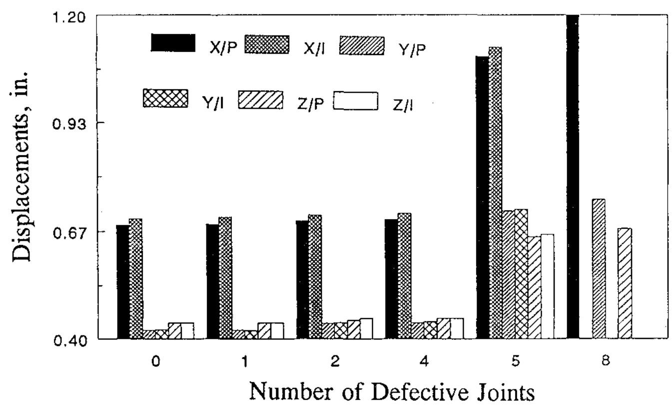

Fig. 4 Deterministic vertical (X) displacements (node 103).

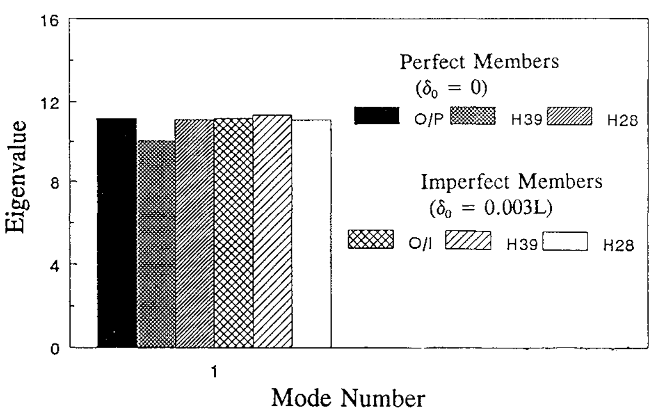

Fig. 5 Deterministic buckling loads (eigenvalue).

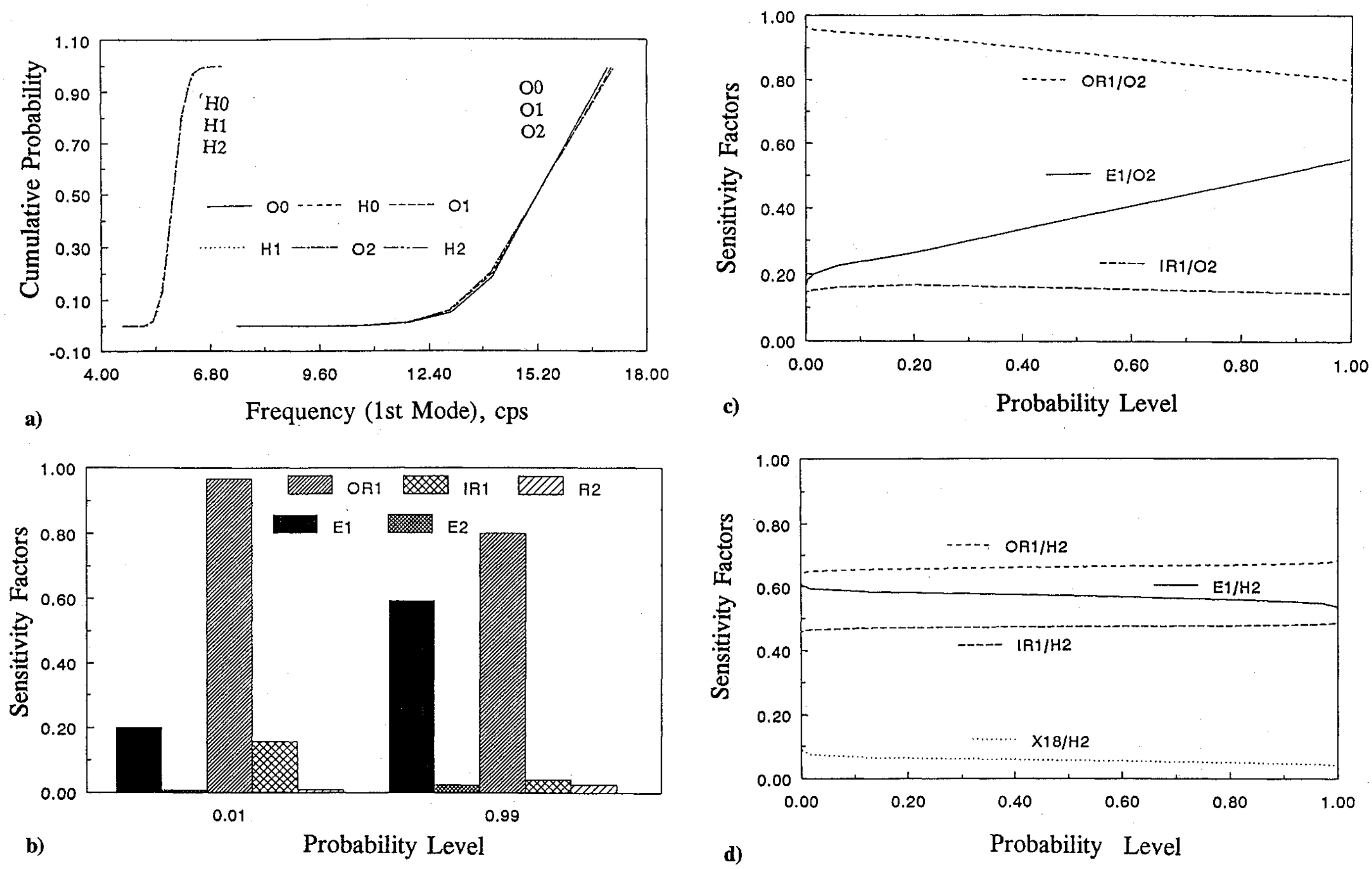

Fig. 6 Probabilistic structural vibration frequency (first mode): a) cumulative probability, b) sensitivity factors for structure with perfectly straight members and no joint defects, c) sensitivity factors for structure with initial member imperfections (mean $\delta_0 = 0.003L$), and d) sensitivity factors for structure with initial member imperfections (mean $\delta_0 = 0.003L$) and connection defect (node 39).

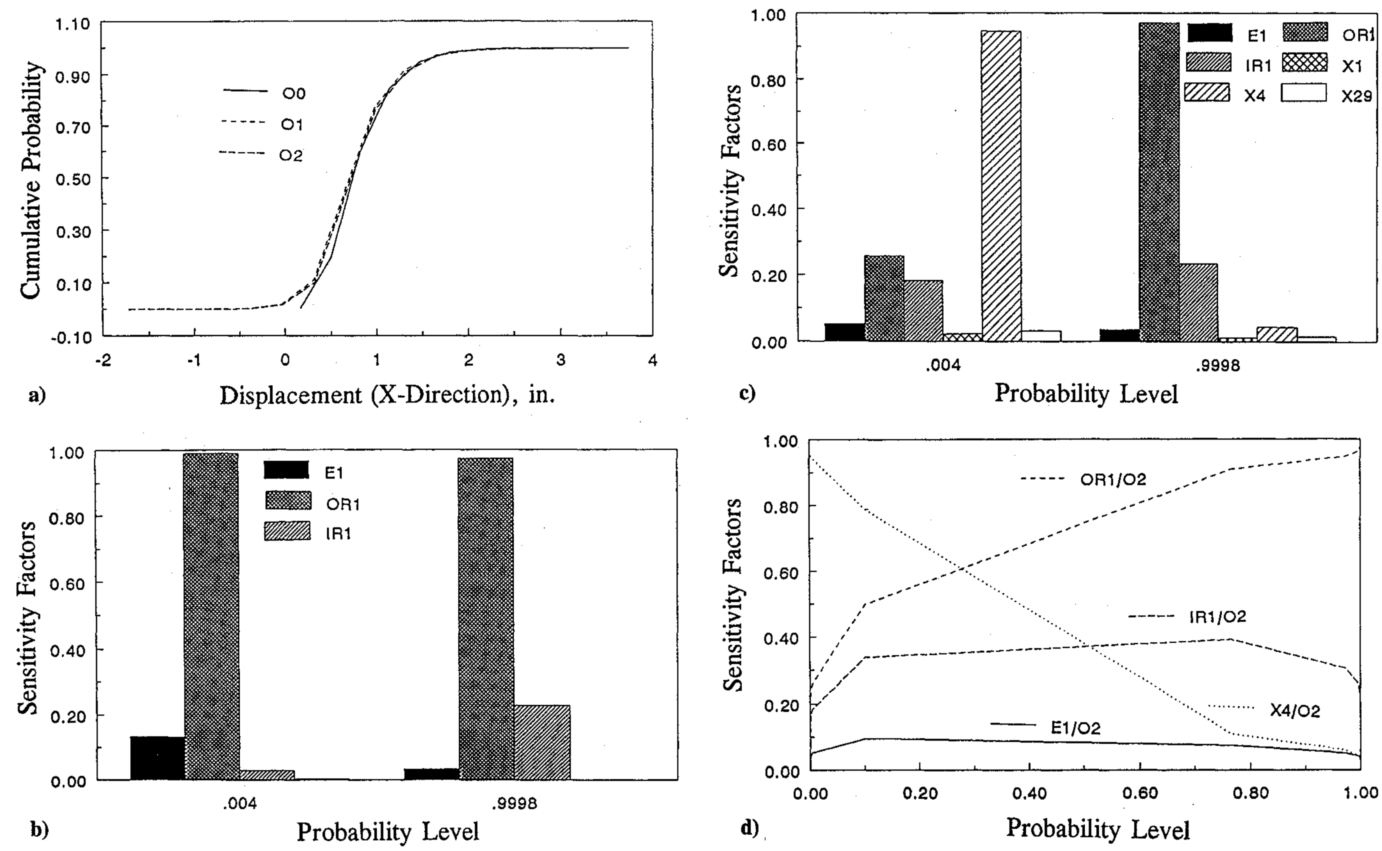

Fig. 7 Probabilistic vertical (X) displacements (node 103): a) cumulative probability, b) sensitivity factors for structure with perfectly straight members and no joint defects, c) sensitivity factors for structure with initial member imperfections (mean $\delta_0 = 0.003L$): bar graph, and d) sensitivity factors for structure with initial member imperfections (mean $\delta_0 = 0.003L$): line graph.

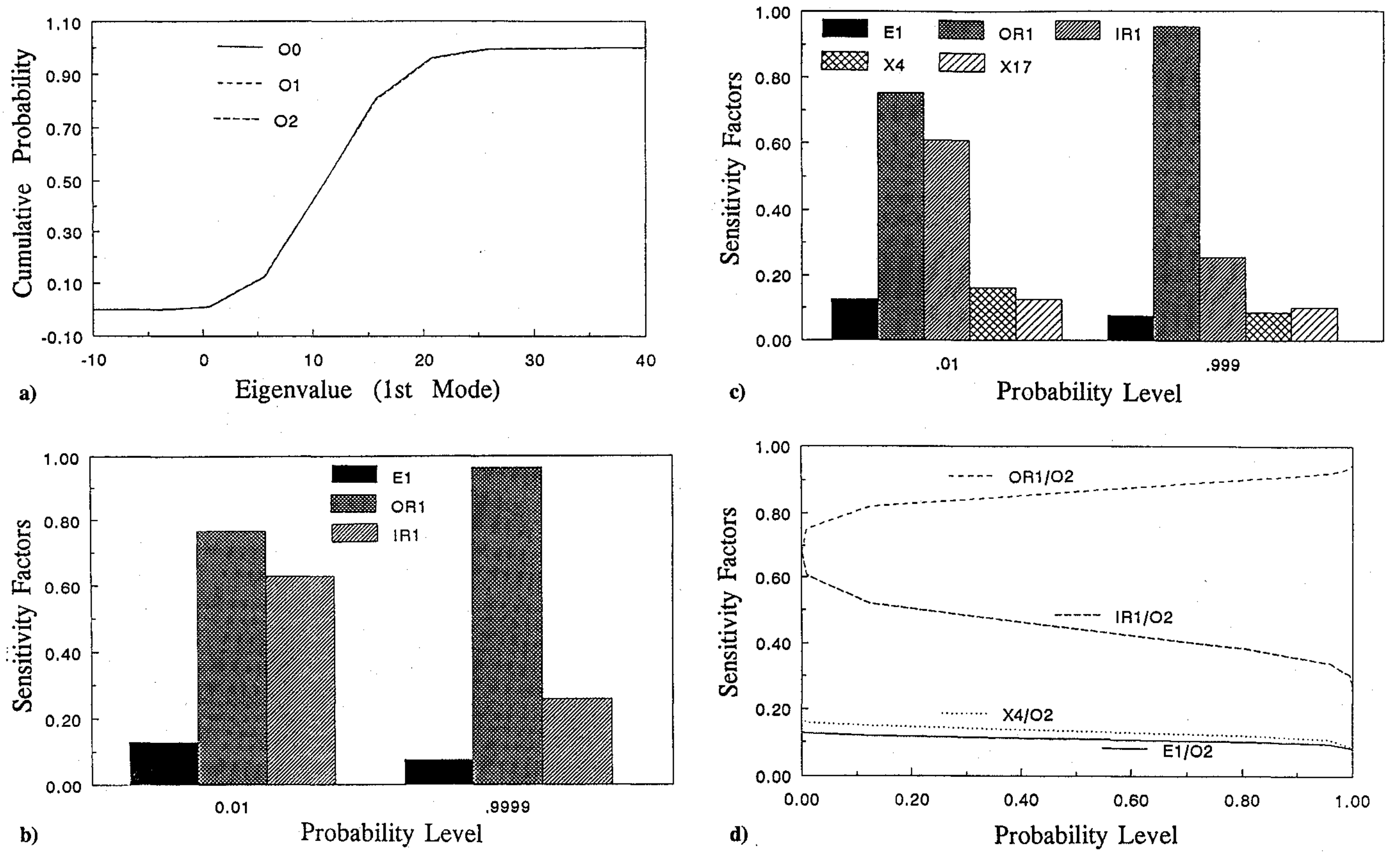

Fig. 8 Probabilistic buckling loads (first eigenvalue): a) cumulative probability, b) sensitivity factors for structure with perfectly straight members and no joint defects, c) sensitivity factors for structure with initial member imperfections (mean $\delta_0 = 0.003L$): bar graph, and d) sensitivity factors for structure with initial member imperfections (mean $\delta_0 = 0.003L$): line graph.

the cumulative probability values as well as sensitivity factors. Figure 6a shows that although formation of a single member-end connection defect affects the cumulative probability of the first frequency drastically (compare between curves O0 and H0, O1 and H1, and O2 and H2), the various amounts of initial member imperfection seem to have very little effect on this parameter (compare between the curves labeled O0, O1, O2 and the curves labelled H0, H1, H2). Figures 6b and 6c show that there is very little effect on the sensitivity factors due to the initial member imperfections. When the structure contains no member-end connection defect but contains members with initial imperfections, the modulus of elasticity and outer radii of the tubular members have significant effects on the probability levels (Fig. 6c). On the other hand, when the structure also has member-end node 39 defective, none of the primitive design variables (e.g., the modulus of elasticity, outer radius, and inner radius of the tubular members) seem to have any sensitivity, i.e., they remain approximately constant throughout the probability levels 0 to 1 (Fig. 6d).

Figure 7a shows the cumulative probability versus X (vertical) displacement. It can be observed that the effects of the various amounts of initial member imperfections [no initial imperfection (curve O0), and mean value of the midpoint displacement δ_0 equal to 0.00 (curve O1) and $0.003L$ (curve O2)] are not significant. Figure 7b shows that when the structure does not have any connection defects or initial member imperfections, the displacement is most sensitive to the outer radius (OR_1) of the tubular member. On the other hand when the structure has initial member imperfections, the initial imperfection ($X4$) of member 4 is most influential at the lower probability level, whereas at the higher probability level it is the outer radius of the tubular members that is most influential (Fig. 7c). Figure 7d shows that the variations in the outer radius (OR_1) and the initial displacement of the midpoint of member 4 have significant effects on the X displacement of node 103.

Results presented in Fig. 8a indicate that the effects of various amounts of initial member imperfections are insignificant in changing the cumulative probability for the buckling loads. A comparison of Figs. 8b and 8c shows that the outer and inner radii, OR_1 and IR_1, respectively, of the tubular members are the most sensitive factors at probability levels of 0.01 and 0.999. These results are for both the structures, with or without initial member imperfections. In addition, for the structure with member initial imperfections, the initial imperfection in members 4 and 17 also has some influence on the buckling loads. It can also be observed from Fig. 8d that of all the design variables, only the outer and inner radii of the tubular structural members have noteworthy effects on the buckling loads (Fig. 8d).

Conclusion

The probabilistic and deterministic response of a space frame structure having special joint defects and member initial imperfections were investigated using the NESSUS finite element computational code of NASA LeRC. Results from the study included vibration frequencies, static displacements, and buckling eigenvalues. Cumulative probability levels and sensitivity factors were obtained for these response parameters to delineate the effects of the two special construction conditions on the response of the structures. The results indicate that even a small number of special member-end connection defects was found to have significant effects on vibration frequencies, especially the first mode. However, effects on displacements and buckling loads due to one end-connection defect were observed to be small. Larger numbers of member-end connection defects have appreciable influence on the displacement. An initial member imperfection was observed to have only a small effect on the cumulative probability of the response. However, the results show that for a structure with initial member imperfection, a set of design variables other than those for the structure with perfectly straight members have more influence on the response.

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