Effect of Degradation of Material Properties on the Dynamic Response of Large Space Structures

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The effect of degradation of material properties on structural frequencies and mode shapes of large space structures (LSS) is investigated herein. The difficulty and cost of maintenance of LSS require that these structures be designed to operate with a certain amount of load-induced damage. This damage is commonly observed in fibrous composite media. Sensitivity studies conducted on representative space truss structures indicate that degradation of material properties will result in a reduction of natural frequencies and may have significant effects on the structural mode shapes. For even small amounts of stiffness reduction (10%), nodal locations may change significantly. It is clear that these effects must be taken into consideration when designing control systems for large space structures.

Introduction

Due to economic constraints, it is projected that advanced, high strength-to-weight-ratio aerospace materials will be utilized in future-generation space structures. Such materials include polymer and metal-matrix fibrous composites, which are known to undergo a certain amount of load-induced damage.[1,2] These materials are also expected to undergo a certain amount of environmentally induced damage or degradation, thus resulting in significant stiffness losses.

Experimental research on advanced composite materials indicates that they may undergo up to a 15% stiffness loss due to thermomechanical fatigue, which causes a variety of damage modes (due to microcracking) in the structure. Additional loss of stiffness may be attributed to elevated temperature and chemical changes due to solar radiation and other enviromental effects. This reduction in stiffness affects the dynamic response, which in turn is critical in the development of control systems for large space structures (LSS). In this paper, sensitivity studies will be presented which investigate the effect of stiffness loss on structural frequencies and mode shapes.

The advent of the Space Shuttle has made possible the development of LSS. Control systems for stabilizing and maneuvering these very large space structures, especially those for precise pointing, will require extension of current technology.

Although large size by itself does not arouse concern, structural flexibility resulting from minimizing the structural weight may present problems. Extremely large structural flexibility may result in large amplitudes and low frequencies (0.01 = 10 Hz) which may create new complications for control designers.

As an example of the precision required,[3] a typical radiometry application may utilize a 200-m antenna with an effective beamwidth of 0.01 deg and have requirements limiting the vibratory beam shift to less than 0.005 deg and dynamic surface distortions to less than 1 mm. Maneuvering or maintaining the altitude of such a satellite leads to flexible body motion which must be well predicted and controlled.

The importance of interaction between control systems and vibratory response has caused considerable research in LSS control systems.[4-6] The current practice of guaranteeing a large separation between modal frequencies and the bandwidth of control will not be attainable in future applications. The combination of large size and payload-weight restrictions will drive structural frequencies down and the need for more accurate pointing will drive the control systems bandwidth up. When sufficient frequency separation becomes impossible, there exists a need for adaptive control systems. This leads to further research in the design of structural control systems actuator/sensor placement, and distributed sensing and actuation as opposed to colocated sensors and actuators.

Techniques for achieving modal control of LSS will require a more accurate knowledge of modal characteristics. Optimum sensor and actuator placement will be greatly influenced by modal effects that must be known to a greater degree of precision. The change in the modal response as a result of material damage will have an adverse impact on the active control of the LSS.

In order to investigate the possible effects of material degradation on the dynamic response of LSS, a representative space truss structure has been selected in the shape of a long boom as shown in Fig. 1. Using several loading histories, stress distributions have been obtained for each truss member. The resulting stress distributions can be used in a material damage model to define material degradation and resultant stiffness reductions. Using the reduced stiffness properties, modal analyses have been conducted on the structure to show the effect of material degradation on natural frequencies, mode shapes, and nodes. Details of the finite element model, material degradation model, and numerical results are presented below.

Model Description

Material Degradation Model

The process of ultimate failure of composite materials is preceded by a sequence of microstructural and macrostructural events, termed as damage. These events may be due to transverse cracking, delamination, fiber breaking, and fiber-matrix debonding.[1,2,7-11] The mechanical response of the structure is affected by this damage. Global material proper-

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ties such as stiffness and residual strength may be substantially altered during the life of the structural components.[1,2] Some of the analytical studies for modeling damage include a shear lag concept,[10] fracture-based concepts,[11] and internal state variable theories.[12-14] Although important progress has been made, current understanding of damage is not complete.

Damage in polymeric composites is modeled in this paper as a load history-dependent reduction in stiffness in each structural element. The internal state variable (ISV) theory is used for modeling mechanical behavior, and the stress-strain relationship is of the form,[12,13]

$$\sigma_{ij} = C'_{ijkl}\ (\epsilon_{kl} - \epsilon^T_{kl}) \tag{1}$$

In this case, the ISVs are assumed to be second-order tensor-valued and to enter only through the modulus tensor. C'_{ijkl} is the effective modulus tensor given by

$$C'_{ijkl} = C_{ijkl} - P^p_{mnklij}\alpha^p_{mn}, \qquad p = 1,\ldots,r \tag{2}$$

where α^p_{mn} are a set of r internal state variables[12] which are given by the ISV growth laws of the following general form:

$$\dot{\alpha}^p_{mn} = \Omega^p_{mn}(\epsilon_{kl}, T, \alpha^q_{kl}) \tag{3}$$

At low homologous temperatures these materials are assumed to be rate-insensitive so that the above model will result in quasielastic (rate-independent) equations in which inelasticity is reflected only through the slowly degrading modulus tensor. Experimental evidence[6,10] indicates that the time scale for degradation of C'_{ijkl} is very long compared to the frequencies and mode shapes of representative structures. Therefore, it is sufficient for many space structural applications to treat Eq. (1) in the degraded state only.

The stress-strain relationship for the truss elements is a one-dimensional approximation of Eq. (2) given by

$$\sigma_{xx} = E'\ (\epsilon_{xx} - \epsilon^T_{xx}) \tag{4}$$

where σ_{xx} and ϵ_{xx} are the uniaxial stress and strain, ϵ^T_{xx} the thermal strain, and E' the axial stiffness of the truss element given by

$$E' = E(1-\alpha) \tag{5}$$

where E is the undegraded axial stiffness and α a scalar valued parameter representing the integrated effect of all damage modes, such as matrix cracking, interlaminar fracture, fiber breakage, and fiber-matrix debonding. It should be emphasized that although E may be spatially constant, as the damage is induced as a function of the local stress, the effective modulus E' will vary spatially in the structure.

Experimental research on composite materials indicates a power-law degradation of axial stiffness as a function of stress history.[11,13] Hence, the damage ISV growth law is assumed to be of the form

$$\dot{\alpha} = k_1(\sigma/\sigma_{\max})^n \tag{6}$$

where k_1 and n are material parameters, $\sigma_{\max}$ the maximum stress in the structure, and σ the axial stress in each truss element. For a given stress amplitude, Eq. (6) may be integrated in time to give the following approximation (which is accurate for fixed stress amplitude and when n is large compared to unity)

$$\alpha(t_1) = k'_1[\sigma(t_1)/\sigma_{\max}]^{n'} \tag{7}$$

where k'_1 and n' are material parameters that may be time-dependent. The amount of reduction in the axial stiffness for the truss elements corresponding to their stress level is given by Eq. (7) with the maximum reduction occurring in the highest stressed element. This maximum reduction was set to a specified percentage of the undegraded stiffness in order to simulate the structure at various times in its life.

A power-law form of damage is used herein for simplicity and for an initial attempt at modeling the structural response with damage. In reality the damage laws will be more complex and are currently being developed for future work.[12]

Finite Element Model

Figure 1 illustrates the geometry of the representative space truss used to simulate an antenna boom. This structure is 60 ft long with 10 bays, 6 ft long and 3 ft wide. The finite element model has 124 space truss elements and 44 nodes. In the initial undegraded configuration, the material properties are the same for all members with the values as given in Table 1.

Each truss member is idealized with a standard six-degree-of-freedom truss element of constant cross section. Because the structure is idealized as linear with slowly varying material properties, conventional linear finite element methodology may be used to write global equations of equilibrium of the form[16,17]

$$[M]\{\ddot{q}\} + [K]\{q\} = \{Q\} \tag{8}$$

where $[M]$ is the mass matrix, $[K]$ the stiffness matrix, $\{q\}$ the nodal displacement vector, and $\{Q\}$the nodal force vector. The stiffness matrix $[K]$ is dependent on the spatially variable damage state α, which varies from element to element. Standard eigenvalue extraction may be performed; in this case, subspace iteration was used to obtain the first five frequencies and mode shapes.

Spatial Distribution of Degradation

The spatial distribution of degradation and stiffness reduction of LSS will be complex and dependent on loading and environmental history. For the present investigation, wherein material degradation is assumed to be a function of stress history, it was necessary to make some assumptions about the corresponding stress history and spatial distribution of stresses within the LSS.

Two approaches were used to obtain candidate stress histories/distributions for predicting the stiffness degradation. In one case, the stress distribution was obtained for an assumed thermal load history/distribution. Second, the stress distributions were obtained from the first two bending modes of the structure. After computing the mode shapes for the first two undegraded bending modes, the nodal displacements were used to compute corresponding stress distributions. The first two bending modes were used to obtain test stress histories and their effects on the mode shapes and frequencies due to stress-induced damage in each of these modes.

In each case, the degradation model given by Eq. (7) was then used to obtain degraded properties for each truss member assuming that the element with the highest stress level was degraded a specified percentage. The resultant structure with degraded properties had spatially variable stiffness that varied from element to element. Mode shapes and frequencies were then computed with varying maximum percentages of degraded properties. The above procedure, although approx-

Table 1 Material properties for undegraded structure

Material type	Graphite-epoxy (Hexel)
Young's modulus, E; psi,	21.5×10^6
Cross-sectional area, in.^{2}	1.0
Density, lb/in.^{3}	0.065
Coefficient of thermal expansion, in./in./°F	2×10^{-6}
Reference temperature, °F	89.6

imate in nature, is the only computationally feasible method for solving this problem for large-order systems, since time integration would require millions of time steps to produce hundreds of thousands of cycles of modal response.

Discussion of Results

Natural frequency and mode shape responses have been obtained for several stress-induced degradation test cases as described above for the representative space truss structure shown in Fig. 1. This particular truss structure geometry, representing a segment of a boom, is similar to ones being used for the space station.[15] Assuming the boom is fixed on one end (at $x=0$), the five lowest frequencies (for the virgin structure) are equal to 3.4, 4.5, 4.6, 19.2, and 20.3 Hz. The first mode is a combined torsion-inplane shear mode, the next two modes are bending modes about the z and y axes, respectively, and the fourth mode is a pure torsion mode.

The first case considers the boom structure shown in Fig. 1 with a thermal gradient over the cross section. It is likely that one surface of the space structure will become significantly hotter than the other surface due to solar heating, attitude of the structural elements, and shadowing effects. To investigate the effect of this thermal gradient through the truss depth, the stresses in each element were calculated by specifying a temperature of 122°F for the members on the top surface, 80.6°F for the members on the bottom surface, and 100°F for the diagonal members connecting the top and bottom surfaces. With this thermally induced stress distribution, the axial stiffness of each element was degraded using Eq. (7). The maximum level of degradation (loss of stiffness) was set to a

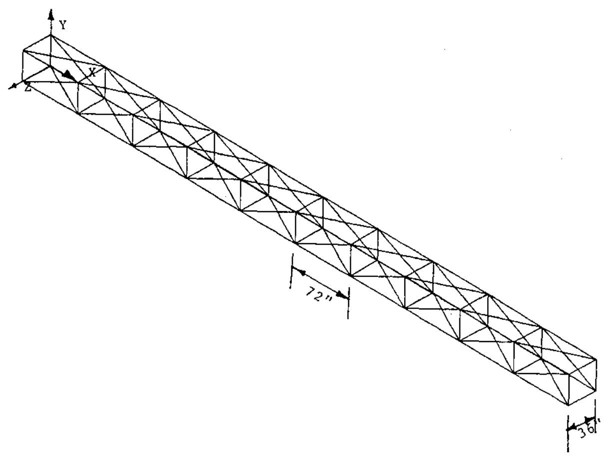

Fig. 1 Space truss structure.

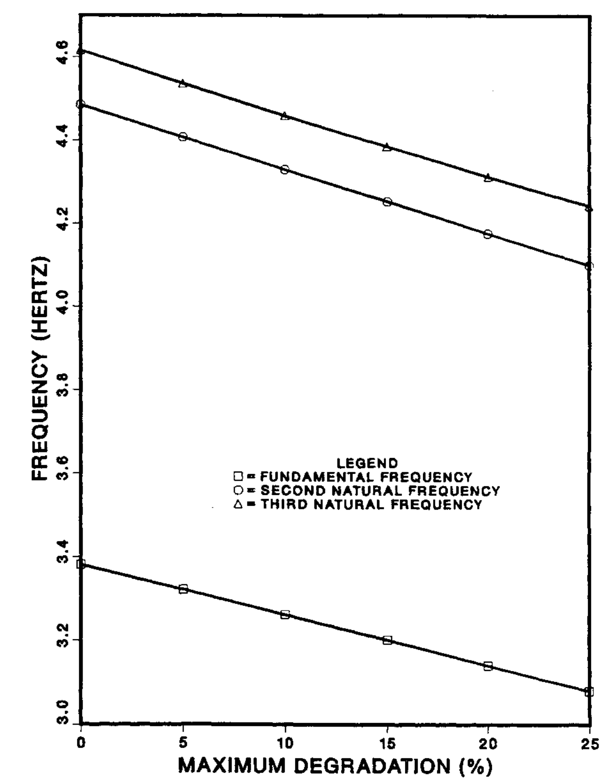

Fig. 2 Effect of damage on natural frequencies for thermal loading.

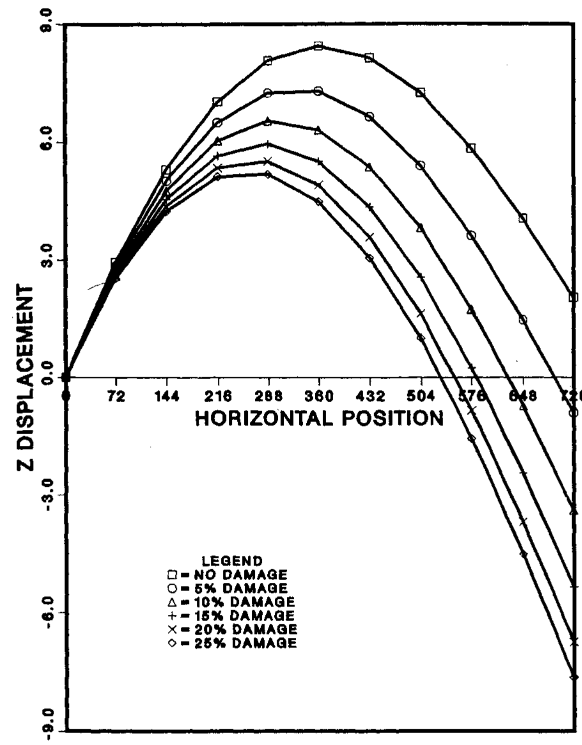

Fig. 3 Effect of degradation on second mode.

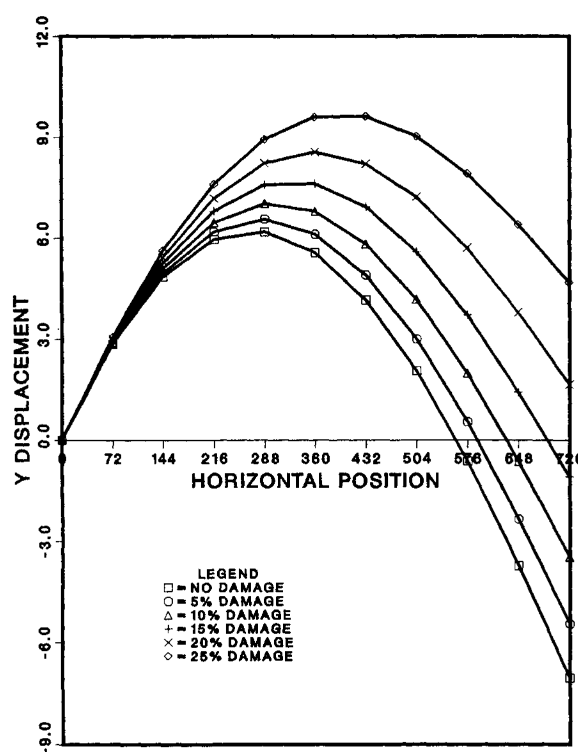

Fig. 4 Effect of degradation on third mode.

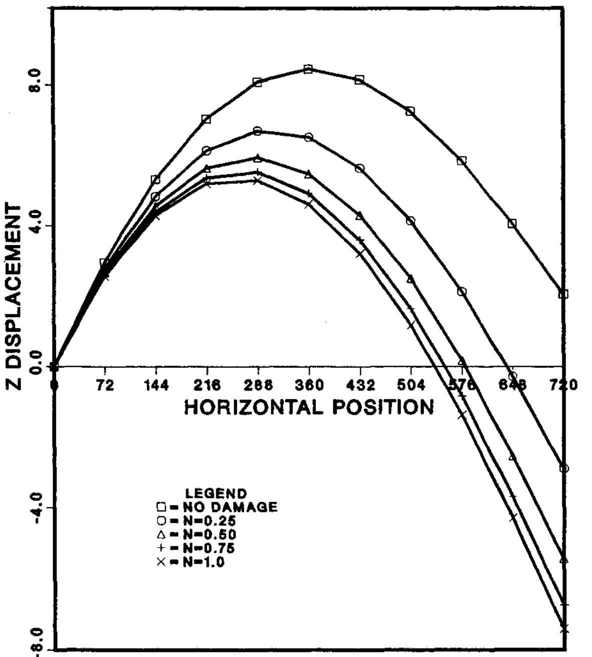

Fig. 5 Effect of material degradation exponent on second mode shape.

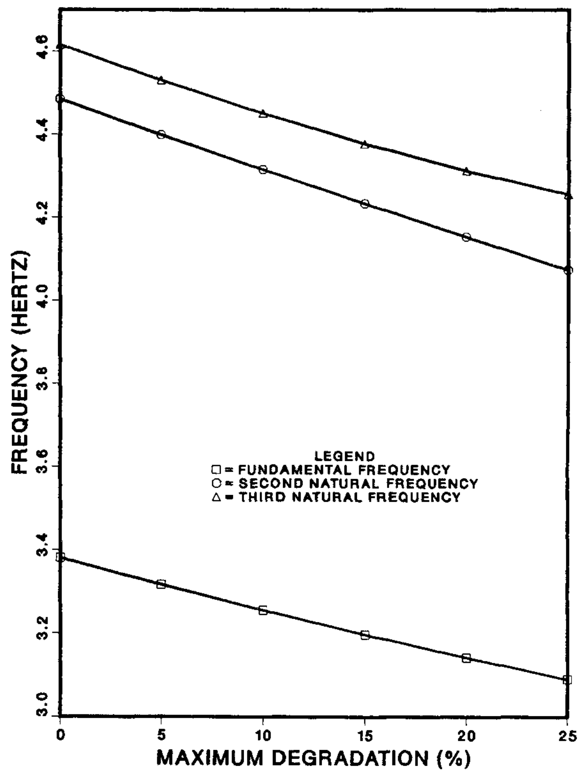

Fig. 6 Effect of damage on natural frequencies for second mode damage state.

prescribed percentage for the element with the highest stress, and remaining elements were degraded according to their stress level using Eq. (7). This procedure approximates the boom at various times in its structural life. The value of n' was assumed to be 0.75 in Eq. (7) (note that n' is not equivalent to n).

In Fig. 2 the first three natural frequencies are plotted for different levels of maximum damage. The effect of damage on the natural frequencies is clear. Increasing the level of damage reduces the stiffness of the space truss and, in turn, drives the

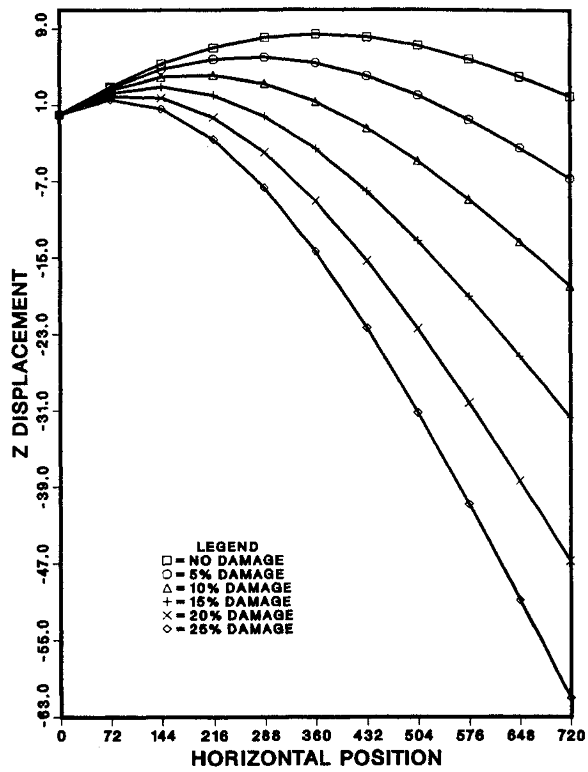

Fig. 7 Effect of degradation on second mode assuming second mode damage state.

natural frequencies down. For a maximum loss of 25% in axial stiffness (for the highest stressed members), the first three natural frequencies are reduced by about 8%. This reduction is due in large part to the spatial distribution of stiffness loss. Since mode shapes are important for designing the control systems of the large space structures, it is desirable that they be constant with time. Although it was found that there was no appreciable change in the first mode shape between the undegraded and degraded cases, higher modes were altered due to material degradation. Figure 3 is a plot of the z displacement for the second mode shape along the length of the space truss ($z=0$, $y=0$). Significant changes in the mode shape and node locations as a function of percent of degradation are observed. The sign of the modal displacement is reversed near the free edge for the degraded and undegraded cases and the location of the node (zero displacement) changes appreciably. Figure 4 is a similar plot of the y displacement along the space truss length for the third mode.

The value of n' in Eq. (7) was varied from 0.25 to 1.0 to study its effect on the mode shapes. It was found that the trend in mode shape changes was insensitive to the varying n'. Figure 5 illustrates this point. Here the z displacement for the second mode is plotted along the length of the space truss for different values of n' (maximum reduction in axial stiffness was 20%). The plot indicates that increasing n' (i.e., decreasing the nonlinearity of the degradation model) tends to increase the changes in the modal displacements. Such nonlinearity becomes increasingly important when stresses vary in a highly nonlinear fashion over the structure.

The next two sample cases consider the situation wherein it is assumed that primary degradation occurs in the first two bending modes. In the first case, we consider that the degradation has occurred in the first bending mode, i.e., degradation is based on stresses calculated from the modal displacements corresponding to the second mode shape. Figure 6 shows the resulting first three natural frequencies for different levels of damage. For a 25% maximum stiffness reduction, the first three natural frequencies decrease by 8.6, 9.2, and 7.6%, respectively. There is little change in the first mode shape for

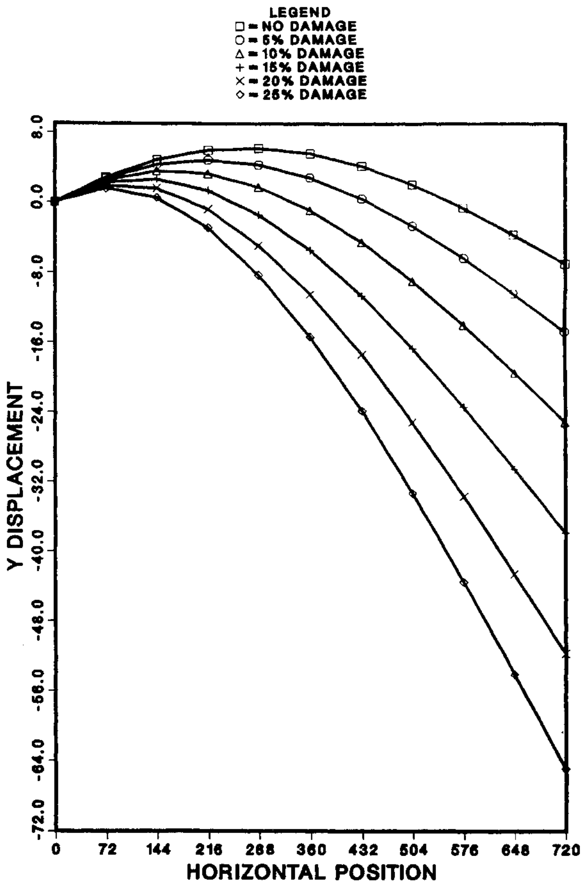

Fig. 8 Effect of degradation on third mode assuming second mode damage state.

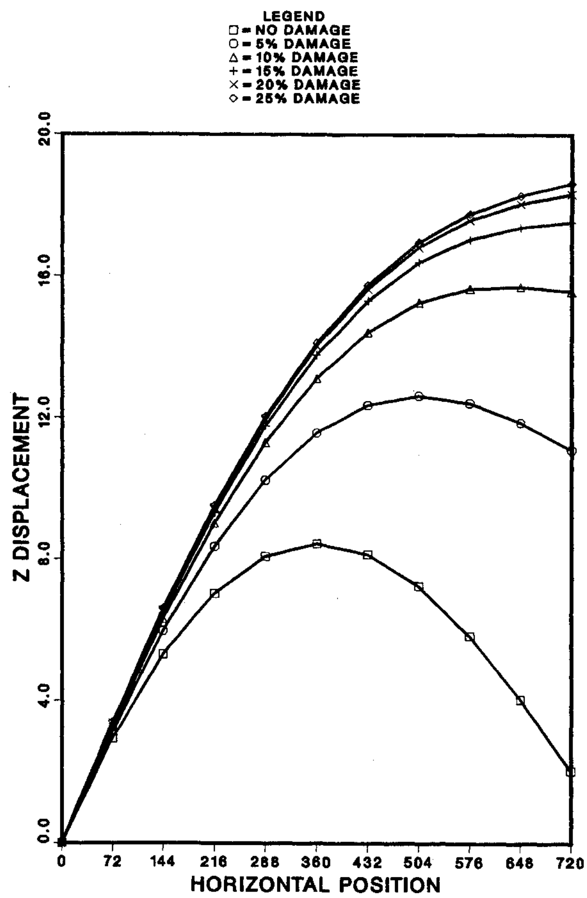

Fig. 9 Effect of degradation on second mode assuming third mode damage state.

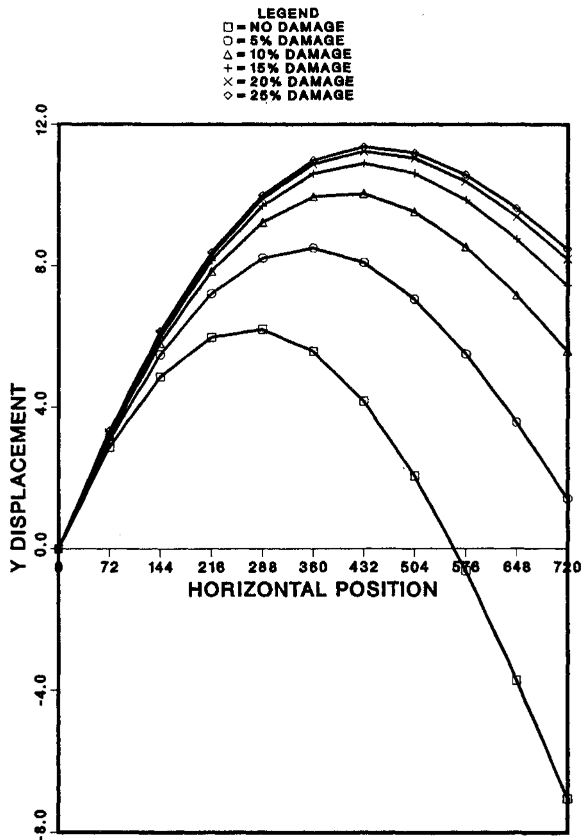

Fig. 10 Effect of degradation on third mode assuming third mode damage state.

the degraded and undegraded cases. Figure 7 is a plot of the z displacement for the second mode shape along the length of the space truss and shows that the modal displacements change quite drastically for the degraded structure. The displacement at the free edge is nearly 30 times the magnitude of the undegraded case for 25% maximum damage (the sign of the displacement is also reversed) and the locations of nodes also change considerably. Figure 8 indicates similar changes in the y displacement for the third mode shape. The fourth mode (torsional), similar to the first mode, is relatively unaffected by the degradation of material stiffness properties. This is as expected because in the present analysis the stress histories were obtained from the nodal displacements of the first two bending modes. The spatial variation in the stiffness of the truss members is related to the stress history and different results would be expected if the stress histories were different.

Results have also been obtained for the case where damage is assumed to occur in the third mode (second bending mode). As in the previous examples, there is no appreciable change in the first mode shape between the undegraded and degraded cases. The z displacement corresponding to the second mode shape is plotted in Fig. 9 for different levels of damage. The displacement at the free edge is very large in the damaged states as compared to the undegraded states. Figure 10 illustrates similar results for the third mode shape. These results show that the mode shapes and node points may change significantly for even small damage amounts. The control systems and its sensors designed for the undegraded structure will be very sensitive to changes in mode shapes. The sensors placed near the regions of peak amplitude of the undegraded structure may not be effective if the degraded structure exhibits significant changes in the mode shapes.

Conclusions

This study has attempted to investigate the possible effects of load- and environment-induced material damage and stiffness reduction on the modal response of large space structures (LSS). Large space structures constructed of fibrous composites will experience some stiffness reductions produced by load-induced and environmentally induced damage of the material. To what extent this will occur is uncertain at this point, but even small damage amounts appear to be significant.

The present work has shown that load-induced degradation of material properties may result in substantial reductions in natural frequencies and significant changes in the mode shapes. For the representative boom structure considered herein, even small amounts of material stiffness degradation (10%) produce node shifts that appear to be significant. It is not inconceivable that mode shapes, node locations, and frequency distributions will change over the design life in such a way that the structural response is very much different from the virgin structure. Such changes in structural response would require "robust" control of a nature that may not be possible with present technology. Consequently, it is important that these effects be taken into consideration when designing the control systems for large space structures.

Although preliminary in nature, this study suggests the need for a more accurate knowledge of the physical nature of material degradation in fibrous composites, its influence on structure stiffness, and how material degradation will affect the long-term modal characteristics for large space structures.

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