DAMAGE LOCALIZATION IN A SPACE TRUSS MODEL USING MODAL STRAIN ENERGY

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ABSTRACT: A three-dimensional scale model of a hexagonal boom truss of the then space station Freedom was built and tested in the laboratory. The purpose of the tests was to extract complete high-quality data of the vibrational characteristics of the structure, before and after damage, to validate damage detection/evaluation theories. The vibration tests consisted of experimental modal analysis before and after the infliction of artificial damage. The structure was subjected to 18 different damage scenarios, at single and multiple locations, of three types: a) cut damage consisting of a cut through half of the element, b) partial damage removing 50% of the area over the middle third of the element, and c) complete damage caused by completely cutting through the member. All damages were induced without changing the mass properties of the structure through specially designed clamping devices.

This paper summarizes the experimental program, the modal test results, the extracted modal shapes and an analysis implemented to localize the damage via modal strain energy distribution. The modal test results consist of the vibrational signatures due to different damages on the structure. The extracted modal results are implemented in a global damage detection/evaluation theory based on modal strain energy distribution. The strain energy distributions due to the static shapes of the modes are computed before and after the inflicted damage. The differences from the normalized strain energy distributions are multiplied times element weight factors proportional to the strain energy distribution of the damaged structure. The weighted modal strain energy differences are lumped into the connecting nodes of the elements to provide indications of the location of the inflicted damage. The technique is able to locate the complete damage and the partial damage, but was not able to detect the cut damage.

1. INTRODUCTION

Structures in a space environment are subjected to multiple forms of damage, such as impact damage inflicted by orbital debris, material thermal cycling degradation damage, structure assembling errors, faulty materials or element connections, and others. Because of the inherent expense and inaccessible nature of these structures, features such as an automatic health monitoring or a damage evaluation system are highly desirable. The common local damage diagnostics techniques used on earth, like ultrasonics, eddy currents, magnetometry, x-rays, and others are highly impractical for a space environment. The methods that seem more suitable for this application are those referred to as global. Among the most known global methods for damage diagnostics are those based on the monitoring of vibrational characteristics and thermography. However, thermography applications are more suitable for surface-type structures and are difficult to implement in skeletal structures. As a result, among the few methods that could be implemented on future space structures are those based on vibrational characteristics. These methods consider the fact that the vibration signatures of the structure are functions of the mechanical properties (stiffness, mass and damping). Since most forms of damage cause changes in structural stiffness, these damages reflect as changes in the vibrational signatures (resonant frequencies, mode shapes and damping ratios). Vibrational damage evaluation/monitoring methods use measurements of the vibrational characteristics at some time and compare them to baseline measurements at some previous undamaged state. Formulating an inverse problem, the changes of the vibrational characteristics are used to back-calculate the changes in the mechanical properties (primarily stiffness), which in turn map into damage magnitudes and locations of the damage. A number of different techniques have been developed to solve the inverse problem. Some of these techniques include sensitivity methods [1], force-residual methods [2], flexibility methods [3], back-calculation of stiffness matrices [4], artificial neural networks [5], and pattern recognition methods [6]. A comprehensive discussion of these methods can be found in Reference [7]. All these techniques have their strengths and limitations in their abilities to correctly detect, locate and quantify damage in structures using changes in vibrational characteristics. In addition, the requirements of each different technique are different, some require the extraction of modal responses over a wide frequency band, while other methods only require the measurement of few resonant frequencies and modes. Some methods also require the measurement of complete mode shapes, while others utilize realization of the modes at few points. Furthermore, all of these
techniques have been experimentally tested and verified using different types and sizes of structures, and a comparison of their performances to detect damage in a space structure is still lacking.

The objective of this paper is to present the experimental procedure, modal test results, the extracted modal shapes and the analysis implemented to localize the damage through the use differences of the weighted modal strain energy distribution.

2. EXPERIMENTAL WORK

2.1 Description of Test Article

The structure was a three-dimensional 1:6 scale model of a typical hexagonal boom truss to be used in the then Space Station Freedom. Fig. 1 shows an overall view of the scaled model in the laboratory. The structure had a total length of 190.25 inches in 12 bays and was fabricated with aluminum tubing. The aluminum members had an outside diameter of 0.674 inches and a wall thickness of 0.087 inches. Interior cross-bracing was fabricated with al-thread steel rods of 0.25 inches in diameter. The model had a total of 300 elements and 91 nodes. Fig. 2 depicts an schematic of the test object.

2.2 Test Setup

The test article was suspended using 12 soft springs from a W8x10 steel beam which was in turn suspended from a mezzanine ceiling. The suspension system can be seen in Fig. 1.

The sensors consisted of 273 accelerometers attached at the nodes of the structure and three force transducers attached to shaker inputs, one per direction. Each hexagonal bay had seven nodes (six at vertices and one at center); a calibrated accelerometer was installed in each of the three directions at each node. Three 50-lb shakers were used, one for each global direction (x, y and z), transmitting the force through a stinger and a transducer. The shakers were attached at nodes 1010-x, 1610-y and 1620-z (see Fig. 2). The shakers were driven by different and uncorrelated white-noise signals band-pass filtered from 30 to 650Hz.

2.3 Damage Cases

There were three types of damage that the structure was subjected to at various locations. Type I damage consisted of a 50% reduction of the cross-sectional area of the elements over a length of 1/16 introduced with a saw cut. Type II damage consisted of a 50% reduction of the cross-sectional area over one-third the length of the element. Type III damage consisted of the total removal of the axial stiffness of the element accomplished by completely cutting the element.

A scheme was devised to introduce the damage, perform the modal testing of the structure in the damaged state and then bring the structure back to the undamaged state without altering the mass properties. To bring the elements back to their undamaged state a clamping device was developed which clamp consisted of a 4 in. aluminum pipe sleeve cut in half longitudinally and four hose clamps. The selection of the elements to be damaged was based on the modal strain energy of the low order modes obtained from a finite element model of the structure. Nine elements were selected to provide a spectrum of elements with high, medium and low strain energy content. The elements selected to be damaged are indicated in Fig. 2 as elements E1 through E9. Table 1 summarizes the sequence of tests conducted for the baseline (undamaged) and damaged cases. There were 22 separate tests performed on the test article at different states. Five of the tests were conducted on the undamaged state to provide baseline measurements of the modal parameters and 17 cases corresponded to damage cases. Further details of the experimental work can be found in Reference [8].

3. MODAL PARAMETER EXTRACTION

3.1 General Description of Stored Functions

There were a total of 273 accelerometers and three FRFs per accelerometer, giving a total of 819 FRFs per case (undamaged and damaged) and 273 multiple Coherence functions. In addition, seven sets of Force Auto Spectrum, Force Time Response and Force Coherence for each of the three reference coordinates were stored. In total, 1,155 functions were stored for each test.

3.2 Modal Parameter Extraction

The poly-reference modal extraction technique was applied to curve-fit the FRFs using the I-DEAS software. Three curve-fitting bands of similar widths were used for all the cases within the frequency range of analysis. Within the three bands used, five global modes were extracted and identified. The global bending modes were labeled with X and Y, to indicate predominant bending in that plane. However, the global modes experienced bending in both planes. Also, within each fit band there were several local modes.

3.3 Identification of Global Modes

Due to a number of local modes and repeated global modes extracted during the curve-fit process, it was necessary to eliminate local and repeated modes for further analysis. This was carried out by the following procedure. First, a set of five global mode shapes was generated for Baseline 1. By visually displaying the modes in the computer screen, the local modes and repeated modes were deleted from the corresponding mode shape file to create a set of “reference” mode shapes. Then, Modal Assurance Criteria (MAC) analyses were performed between all the modes in each of the remaining baseline files and the reference mode shapes to identify the modes that match the global modes of the reference measurements. This process generated files that only contain the global modes. The same procedure was then repeated for the mode shapes corresponding to the damage cases.

Table 2 shows a list of the resonant frequencies of the identified global modes for all cases. Note that in the description of the modes, we are using bending X and bending Y which indicates bending in the corresponding plane. In some cases the plane of bending was not parallel to the global coordinate system, it was slightly tilted. In some cases, specially the full damaged ones, the plane of bending shifted with respect to the undamaged, yielding very low MAC values and making difficult the identification of the modes. In these cases, the identification was completed through a dynamic animation of the mode shapes.
4. DAMAGE DETECTION USING THE LUMPED MODAL STRAIN ENERGY METHOD

4.1 Modal Strain Energy Method

The Modal Strain Energy Method Distribution Method considers a structure in the undamaged state and the same structure in the damaged state. Any form of damage can be characterized as changes in the mechanical properties. In the particular case of the test object of this paper, there were no changes in the mass properties. The modal dynamic responses consists of sets of dynamic modal properties for the undamaged structure and for the damaged structure. When damage occurs, the stiffness of the damaged element changes. As a result, the modal deformations in the vicinity of the damaged element also change.

First, the total modal strain energy for each of the identified modes was computed and the eigenvectors were normalized so that the total strain energy equaled 1000. The total modal strain energy $U_j$ was computed using the expression

$$ U_j = \frac{1}{2} \{ \phi_i \}^T [K] \{ \phi_i \} \quad (4.1) $$

and an idealized finite element description for the stiffness $[K]$ assembled with 3D truss elements. This total strain energy can be visualized as the sum of the strain energy stored in all the structural elements, that is

$$ U_j = \sum_{i=1}^{N} U_{ij} \quad (4.2) $$

where $U_{ij}$ is the modal strain energy contribution of the element $i$ in the $j$th mode, and $N$ is the number of structural elements. $U_{ij}$ is defined by the following equation:

$$ U_{ij} = \frac{1}{2} \{ \phi_{ij} \}^T [k_j] \{ \phi_{ij} \} \quad (4.3) $$

where $[k_j]$ is the stiffness matrix of the $j$th element and $\{ \phi_{ij} \}$ is a collection matrix, containing the $j$th mode shape components associated with the degrees of freedom of the element $i$.

The rationale for the localization of the damage is based on the fact that the element stiffness matrix of (4.3) changes, giving changes in the modes and in the modal energy contribution of that element. Then, the change in energy distribution between the undamaged and damaged cases, computed by the following equation:

$$ \Delta U_{ij} = U_{uij} - U_{dij} \quad (4.4) $$

can give differences in the modal strain energy distribution localized around the vicinity of the damage. The subscripts $u$ and $d$ in (4.4) indicate undamaged and damaged, respectively. Since the modal deformations also change, differences computed using (4.4) also give localized differences in elements adjacent to the actual damaged element. A better method for localizing damage is by lumping the element contribution of the modal energies to the nodes connecting the elements. This way, a successful localization of the damage should be indicated by two peaks, one at each of the nodes connecting the damaged elements.

4.2 Weighted Modal Strain Energy Differences

Because of the damage sensitivities of the various structural elements for the different modes, noise in the experimental measurements in the insensitive elements would have a tendency to cause false predictions. The weighted modal strain energy differences is defined by multiplying equation (4.4) times a weight factor proportional to the modal strain energy distribution for the undamaged case. Thus, the weighted modal strain energy differences are given by,

$$ \Delta \bar{U}_{ij} = (U_{uij} - U_{dij}) \bar{U}_{ij} \quad (4.5) $$

Implementation of the above equation has a tendency to shadow noise effects by assigning large weights to the sensitive elements and small weights to the insensitive elements.

4.3 Lumped Weighted Modal Strain Energy Differences

To compensate the effects explained in Section 4.1, where elements adjacent to the one damaged may experience false positive damage localization, the weighted modal strain energy differences of the elements are lumped into the nodes connecting the elements. The lumping procedure was simply applied by attributing half of the weighted modal strain energy of an element to each of the two connecting nodes, superimposing the contributions coming from all the elements into all the exterior nodes.

4.4 Damage Localization Results

Figs. 3 through 6 show the lumped weighted modal strain energy differences for some of the damage scenarios. For the complete set of results see Reference [8]. Each graph contains the results of equation 4.5 applied to five global modes, lumping the results to the connecting nodes. The x-axis of these figures goes from 1 through 78, corresponding to the outer nodes of the structure in sequential order as shown in Fig. 2. The venal axis corresponds to the weighted modal energy difference when the total modal energies were normalized to values of 1,000. The five modes correspond to the two first bending, the first torsional and the two second bending modes. The unique feature of these graphs is that to positively localize damage in an element, there needs to be a pair of peaks, one at each of the connecting nodes of the element.

Fig. 3 (case 1) corresponds to a cut damage (type I). In this case the damage was not detected by any mode; but the magnitude of the peaks is relatively small when compared to the other figures. Fig. 4 (case 8) corresponds to a Type III damage. In this case the damage was localized by modes 1, 3 and 4, mode 3 being the most predominant. Fig. 5 (case 13) shows the results for a Type III damage at two locations. For this case the two damage locations were positively localized by different modes for each damaged element. Fig. 6 (case 18) shows the results of a partial damage case (Type II). In this case the damage was positively localized but also some false damage identifications were found.
5. CONCLUSIONS

The following conclusions can be stated:

1) Type I damage, consisting of a cut through half the depth of the elements, was not detected using the lumped weighted modal strain energy method.
2) For the cases where Type I damage was attempted to localize, there were false positive predictions at the same locations that seem to be caused by the application of the weights proportional to energy content. The noise at the element with high sensitivity was amplified causing the false positive detection.
3) Type III damages at single locations, consisting of a complete severance of a member were correctly located by the weighted lumped modal strain energy difference.
4) No single damage was detected by all five modes considered.
5) In all the two-location cases, Type III damage was correctly located by at least one of the modes.
6) A comprehensive damage localization scheme requires the utilization of several global modes to the extent that each element must have sensitivity to at least one of the modes.
7) For the damage detection in a complex structure as the one dealt in this study, lumping the modal strain energies to the nodes is a better method for locating the damage than observing the strain energy differences at the element level.

6.0 ACKNOWLEDGMENTS

The experimental phase of this study was sponsored in part by the NASA Johnson Space Center, contract number NAG 9-483. The analytical efforts were sponsored by the Air Force Office of Scientific Research, Air Force Materiel Command, USAF, under grant number F49620-95-1-0518. The authors would like to thank Dr. Joseph Atkinson and Mr. Rodney Rocha for their continued support of this research and allowing UTEP students to perform the tests at NASA JSC. Mr. Francisco Castaño, president of Geometrica, Inc. is acknowledged for donating the structure.

7.0 REFERENCES


Table 1. Damage cases and sequence of tests

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* Case 17 is with respect to Baseline 5
** Case 18 are the same measurements of case 17 but taking Case 16 as the baseline.
Fig. 1. Overall view of structure

Fig. 2. Schematic of structure model and locations of elements damaged
Table 2. List of frequencies of identified global mode shapes

<table>
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<th>Scenario</th>
<th>1st Bend. X (Hz)</th>
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<th>Torsional  (Hz)</th>
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Not identified with the MAC Procedure but identified visually.

Fig. 3. Lumped weighted modal strain energy differences, Case 1, Type I damage at element El connected between nodes 9 and 14
Fig. 4. Lumped weighted modal strain energy differences, Case 8, Type III damage at element E4 connected between nodes 47 and 52.

Fig. 5. Lumped weighted modal strain energy differences, Case 13, Type III damage at elements E2 and E4 connected between nodes 21, 26 and 47, 52.

Fig. 6. Lumped weighted modal strain energy differences, Case 18, Type II, damage at element E9 connected between nodes 50 and 56.

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