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Vibration Technique for Locating Delamination in a Composite Beam

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An experimental nondestructive vibration-based technique for locating a delamination in a composite beam is presented. The method operates on the fundamental displacement eigenvector, which is converted to a curvature mode shape. The application of a unique, gapped smoothing damage detection method to the curvature yields a damage index that locates the delamination, irrespective of its position along the beam or depth within the beam. The procedure can operate solely on data obtained from the damaged structure. Models or data from the undamaged structure are specifically not required or used during the analysis. The procedure reported here is highly satisfactory for experimental data, where small variations in the measurement cause false features in other published curvature-based damage detection methods. The damage location method is demonstrated with a finite element model of a composite beam, where a delamination is modeled by relaxing connectivity between elements at the desired location of the delamination. The results of an experimental investigation of a composite beam with a manufactured delamination are also presented. When the gapped smoothing method was used on the experimental modal data, the delamination was successfully located.

Introduction

WHEN composite structures are damaged, delamination can cause serious structural degradation. A great variety of techniques can be used to locate such damage, and this paper considers only those based on vibrational methods. Many vibration-based nondestructive examination (NDE) methods use the observed change in natural frequency between an initially undamaged structure and the latter damaged structure as a damage indicator. Williams et al.[1] tracked several natural frequencies of a damaged structure. They defined a damage location assurance criterion using the difference between the measured values and those from a finite element (FE) model containing simulated damage to locate the actual damage. Cawley and Adams[2,3] used the changes in natural frequency of a composite structure in conjunction with a mathematical model of the structure to detect, locate, and roughly quantify damage. Adams et al.[4] also used changes in natural frequency and "anomalous mode shapes" as damage indicators for a glass-reinforced plastic lattice structure. The effect of damage on natural frequencies has also been investigated by Crema et al.,[5] who compared the eigenvalues for a damaged and an undamaged composite beam, and Okafor et al.,[6] who used a neural network to analyze the change in natural frequencies due to delamination in composite plates to determine the location and size of damage. The effect of impact damage on laminated graphite/epoxy plates has been investigated using modal analysis techniques by Tracy et al.,[7] who impacted plates with a 12-mm ($\frac{1}{2}$-in.)-diameter projectile traveling up to 40 m/s (138 ft/s). They compared the natural frequencies, damping, and mode shapes with those of the pretest plates and found that impact damage caused reductions in frequencies for selected modes.

Extensive work on a reinforced plastic composite structure by Lai and Young[8] concluded that a delamination decreases the natural frequency that corresponds to the fundamental mode and increases the structural damping. Lai and Young also found that the damping ratio was significantly decreased by prolonged exposure to a humid environment, whereas exposure to a high temperature permanently increased the fundamental frequency. The latter finding is consistent with the findings of Ratcliffe.[9] For some modes, Peroni et al.,[10] when studying modal damping of a sandwich panel using broadband excitation, found that an increase in the severity of damage caused a slight increase in damping coefficient. Vantomme[11] correlated modal parameters and the accumulated damage of composite joints of a stiffened plate structure. Based on the relative observable changes in the various quantities, Vantomme concluded that "modal frequency measurements are more appropriate as parameters in [nondestructive examination] . . . than modal damping measurements."

Composites made from concrete have also been studied, and a committee report by Javor[12] gives international technical guidelines that recommend monitoring the fundamental frequency for the long-term observation of structures. Conversely, when considering a scalar performance error index including the sum-square difference between baseline and measured mode shapes and natural frequencies, Casas and Aparicio[13] found that "the measurement of only one frequency [mode shape] is not enough to distinguish [structural damage]."

Clearly, there is no single dynamic property that can reliably be used to identify and to locate all forms of damage in composite structures. First, this paper considers a FE model of a composite beam with a delamination at various positions and depths. Second, the paper develops and demonstrates the gapped smoothing damage detection method for determining the location of damage using the spatially discrete fundamental mode shape for the damaged beam. Unlike most existing modal NDE methods, the calculations for the method presented here do not require an undamaged reference; the procedure operates solely on the measured mode shape obtained from the damaged structure. Note that removing the need for an undamaged reference imposes the assumption that the curvature for the undamaged structure is smooth and continuous. The curvature will be smooth and continuous if the structure has no stiffness discontinuities. For structures with such discontinuities, the procedure presented here may be improved by comparing the damage index determined for the damaged structure with that obtained from an undamaged reference. Thus this method offers a significant advantage over other techniques in that it can be applied to an existing structure where there is no a priori knowledge of its state, and damage may be located in an efficient and cost-effective manner. Third, the gapped smoothing damage detection method is validated by experiments on a composite beam with a manufactured delamination.

Damage Detection Using Curvature

Several authors, including Chang et al.[14] and Pandey et al.,[15] have shown that, when damage in an otherwise homogeneous beam is severe, the location can sometimes be seen as an irregularity in the

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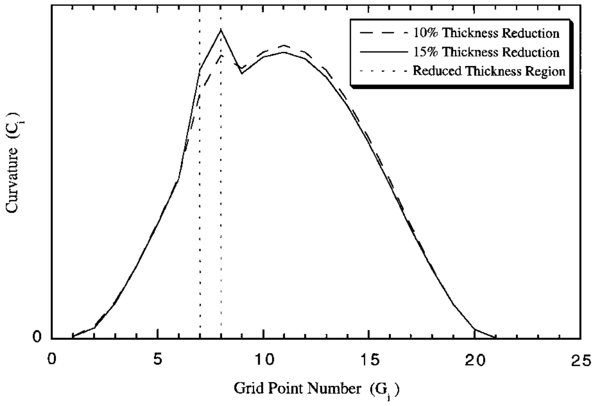

Fig. 1 Curvature for the fundamental mode of a theoretical homogeneous free-free beam with thickness reduction between grid points G_7 and G_8.

curvature mode shape. For less damage, the irregularity in curvature is less obvious. As an example, Fig. 1 compares the theoretical curvature for the fundamental mode of a homogeneous free-free beam with 10 and 15% thickness reduction between grid points G_7 and G_8. Note that both of these cases represent severe damage. Different methods of enhancing this irregularity of the curvature have been tried: Maia et al.[16] differentiated the curvature shape, and Ratcliffe[17] used a smoothing process to determine a damage index that located as little as 1% localized reduction in stiffness in an otherwise homogeneous beam. Ratcliffe showed that this technique is better for experimental data, and it is this procedure that is investigated here for its suitability for detecting a delamination in a composite beam.

The procedure presented here processes the mode shape in two stages. First, the displacement mode shape is converted to a curvature shape (curvature being the reciprocal of the radius of curvature) using Laplace's difference equation.[18] It is well known that differentiation, including using Laplace's difference function, enhances irregularities such as measurement noise in the original function. To extract small features from such a function, the curvature is locally smoothed with the gapped smoothing method. This is done by locally fitting a gapped cubic polynomial to the curvature. The gapped cubic calculated for the ith element of the curvature C_i at position x_i along the beam is defined as

$$p_0 + p_1 x_i + p_2 x_i^2 + p_3 x_i^3 \tag{1}$$

The coefficients p_0, p_1, p_2, and p_3 are determined using curvature elements C_{i-2}, C_{i-1}, C_{i+1}, and C_{i+2}. Notice that the curvature C_i of the ith element is left out (gapped) from the calculation of the cubic. The damage index δ_i for the ith position on the beam is calculated from the cubic and the curvature as follows:

$$\delta_i = \left[\left(p_0 + p_1 x_i + p_2 x_i^2 + p_3 x_i^3\right) - C_i\right]^2 \tag{2}$$

The right-hand side of Eq. (2) is squared so that the procedure can also be applied to curvature shapes that have complex coefficients. Separate gapped cubic polynomials and damage index values are determined for each grid point in turn. The damage indices calculated for the curvatures shown in Fig. 1 are plotted in Fig. 2. Figure 2 gives a strong indication of the procedure's suitability for locating small amounts of damage.

FE Modeling Technique

A theoretical FE model of a composite cantilever beam, 920 mm long × 95 mm wide × 6.5 mm thick, was generated using a 35 × 2 × 6 element mesh. The beam model and coordinate system are shown in Fig. 3. The modeling was done in MSC/NASTRAN® using CHEXA solid elements with eight corner grid points per element. Elements with 20 grid points were not used because the model did not have curved edges and the linear modal analysis method (described later) assumes small displacements. The resulting elements were 26.2 mm long × 47.5 mm wide × 1.08 mm deep. The material properties of each element were chosen to represent a $[0/90]_6$ composite beam fabricated from plain-weave S2 glass fiber cloth in an epoxy resin matrix. The depth of each element was chosen to represent one layer of cloth. This represents a nonstandard modeling philosophy. The customary method uses elements that have the average property of several layers of fibers. Modeling the depth of the beam in this nonstandard manner, with each element representing a single layer, was necessary to be able to introduce the delamination into the model between layers at various depths through the beam.

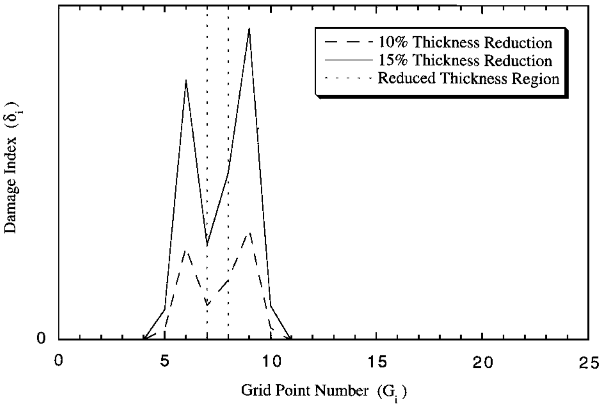

Fig. 2 Damage index for the fundamental mode of a theoretical homogeneous free-free beam with thickness reduction between grid points G_7 and G_8.

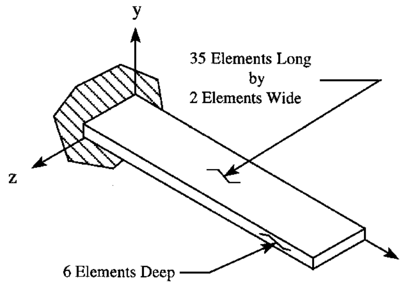

Fig. 3 FE model.

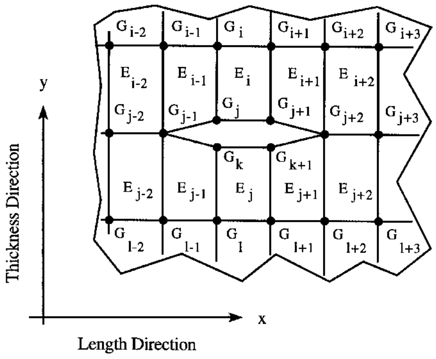

Fig. 4 Delamination as seen on the near-side vertical edge of the beam with grid points G (●) and elements E surrounding the delamination.

The delamination was created in the FE model by having a region where elements were not connected together, as is illustrated in Fig. 4. Figure 4 shows the near-side vertical edge of the beam. For this model, the grid points on either side of the delamination were free to move relative to each other without constraints due to stiffness or damping. In an actual delamination, both of these effects would be present to some degree. In Fig. 4 the grid points are designated G (shown as ●), and the elements are designated E. For clarity of illustration, grid points G_j, G_{j+1}, G_k, and G_{k+1} are separated and appear to form a six-sided hole. In the FE model, the (x, y, z) coordinates of grid points G_j and G_k are the same, as are those for grid points G_{j+1} and G_{k+1}. The element connectivity is as follows: Elements E_i and E_j are not connected to each other; elements E_{i-1} and E_{j-1} are connected only at grid point G_{j-1}; and elements E_{i+1} and E_{j+1} are connected only at grid point G_{j+2}. The delamination is built across the entire width of the beam, and therefore the same element connectivity holds for the grid points on the vertical centerline plane and on the far vertical edge of the beam. Note that, if the ith row of grid points lies on the top surface of the beam, the delamination lies between the outer topmost layer and the second topmost layer of elements. If the jth row of grid points lies below the third layer from the top, then the delamination is on the neutral surface of the beam. The delamination was moved in both the x and y directions to determine the insensitivity of the gapped smoothing damage detection method to the position of the delamination.

The SOL3 (normalized modes) solution method was used to find the first bending eigenvector of the beam. Because SOL3 is a linear solution method, it would have been incorrect to model the delamination using the nonlinear CGAP element. The eigenvector was normalized by setting the largest grid point displacement equal to 1. The eigenvector (x, y, z) displacements of the grid points on either side of the delamination were examined. The y direction (through thickness) eigenvector displacements for grid points G_j, G_k, G_{j+1}, and G_{k+1} were compared. To an accuracy of six decimal places, the y displacement of grid point G_j was equal to that for G_k, and the y displacement of grid point G_{j+1} was equal to that for G_{k+1}. This result indicates that the grid points above and below the delamination did not penetrate into the surrounding elements. Both the x-direction (length) and z-direction (width) eigenvector displacements for grid points G_j and G_k and G_{j+1} and G_{k+1} showed motion relative to each other. The x-direction relative motion is explained by the fact that the elongations of the elements above and below the delamination are different due to their different distances from the neutral surface. The z-direction relative motion is explained by the different Poisson effects for the elements above and below the delamination. For an actual beam, the delamination would have both residual stiffness and damping. However, the residual stiffness in the delamination would be much lower than the stiffness of the surrounding undamaged material. This residual stiffness in an actual beam would result in slightly smaller relative motions compared with this theoretical model. The residual damping force in an actual beam probably would be negligible because the relative displacements and velocities of the material surrounding the delamination would be very small for small beam deflections.

FE Damage Detection Results

As described earlier, many different FE models were generated with the delamination at different depths and positions along the beam. The y-direction fundamental eigenvectors obtained from the centerline for each model were converted to curvature, an example of which is shown in Fig. 5. Although there is a slight irregularity in curvature near the delamination, it is not sufficient to successfully and reliably locate the delamination.

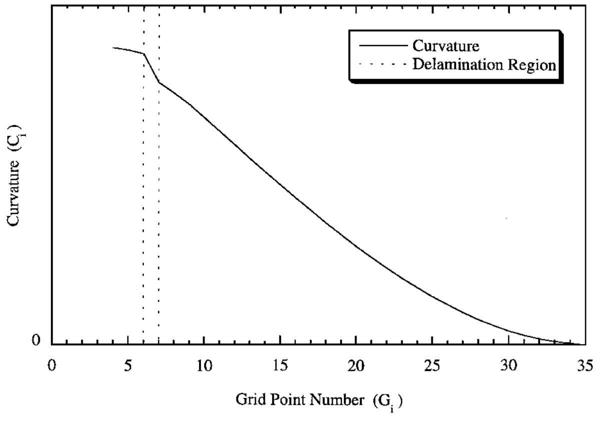

Fig. 5 Curvature for the fundamental mode of the cantilevered beam FE model with a delamination between grid points G_6 and G_7 and just under the outer layer of elements.

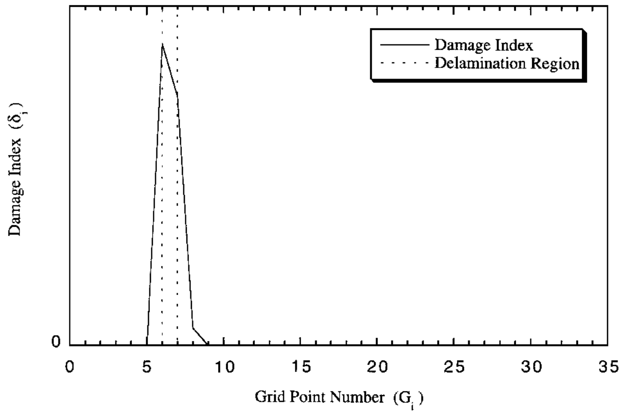

Fig. 6 Damage index for the fundamental mode of the cantilevered beam FE model with a delamination between grid points G_6 and G_7 and just under the outer layer of elements.

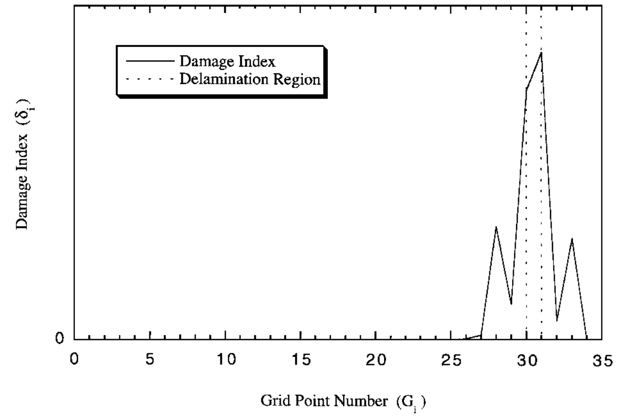

Fig. 7 Damage index for the fundamental mode of the cantilevered beam FE model with a delamination between grid points G_{30} and G_{31} and at the neutral surface.

The damage index was calculated from the curvature using the gapped smoothing method. Figure 6 shows the damage index calculated from the curvature in Fig. 5 for a delamination just under the outer layer of elements near the root of the cantilever. Figure 7 shows the damage index for a delamination on the neutral surface near the tip of the beam. Figures 6 and 7 show the results for the extreme locations of the delamination. For all of the cases investigated, the major feature in each damage index plot successfully located the delamination, irrespective of the position of the delamination along the length or through the depth of the beam.

Experimental Demonstration

A flat S2 glass-reinforced epoxy beam, approximately 810 × 100 × 6 mm^3, was manufactured out of plain-weave fabric with orientations of $[0/90]_{10}$. A 25-mm-long, cross-width delamination was introduced at the neutral surface, close to the midspan of the beam, by using Teflon® tape to prevent layers from bonding together. The layup and autoclaving gave a very tight high-friction delamination with no observable gap. The beam was suspended by thin monofilament thread through two small holes drilled near one edge of the beam at quarter-points along its length. There were 37 equally spaced grid points along the centerline, this number being chosen as comparable to the number of measurements typically taken in the experimental investigation of complex structures. The response accelerometer was placed near one end at grid point G_1, and frequency response functions (FRFs) were measured using impact excitation/fixed response techniques between each of the grid points and the accelerometer. The FRFs were subject to a modal analysis using the commercial STAR™ software.

The fundamental mode shape was exported from STAR into an analysis program written in MATLAB®. The curvature mode shape was calculated and is shown in Fig. 8. The curvature exhibits numerous sharp swings in both magnitude and sign with no single

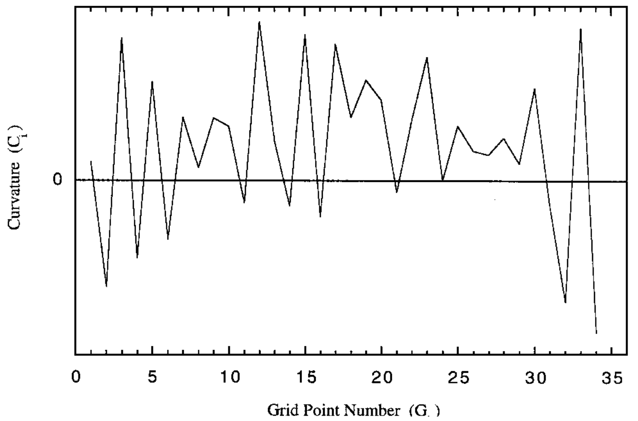

Fig. 8 Curvature for the experimentally measured fundamental mode of the composite beam with the manufactured delamination.

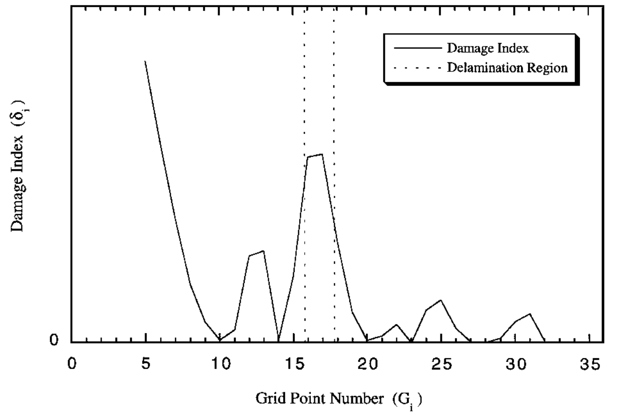

Fig. 9 Damage index for the experimentally measured fundamental mode of the composite beam with the manufactured delamination at the marked position.

dominant feature. Because there is no single dominant feature in the curvature, the delamination was not located by the curvature method proposed by Pandey et al.[15] The irregularities in the curvature are caused by the small variations from a smooth mode shape that exist in the experimental data. The curvatures shown in Figs. 1 and 5 do not exhibit the type of variations seen in Fig. 8 because Figs. 1 and 5 are based on theoretical mode shapes.

Next the damage index was calculated from the curvature of Fig. 8 using the gapped smoothing method described previously. The damage index is shown in Fig. 9. The major feature of this plot is coincident with the delamination. Thus the delamination was successfully located. It is theorized that the feature at the left of the damage index plot is associated with the mass loading effect of the accelerometer. The mass loading effect would be less significant with the larger mass of a real structure. The scatter in the measured data and variability inherent in the experimental modal analysis methods have introduced the other minor features in the damage index plot. Note that, because Figs. 6 and 7 are based on a theoretical FE model, they do not show the minor features that are characteristic of experimental data.

Other damage detection methods, including that of Maia et al.,[16] propose differentiating the curvature and looking for dominant features to locate the damage. As demonstrated in Fig. 8, small irregularities in the measured data can cause numerous large changes in both the magnitude and slope of the curvature that, when differentiated, would obscure the effect of the damage. The significant advantage of the gapped smoothing method was that it located the delamination in the test beam, whereas the curvature and differentiated curvature methods did not.

Conclusions

Delamination in a composite beam was successfully located using the gapped smoothing damage detection method presented in this paper. The smoothing inherent in this method makes it suitable for experimental data. The FE model demonstrated the successful application of the method for the theoretical case of a delamination with no residual stiffness or damping. The FE model results give a sound theoretical basis for the validity of the gapped smoothing method. At the other extreme, the experiment using the beam, with the manufactured delamination, showed the effectiveness of the method for a real delamination with high residual stiffness and damping.

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