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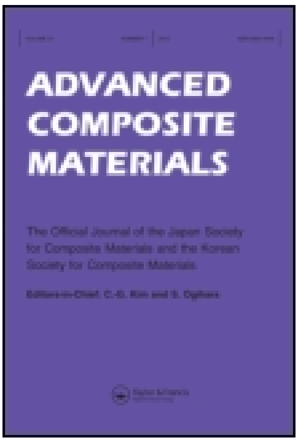

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Damage identification of laminated composite structures based on dynamic residual forces

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Abstract—This paper shows a damage identification method based on dynamic residual forces which can be evaluated using an analytical model of undamaged structures and measured vibration data of damaged structures. The method consists of a two-step damage detection procedure. In the first step, a rough damage region is identified from the dynamic residual forces. In the next step, error vectors of the residual forces are minimized to identify the accurate location and extent of structural damage. Effect of measurement points and measurement errors on the identification results is examined through numerical examples on symmetric laminated plates.

Keywords: Damage identification; laminated composite; vibration; residual force; natural frequency; natural mode.

1. INTRODUCTION

Structural health monitoring is an important technology to evaluate structural degradation or damage for laminated composites in aircraft wing structures or space structures. Damage inspection methods such as X-ray or ultrasonic testing which have often been used for composite structures can be time consuming and are local assessments. They also require the exposure of structural elements to the inspector and equipment for detecting damage, and thus they may not be appropriate as a real-time nondestructive evaluation. An alternative approach making use of vibration test data or static test data can be useful as the structural health monitoring system. Several approaches have been suggested for the structural health monitoring. Nonlinear optimization techniques have been applied to identify material properties and damage using the static or vibration test data [1]. The use of vibration test data has been attempted to locate structural damage in composite

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materials [2]. For the evaluation of damage location and magnitude in structures, two main approaches have been suggested where one is based on the flexibility matrix [3, 4] and the other is based on the residual force vector [5, 6].

The present paper shows a damage identification method of laminated composite structures using dynamic residual forces. The method consists of a two-step damage detection procedure that initially uses dynamic residual force vectors to locate potential damage regions, and next error vectors of the residual forces are minimized to identify the accurate location and extent of structural damage.

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2. DAMAGE IDENTIFICATION METHOD

We consider a cantilevered CFRP plate with $[30/-30/90]_s$ laminate as shown in the finite element model of Fig. 1. Table 1 represents six bending stiffness components of the laminate. The natural vibration equation is given by

$$[K]\{\phi\}_i = \lambda_i[M]\{\phi\}_i, \tag{1}$$

where K and M, respectively, denote the (n, n)-type stiffness and mass matrices; λ_i and ϕ_i, respectively, denote the i-th eigenvalue (square of the circular natural frequency) and the corresponding vibration mode.

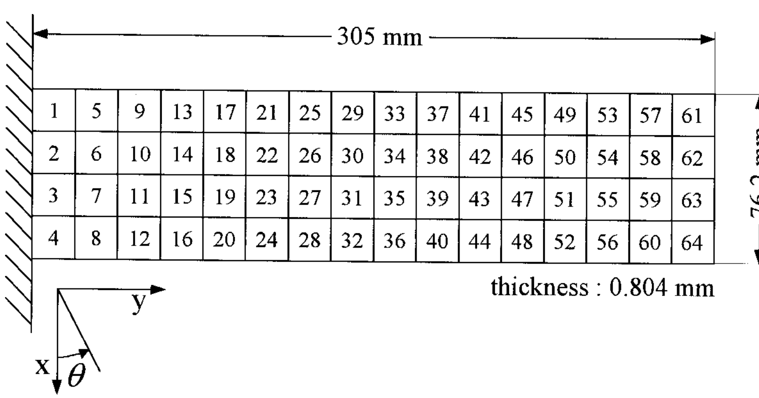

Figure 1. Finite element model of CFRP plate.

Table 1.
Bending stiffness of $[30/-30/90]_s$ laminate

D_{11}	2.56×10^{0} [N · m]
D_{12}	7.20×10^{-1} [N · m]
D_{16}	5.44×10^{-1} [N · m]
D_{22}	8.12×10^{-1} [N · m]
D_{26}	2.12×10^{-1} [N · m]
D_{66}	8.66×10^{-1} [N · m]

We identify the damage location and the damage extent from the eigenvalues λ_i and the corresponding eigenmodes ϕ_i. The measurement of eigenmodes at all degrees of freedom involving the angle of deflection is, in fact, difficult and also not all need to be measured. Partitioning equation (1) into two terms corresponding to the measured ϕ_{1i} and unmeasured vectors ϕ_{2i} leads to

$$\begin{bmatrix} K_{11} & K_{12} \\ K_{12}^T & K_{22} \end{bmatrix} \begin{Bmatrix} \phi_1 \\ \phi_2 \end{Bmatrix}_i = \lambda_i \begin{bmatrix} M_{11} & M_{12} \\ M_{12}^T & M_{22} \end{bmatrix} \begin{Bmatrix} \phi_1 \\ \phi_2 \end{Bmatrix}_i . \tag{2}$$

The damage in laminated composites is modeled as a proper stiffness reduction within an element in the finite element division. The stiffness matrix components are assumed to vary due to damage as follows:

$$[K'_{rs}] = [K_{rs}] + [\Delta K_{rs}] \qquad (r, s = 1, 2). \tag{3}$$

From equations (2) and (3), the equation for natural vibration after damage is given as follows:

$$\begin{bmatrix} K_{11} + \Delta K_{11} & K_{12} + \Delta K_{12} \\ K_{12}^T + \Delta K_{12}^T & K_{22} + \Delta K_{22} \end{bmatrix} \begin{Bmatrix} \phi'_1 \\ \phi'_2 \end{Bmatrix}_i = \lambda'_i \begin{bmatrix} M_{11} & M_{12} \\ M_{12}^T & M_{22} \end{bmatrix} \begin{Bmatrix} \phi'_1 \\ \phi'_2 \end{Bmatrix}_i , \tag{4}$$

where the prime ($'$) denotes the properties after damage.

From equation (4), dynamic residual forces are defined as follows:

$$\begin{aligned} \begin{Bmatrix} \Delta R_1 \\ \Delta R_2 \end{Bmatrix}_i &\equiv \begin{bmatrix} \Delta K_{11} & \Delta K_{12} \\ \Delta K_{12}^T & \Delta K_{22} \end{bmatrix} \begin{Bmatrix} \phi'_1 \\ \phi'_2 \end{Bmatrix}_i \\ &= \lambda'_i \begin{bmatrix} M_{11} & M_{12} \\ M_{12}^T & M_{22} \end{bmatrix} \begin{Bmatrix} \phi'_1 \\ \phi'_2 \end{Bmatrix}_i - \begin{bmatrix} K_{11} & K_{12} \\ K_{12}^T & K_{22} \end{bmatrix} \begin{Bmatrix} \phi'_1 \\ \phi'_2 \end{Bmatrix}_i . \end{aligned} \tag{5}$$

When eigenmodes at all degrees of freedom can be measured, $\Delta R_i = \Delta K \phi'_i$ and non-zero residual forces occur only at the damage element. On the other hand, when all components cannot be measured, we cannot determine the values of ΔR_1 and ΔR_2 separately. Deleting ϕ'_{2i} in the second row of equation (5), we can obtain

$$\begin{aligned} \{\Delta Q\}_i &\equiv \{\Delta R_1\}_i - [\lambda'_i M_{12} - K_{12}][\lambda'_i M_{22} - K_{22}]^{-1}\{\Delta R_2\}_i \\ &= \left([\lambda'_i M_{11} - K_{11}] - [\lambda'_i M_{12} - K_{12}][\lambda'_i M_{22} - K_{22}]^{-1}[\lambda'_i M_{12}^T - K_{12}^T]\right)\{\phi'_1\}_i . \end{aligned} \tag{6}$$

In equation (6), the right-hand term can be evaluated since K_{ij} and M_{ij} are known and λ'_i and $\left\{\phi'_1\right\}_i$ can be measured. The combined residual force vector ΔQ in equation (6) consists of the residual force vectors ΔR_1 and ΔR_2, and ΔQ has the same degree of freedom as the measurement data. It is expected that ΔQ is an indicator for the damage location.

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We define the normalized damage indicator as follows:

$$\{\varepsilon\}_i = \frac{\{|\Delta Q|\}_i}{\sqrt{\{\Delta Q\}_i^T\{\Delta Q\}_i}} \quad (0 \leqslant \varepsilon_i \leqslant 1), \tag{7}$$

where $\{|\Delta Q|\}_i$ denotes a vector where the component consists of an absolute value of each component of $\{\Delta Q\}_i$, and $\{\varepsilon\}_i$ represents the normalized damage vector for the i-th mode.

The average damage vector from first to m-th mode is expressed as follows:

$$\{\varepsilon\}_0 = \sum_{i=1}^{m} \{\varepsilon\}_i \,/m. \tag{8}$$

The average damage vector has a large absolute value near the damage element. In this paper, we use the damage criterion that the region is damaged when $|\varepsilon| \geqslant 0.1$ in all nodes surrounding the region.

When the damage region is determined by the criterion of equation (8), we estimate the damage elements within the damage region. In this step, we use the following error vector for i-th mode:

$$\{E\}_i = \left([\lambda_i' M_{11} - K_{11}'] - [\lambda_i' M_{12} - K_{12}'][\lambda_i' M_{22} - K_{22}']^{-1}[\lambda_i' M_{12}^T - K_{12}^{'T}]\right)\{\phi_1'\}_i, \tag{9}$$

where $K' = K + \Delta K$ are unknown, and the error vector $\{E\}_i$ is a function of the j-th bending stiffness in the k-th element $(D_j')_k$. When $(D_j')_k$ gives the true bending stiffness after damage, the error vector vanishes.

Thus the damage elements can be determined by minimizing the following error vector norm with respect to $(D_j')_k$:

$$\min \sum_{i=1}^{m} \{E\}_i^T\{E\}_i. \tag{10}$$

In the determination of the damage region using the criterion of equation (8), there are many possible damage elements. Then the minimization problem of equation (10) has many variables when the bending stiffness components in possible damage elements are used as direct variables. In order to reduce the number of variables and to locate the damage elements roughly, we solve equation (10) using the following variable linking:

$$(D_j')_k = (1 - \alpha_k/100)(\overline{D}_j)_k \qquad \begin{pmatrix} j = 11, 12, 16, 22, 26, 66 \\ k = 1, 2, \ldots, K \end{pmatrix}, \tag{11}$$

where K and α_k are, respectively, the number of possible damage elements and the variable in the k-th element. $(\overline{D}_j)_k$ is the j-th bending stiffness in the k-th element before damage. Thus the number of variables is reduced to K. In equation (11), it is assumed that the stiffness components decrease uniformly in the damage elements.

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By minimizing the error vector norm of equation (10) with respect to α_k, the damage elements are determined. Then the next step is to obtain the damage magnitude in the damage elements. The damage magnitude can be obtained by the minimization of equation (10) using the variables $(D'_j)_k$ in the damage elements. As a nonlinear optimization technique to solve equation (10), the Davidon–Fletcher–Powell method was adopted with the golden section method in the ADS program [7].

3. NUMERICAL RESULTS

As numerical examples, we consider a $[30/-30/90]_s$ laminated composite plate shown in Fig. 1. The plate is divided into 4×16 rectangular bending elements where the damage element has one element size. The damage in laminated composites is modeled as a proper stiffness reduction of all bending stiffness components. From the practical viewpoint of vibration tests, it is better to use fewer vibration modes and fewer measurement points. We use only the three lowest vibration modes and the number of measurement points of deflection components in each vibration mode is 80 (○ and ● points) and 24 (● points) as shown in Fig. 2.

We consider the following three damage cases:

Case 1: $(D_1, D_2, D_3, D_4, D_5, D_6) = (50, 50, 50, 50, 50, 50)\%$ reduction of bending stiffness components in the No.31 element.

Case 2: $(D_1, D_2, D_3, D_4, D_5, D_6) = (23, 18, 16, 35, 21, 23)\%$ reduction of bending stiffness components in the No.31 element.

Case 3: $(D_1, D_2, D_3, D_4, D_5, D_6) = (50, 50, 50, 50, 50, 50)\%$ reduction of bending stiffness components in the No.26 and No.36 elements (24-points measurement).

3.1. Damage location

It is assumed that the exact vibration data can be measured without any measurement error. In the first step of damage identification, the damage location is iden-

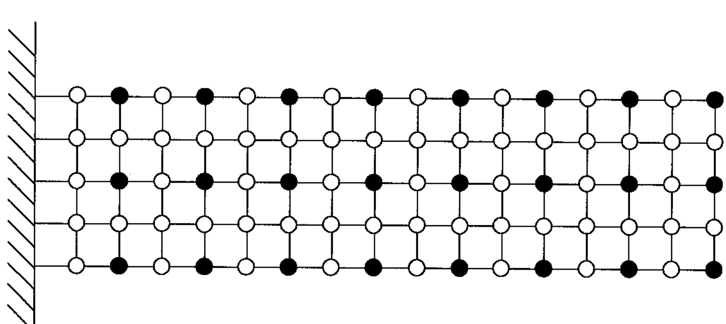

Figure 2. Measurement points of deflection components.

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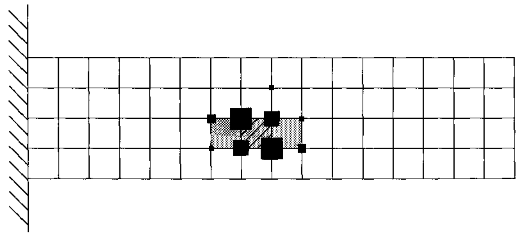
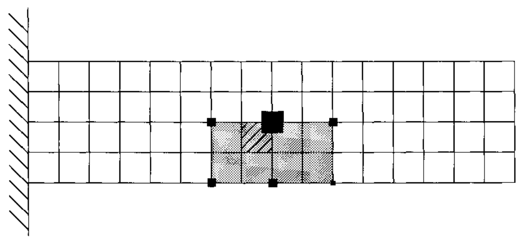


(a) 80-points measurement



(b) 24-points measurement

Figure 3. Identification results for Case 1. (a) 80-points measurement. (b) 24-points measurement.

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tified by using the criterion of equation (8) based on the combined residual force vector. Figure 3 shows the identification results of damage location for Case 1 where the damage is modeled as the 50% reduction of all bending stiffness components in the No.31 element. The hatched region represents the true damage element, and the shaded region represents the one of $|\varepsilon| \geqslant 0.1$ in all nodes surrounding the region. The magnitude of the average damage vector in equation (8) is also indicated by the ■ mark. It is seen that the identified damage region includes the true damage element for both cases of 80-points and 24-points measurement, although the identified damage region is larger for the fewer measurement points. Figure 4 shows the identification results of damage location for Case 2 where the damage model corresponds to the 20% reduction of Q_{11} and the 50% reduction of Q_{12}, Q_{22} and Q_{66} in unidirectional composites. Figure 5 shows the identification results for Case 3 where the measurement points are 24. It is seen in Figs 4 and 5 that the damage region can also be identified precisely. Thus the present identification method based on the criterion of equation (8) can adequately locate the damage region into a small region when the measurement error vanishes.

Now we examine the effect of measurement errors on the identification results of damage location. We treat the identification problem of Case 1 where the measurement points are 24. Figure 6 shows the effect of measurement errors

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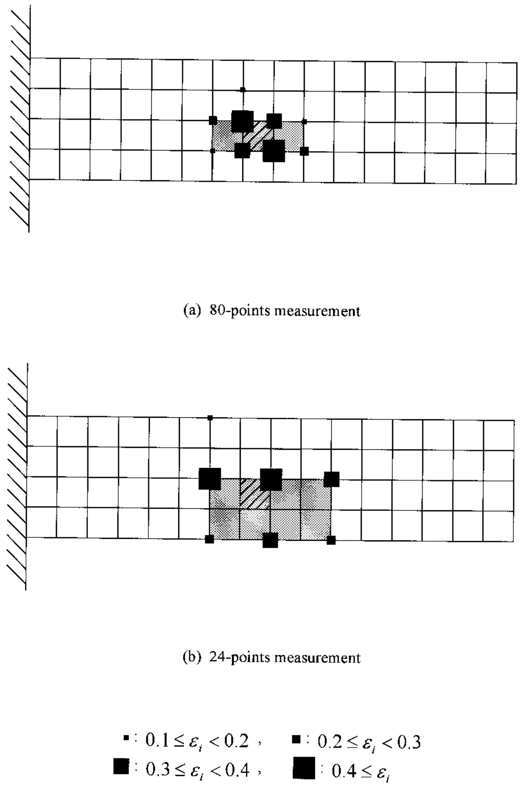

Figure 4. Identification results for Case 2. (a) 80-points measurement. (b) 24-points measurement.

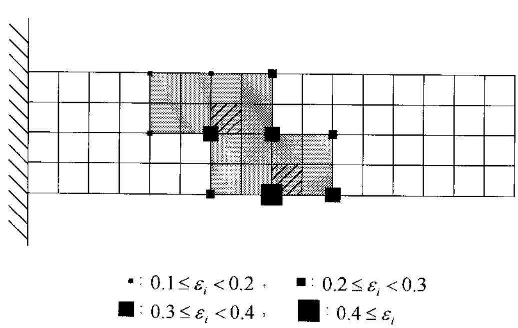

Figure 5. Identification results for Case 3.

where the measurement noise with the normal distribution is added to the deflection components. It is seen that we can locate the damage region accurately for 0.1% measurement error while it is difficult to identify the damage location for 0.5% measurement error.

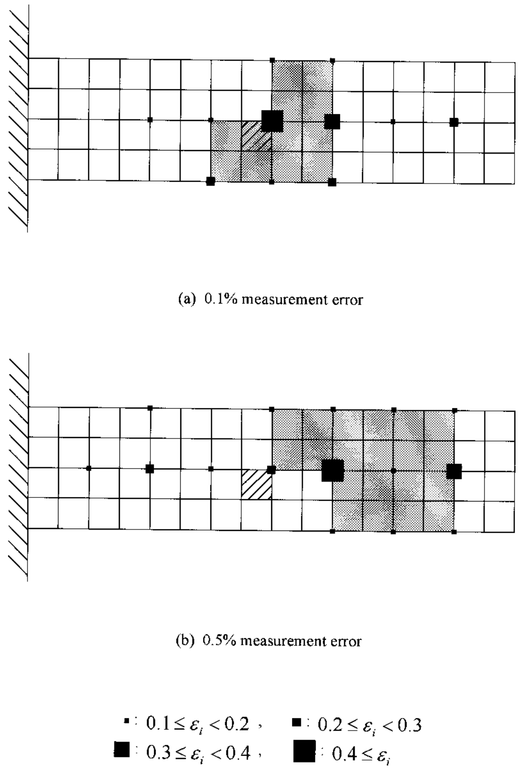

Figure 6. Effect of measurement errors on identification results for Case 1. (a) 0.1% measurement error. (b) 0.5% measurement error.

3.2. Damage magnitude

When the damage region is determined by the criterion of equation (8), we estimate the damage elements within the damage region. Here we assume that the exact vibration data can be measured without any error. Assuming that the stiffness components in elements decrease uniformly after damage, the damage element is identified by minimizing equation (10) with respect to α_k in the possible damage elements. We consider the case of 24-points measurement. As shown in the shaded region of Figs 3–5, the number of possible damage elements is 8 elements for Cases 1 and 2, and 16 elements for Case 3. Figure 7 shows the estimation results using α_k for Cases 1–3. As the initial values of a nonlinear optimization technique, $\alpha_k = 0$ are used. It is seen that the damage element can be identified adequately for Cases 1–3.

When the damage elements are determined as stated above, we obtain the damage magnitude in the damage elements, that is, the stiffness reduction rate. The damage magnitude is obtained by the minimization of equation (10) using the variables $(D'_j)_k$ in the damage elements. Figure 8 shows the identification results for Case 1. The estimated stiffness reduction is shown in the figure with the comparison of exact

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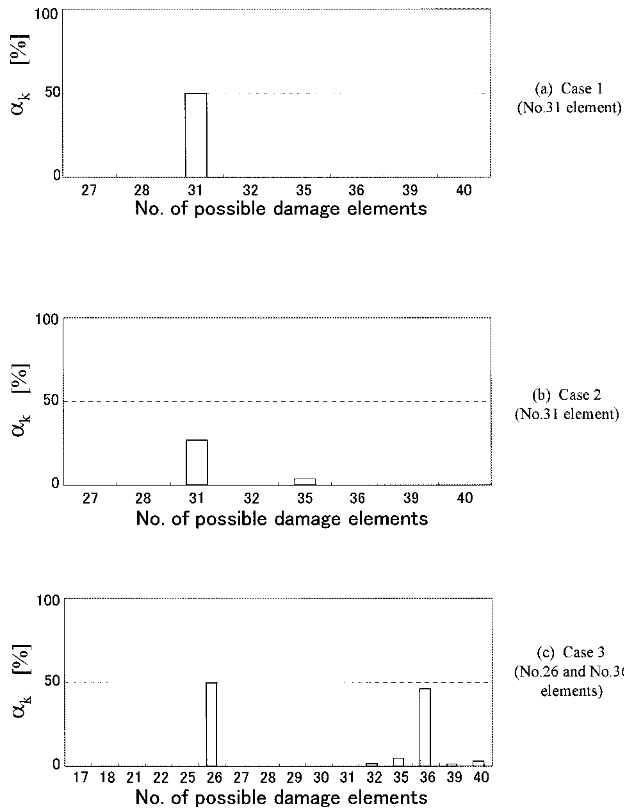

Figure 7. Estimation of damage element using α_k. (a) Case 1 (No.31 element). (b) Case 2 (No.31 element). (c) Case 3 (No.26 and No.36 elements).

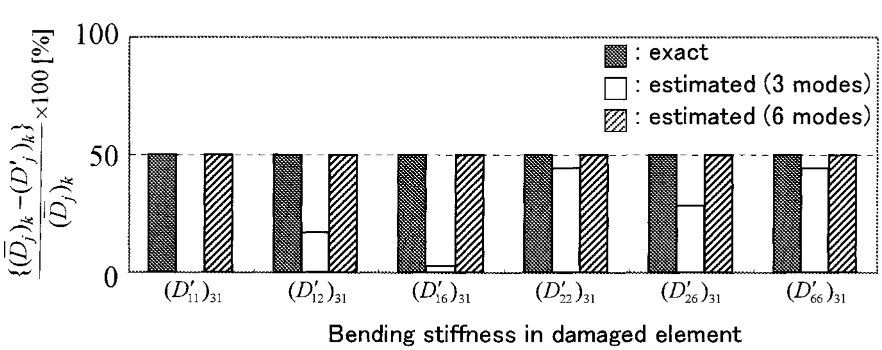

Figure 8. Estimation of bending stiffness using $(D'_j)_k$ for Case 1.

one when we use the three and six lowest vibration modes. It is seen that only the two bending stiffness components, D'_{22} and D'_{66}, are identified for the use of three modes. This is due to the limited sensitivity of other bending stiffness components to the three lowest vibration modes. When we use the six vibration modes, all of the bending stiffness components can be identified precisely.

4. CONCLUSIONS

In the present paper, we suggest a damage identification method for laminated composite structures based on dynamic residual forces. The method consists of a two-step damage detection procedure that initially uses dynamic residual force vectors to locate potential damage regions, and next error vectors of the residual forces are minimized to identify the accurate location and magnitude of structural damage. Effect of measurement points and measurement errors on the identification results is examined through numerical examples on symmetric laminated plates. It is shown that the present method can be useful as a health monitoring of composite structures although the high sensitivity to measurement noise should be improved.

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