Key Engineering Materials Vols. 270-273 (2004) pp. 1852-1858
online at http://www.scientific.net

Development of the Two-step Delamination Identification Method by Resonant and Anti-resonant Frequency Changes

Takaomi Inada[1], Yoshinobu Shimamura[2],
Akira Todoroki[2] and Hideo Kobayashi[2]

[1] Ishikawajima-Harima Heavy Industries Co., Ltd., 1, Shin-nakahara-cho,
Isogo-ku, Yokohama, JAPAN

[2] Department of Mechanical Sciences and Engineering,
Tokyo Institute of Technology, Tokyo, JAPAN

Keywords: Delamination identification, Resonant frequency, Anti-resonant frequency, Composite.

Abstract. Identification of the location and size of delamination is important for structural health monitoring of composite laminated structures, since delamination degrades compression stiffness of the structures. In the present study, a two-step delamination identification method using resonant and anti-resonant frequency changes is proposed. It is well known that resonant frequencies are changed depending on the location and size of delamination. As for anti-resonant frequencies, they also change mainly depending on the location of delamination. Since the resonant and anti-resonant frequencies are specified easily in the frequency response function, the present method is low cost and applicable to any structures. The present method is applied to delamination identification of carbon/epoxy cantilever beams, and effectiveness of the present method is discussed.

Introduction

Recently, composite laminated structures have been applied to many structures of vehicles because of its high specific stiffness and strength. Since interlaminar strength of composite laminated structure is relatively low, internal damage, such as delamination, can be easily induced in service. Since delamination degrades compression strength of the structure, it is necessary to identify the size and location of delamination nondestructively for the assessment of structural integrity. However, conventional nondestructive inspection methods, such as X-ray or ultrasonic inspection, are high cost, and application to large structures is difficult owing to size restriction of the apparatuses.

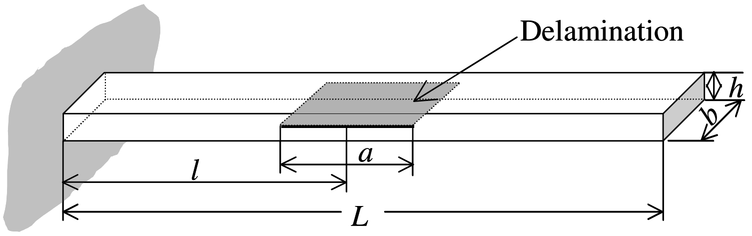
The present study proposes a two-step delamination identification method using resonant and anti-resonant frequency changes. In order to examine effectiveness of the present method, delamination identification of a carbon/epoxy cantilever beam is conducted. As a preparation for delamination identification, the beam is divided into two domains based on the mode shapes. The delaminated domain in which delamination is supposed to exist is first identified from the anti-resonant frequency changes, and the delamination location and size are identified from the resonant frequency changes to the next. In order to analyze frequency response changes caused by delamination, finite element method was applied. Effectiveness of the present identification method was investigated both in analysis and experiment.

Symmetry of Resonant Frequency Changes

Fig.1 shows schematic of a carbon/epoxy cantilever beam with delamination. The beam is 1.45mm thick, 19mm wide and 200 mm long. The laminate configuration of the beam is $[0_2/90_2]_S$, and a through width delamination is existed at one 0/90 interlayer. In order to examine effect of delamination location and size on the resonant frequencies of the beam, modal analyses of the beam were conducted by using ANSYS, a commercially available general-purpose finite element code. Table 1 shows material properties of uni-directional carbon/epoxy lamina used for calculation, where subscript 1 means the direction parallel to the fiber and subscripts 2 and 3 means the direction perpendicular to the fiber. In the present paper, normalized values l/L and a/L are employed to express the delamination location and size respectively, where L is beam length.

Fig.2 shows resonant frequency changes of the beam as a function of delamination location obtained by FEM analysis, where delamination size is constant value 0.1. In fig.2, abscissa means delamination location and ordinate means frequency value normalized by the intact value of each mode. In general, reduction of resonant frequency is caused by stiffness reduction of structures. For a composite laminated beam with delamination, reduction of the bending stiffness is caused when shear force acts on the delamination, and shear force distribution of each mode depend on each modal shape. For this reason, the resonant frequency changes of the cantilever beam shows quasi-symmetry in the region defined by $0.3 \leq l/L \leq 0.7$ except for the first mode, though the cantilever beam is not a symmetric structure. This causes failure in identification of delamination location based on resonant frequency changes [1].

In order to make it possible to identify delamination location in the cantilever beam, another parameters that have information about delamination location and no symmetry. In the present study, anti-resonant frequency is adopted.



(L=200mm, b=19mm, h=1.45mm)

Fig. 1. CFRP cantilever beam with delamination (laminate configuration: $[0_2/90_2]_S$)

Table 1. Material properties of unidirectional CFRP lamina

Longitudinal modulus E_1	91.5 GPa
Transverse modulus E_2 (=E_3)	8.5 GPa
Longitudinal shear modulus G_{12} (=G_{13})	4.3 GPa
Transverse shear modulus G_{23}	3.15 GPa
Major Poisson's ration ν_{12} (=ν_{13})	0.31
Transverse Poisson's ratio ν_{23}	0.35
Density ρ	1466 kg/m^3

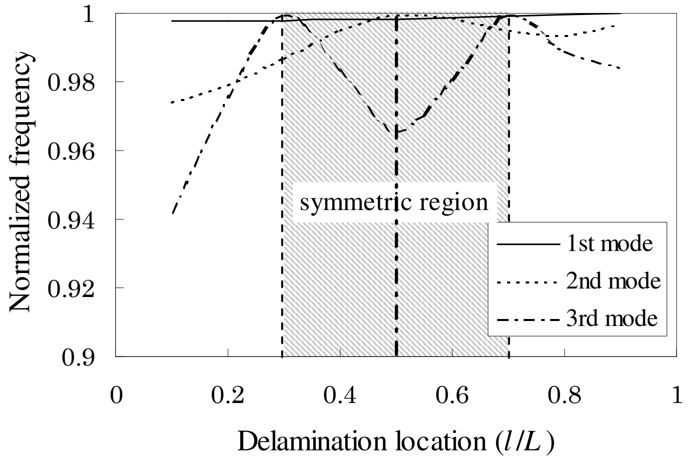


Fig. 2. Resonant frequency changes as a function of delamination location (a/L=0.1)

Two Step Delamination Identification Method

Many researchers have investigated damage identification methods using the resonant frequency changes [1-6]. However, the resonant frequency change method alone may not be sufficient for unique identification of damage location as mentioned previously [1,6]. For example, in symmetric structure like a clamped-clamped beam, the appearance of the resonant frequency change as a function of damage location is symmetric. In this case, two candidates for damage location are obtained from the resonant frequency changes, but it is impossible to select the correct one.

In the present study, a two-step delamination identification method using resonant and anti-resonant frequency changes is proposed. The delaminated domain is first identified from the anti-resonant frequency changes, and delamination location and size are identified from the resonant frequency changes to the next.

Delaminated Domain Identification Using Anti-resonant Frequency Changes. Delaminated domain identification means identifying the domain in which delamination is supposed to exist. As mentioned in the previous section, identification of delamination location of the cantilever beam is difficult owing to symmetry of the resonant frequency changes. In order to make it possible to identify delamination location of the cantilever beam, effect of symmetry of the resonant frequency changes must be removed. In the present study, the cantilever beam is divided into two domains that have no symmetry of the resonant frequencies. If the delaminated domain is identified before the delamination identification using resonant frequency changes, we can obtain correct delamination location. Anti-resonant frequency changes are adopted for delaminated domain identification.

Fig.3 shows a definition of the domain of the cantilever beam. The resonant frequency changes as a function of delamination location show symmetry with respect to center of the beam. In order to remove effect of symmetry of the frequency, the beam must be divided into two spanwise domains around the center of the beam as shown in fig.3. Domain A is defined by $0<x/L<0.5$, and Domain B is defined by $0.5\leq x/L<1$. The anti-resonant frequencies are obtained by the frequency response function of the beam. For delaminated domain identification, the actuating point and measuring point have to be located around both ends of one domain. We set the actuating point as $x/L=0.05$ and the measuring point as $x/L=0.45$. Since the boundary of the domains corresponds to nodal point of the second flexural mode, its peak and the corresponding dip are undetectable on the frequency response measured at $x/L=0.5$. For this reason, the measuring point is displaced from $x/L=0.5$ to $x/L=0.45$. The offset effect on the delamination identification is negligible.

For delaminated domain identification using the anti-resonant frequnecy changes, we define a non-dimensional parameter D as follows.

$$D_{ij}=\frac{\Delta f_{A,ij}}{\left|\Delta f_{R,i}\right|+\left|\Delta f_{R,j}\right|}\times 100 \qquad \left(i\geq 1,\ \ j=i+1\right) \tag{1}$$

where $\Delta f_{R,i}$ and $\Delta f_{R,j}$ mean the resonant freqnency changes of the ith and the jth mode respectively. $\Delta f_{\mathrm{A},ij}$ means the anti-resonant frequency change observed between the ith and the jth resonant peaks on the frequency response diagram. Fig.4 shows delaminated domain identification example based on parameter D. In fig.2, case I and case II show the results when delamination is located in domain A, and case III shows the result when delamination is located in domain B. Since the anti-resonant frequencies may decrease on case I, we set a threshold line of decrement as shown in fig.2 with a dashed line. When at least one of the parameter D_{ij} calculated by the frequency response function is larger than the threshold level, the delaminated domain is identified as Domain A. When at least one of them is smaller than the line, the delaminated domain is identified as Domain B.

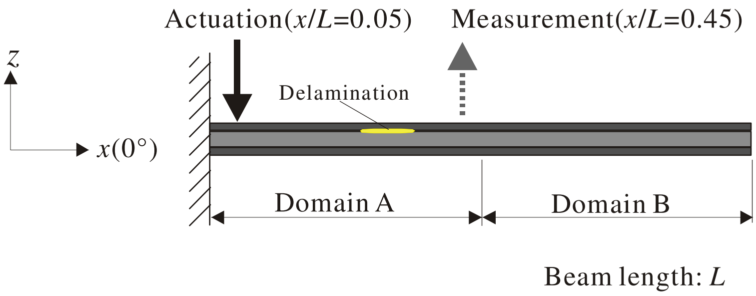


Fig. 3. Definition of the domains (Domain A: $0<x/L<0.5$, Domain B: $0.5\leq x/L<1$)

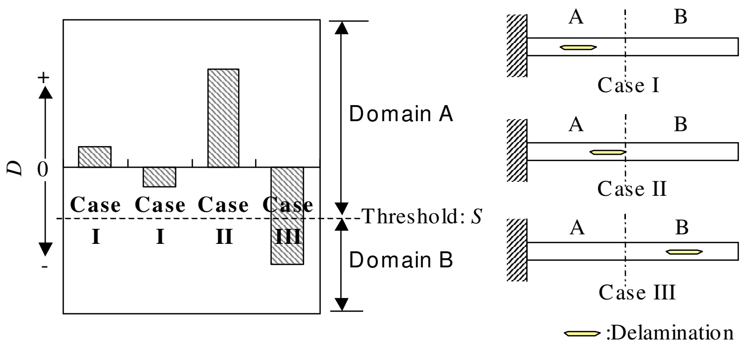


Fig. 4. Delaminated domain identification based on parameter D (Example)

Delamination identification using resonant frequency changes. After identifying delaminated domain identification using anti-resonant frequency changes, delamination identification is conducted using resonant frequency changes to the next. Since the resonant frequency changes are very complex, error minimization technique is used for delamination identification[1].

As preparations for delamination identification, relationship between the resonant frequency changes and the delamination size and location must be investigated by FEM analysis or numerical calculation. After obtaining the data set, response surfaces of the resonant frequency changes are constructed. Namely, response surfaces are used to obtain the approximate expressions of relation between the first three resonant frequencies and the delamination parameters. If we use a quadratic polynomial expression, response surface is expressed as follows:

$$y=\beta_0+\beta_1x_1+\beta_2x_2+\beta_3x_1^2+\beta_4x_2^2+\beta_5x_1x_2 \tag{2}$$

where y is the resonant frequency, x_1 is the delamination location and x_2 is the delamination size. To calculate the coefficients β, least squares method are used. Judging from the resonant frequency changes shown in fig.2, a third order polynomial is used to approximate the resonant frequency change of the first mode in each domain. In a similar way, fourth order polynomial and fifth order polynomials are used to approximate the frequency changes of the second and third mode, respectively. Now, we define these response surfaces as $\Omega_{1,A}(x_1,x_2)$, $\Omega_{2,A}(x_1,x_2)$, $\Omega_{3,A}(x_1,x_2)$ in domain A, as $\Omega_{1,B}(x_1,x_2)$, $\Omega_{2,B}(x_1,x_2)$, $\Omega_{3,B}(x_1,x_2)$ in domain B. Also, we define the resonant frequencies of the beam with unknown delamination as $(\omega_1,\omega_2,\omega_3)$. In order to identify delamination of the beam, we make a performance function as follows.

$$F=\sum_{i=1}^{3}\left\{\omega_i-\Omega_{i,Domain}\left(x_1,x_2\right)\right\}^2 \tag{3}$$

where subscript “Domain” means delaminated domain identified by the anti-resonant frequencies. We can identify the delamination location and size by minimizing the function F. Since there are some local minimums in the function, minimizations are conducted with 10 kinds of initial values. From the candidate obtained by minimization, global minimum is obtained.

Delamination Identification Results

In order to examine effectiveness of the present method, delamination identification of a cantilever beam is conducted based on analytical data and experimental data. The delaminated domain is identified first from the anti-resonant frequency changes, and the delamination location and size are identified from the resonant frequency changes to the next.

Identification Results Based on Analytical Data. Fig.5 shows delaminated domain identification results of the beam based on parameter D at normalized delamination size is 0.1. In the figure, the ordinate means the value of parameter D, and the abscissa means delamination location normalized by the beam length. We used three anti-resonant frequency changes for delaminated domain identification, D_{12}, D_{23} and D_{45}. Since the anti-resonant frequency between the two resonant peaks may change by mean value of the two resonant frequency changes, threshold level is set as –50. By using the threshold, we can identify the delaminated domain correctly as shown in fig.5.

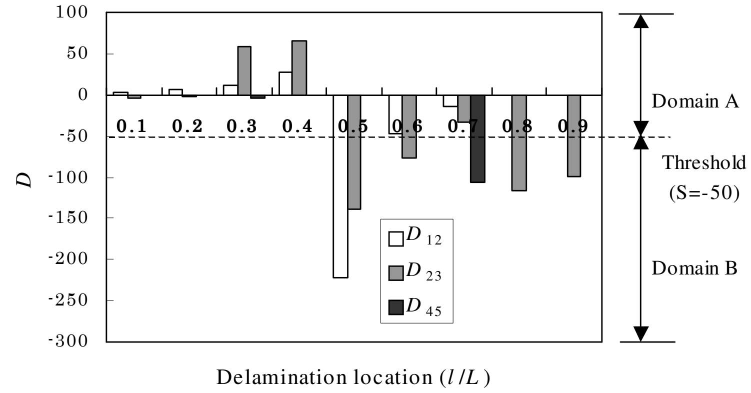


Fig. 5. Delaminated domain identification results based on parameter D (Analysis, a/L=0.1)

Fig.6 shows comparison between actual and predicted delamination locations. Though the data sets are not considered in the response surfaces of the resonant frequency changes, the identified values are well agreed to the actual ones. Though it is not shown in the paper, we can also identify the delamination sizes precisely. The mean identification error of the delamination sizes is about 0.5%.

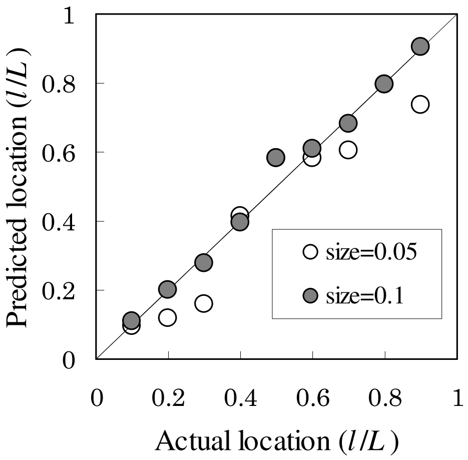


Fig. 6. Identification results of delamination locations based on analytical data