Research on Damage Identification Method of Composite Materials Based on Displacement Modal Shape Parameters

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Abstract. In terms of dynamic detection, in order to improve the identification effect of model parameters on damage, in this paper, a displacement modal shape processing method based on difference accumulation is proposed, and the calculated result of the accumulated difference is used as a damage characterization parameter. With regards to the damage of composite materials, Camanho-Matthews stiffness degradation criterion is introduced to simulate the stiffness degradation characteristics of four damage forms of composite materials: matrix cracking, matrix extrusion, fiber stretching and fiber compression. Taking the composite cantilever beam as the research object, the numerical simulation shows that the difference accumulation method can simultaneously identify the damage of single damage and multiple damage structures under four damage forms, and it can effectively identify the damage forms and damage locations. Moreover, the damage identification sensitivity of the difference accumulation method gradually increases with the position of the damage approaching the fixed end, which has an advantage for the damage identification of the cantilever beam approaching the fixed end.

1. Introduction

Carbon fiber reinforced composites have the advantages of high specific strength, high specific modulus, strong design ability and good fatigue properties, having been widely used in many fields such as aviation, aerospace and military industries[1]. With the development of technology, composite material is gradually developing into the main bearing component material, becoming the fourth largest structural material after aluminum, steel and titanium[2]. How to ensure the safety of composite structural components in the actual work process is a research focus in the field of engineering. Under this background, composite structural health monitoring technology has developed rapidly and become an important way to ensure the safe operation of engineering structures.

Damage identification technology is one of the core contents of health monitoring, and dynamic detection is an important development direction of damage identification[3-5]. Damage is defined as a change that has an adverse effect on structural performance. Common manifestations are local stiffness decrease or damping increase [6]. Once the structure is damaged, the dynamic parameters of the structure will change accordingly. The dynamic detection technology based on modal analysis identifies the damage condition of the structure precisely by analyzing the dynamic response characteristics of the structure[7].

Modal shape is an accessible modal parameter, which contains abundant information about damage location and damage degree, and it is not sensitive to structural feature changes caused by anisotropy of composite materials. Therefore, modal shape parameters have a good application value in the field
of damage detection of composite materials [8-9]. West systematically uses modal shape parameters to identify structural damage earliest [10]. In recent years, many researchers have proposed some new damage identification methods based on modal shapes. Wan X, et al. have proposed a structural damage identification index based on the change rate of first-order modal shapes, and simulation shows that the index has a good damage identification effect on single-damage structures [11]; Gu G, et al. proposed a damage identification index of axial mode difference change rate for the fan blade structure, and the test verified that this parameter can accurately identify the damage location [12]; Yu J, et al. deduced the modal shape curvature method, the load section curvature method and the virtual axial strain method theoretically, proposed a new damage identification index for the phenomenon of modal migration, and applied it to the damage detection of truss structures [13].

Through the above analysis, it can be found that although a great deal of research work has been done on damage identification based on modal shapes, most of the damage identification methods need both intact structure and damaged structure modal shapes to construct damage identification indexes, such as modal difference method and modal change rate method, and these methods are only applicable to single damaged structure and cannot be used for damage identification of structures with multiple damage at the same time. By analyzing the characteristics of displacement mode shapes of damaged structures, this paper proposes a damage identification method that only needs damage mode shapes, which has an accurate damage identification effect for both single damage and multi-damage structures.

2. Damage Identification Principle Based on Modal Shape

2.1. Transverse Vibration of Beam

According to the simplified theory of beam bending vibration, the bending equation of beam bending curve can be expressed as follows:

$$EI \frac{\partial^2 y}{\partial x^2} = M$$  (1)

Thereinto, $y$ is the transverse displacement of the beam; $EI$ is the bending stiffness of the beam; $M$ is the section bending moment.

When the beam vibrates freely, according to the d’Alembert principle, the differential equation of the transverse vibration of the beam can be expressed as follows:

$$\frac{\partial}{\partial x} [EI(\frac{\partial y}{\partial x})] + m \frac{\partial y}{\partial t^2} = 0$$  (2)

Thereinto, $m$ is the mass of the unit beam length.

According to the boundary conditions of the cantilever beam, the modal shapes of the cantilever beam structure can be expressed as below:

$$\phi(x) = ch \frac{\omega_i}{l} x - \cos \frac{\omega_i}{l} x + \zeta (sh \frac{\omega_i}{l} x - \sin \frac{\omega_i}{l} x)$$  (3)

Thereinto, $\omega_i$ is the natural frequency of Order $r$; $\zeta$ is the Order $r$ damping ratio; $L$ is the length of the beam.

2.2. Damage Identification Method

When the structure is damaged at a certain position, the displacement modal shape curve at the damaged position will be affected, resulting in a sudden change in the vibration displacement of the damaged position relative to the adjacent position, but this sudden change value is small relative to the vibration displacement itself and cannot be directly observed through the modal shape curve. Therefore, in view of the difficulties faced by damage identification based on displacement mode shapes, this paper proposes a mode shape processing method with cumulative difference, and defines the calculation result of this method as cumulative difference, which is used to represent structural damage. This method eliminates the effect of the amplitude of the original mode curve on damage.
identification, and it can significantly improve the damage detection sensitivity of the accumulated difference value through the accumulative effect.

By taking the damage of cantilever beam considering only transverse bending vibration as an example, the application method of difference accumulation method is described in detail. The cantilever beam is equally divided into n elements along the axial direction, and the lateral vibration displacement of the i-th element (i is greater than 1) is \( y(i) \); the lateral vibration displacements of adjacent elements on the left and right sides are \( y(i-1) \) and \( y(i+1) \), respectively, and the expression of the difference accumulation method of the r-th order displacement modal shape is as follows:

\[
T_r(i) = [y_r(i+1) - y_r(i)] - [y_r(i) - y_r(i-1)]
\]

2.3. Stiffness Degradation Criterion for Composite Materials

The composite materials will be subjected to various loads during use, resulting in various forms of damage to the composite material \([14-15]\). In this paper, Camanho-Matthews stiffness degradation criterion is introduced to simulate the damage forms of composite materials for the four damage forms of fiber stretching, fiber compression, matrix stretching and matrix compression. The specific damage criteria are as shown in table 1.

| Modal of damage       | Degradation low                                                                 |
|-----------------------|----------------------------------------------------------------------------------|
| Fiber tensile damage  | \( E_{11}, E_{22}, G_{12}, G_{13}, G_{23}, \mu_{12}, \mu_{13} \), and \( \mu_{23} \) are reduced to 7% of the initial value |
| Fiber compressive damage | \( E_{11}, E_{22}, G_{12}, G_{13}, G_{23}, \mu_{12}, \mu_{13} \), and \( \mu_{23} \) are reduced to 14% of the initial value |
| Matrix tensile damage | \( E_2 = 0.2 \times E_{22} \), \( G_{12} = 0.2 \times G_{12} \), \( G_{23} = 0.2 \times G_{23} \) |
| Matrix compressive damage | \( E_2 = 0.4 \times E_{22} \), \( G_{12} = 0.4 \times G_{12} \), \( G_{23} = 0.4 \times G_{23} \) |

3. Simulation Example

The research object of this paper is a four-layer CFRP cantilever beam structure. The geometric size of the sample is \( 100 \times 10 \times 1 \) (mm, \( L \times B \times H \)) and the thickness of the single layer plate is 0.25 mm. The angle between the principal axis coordinate system of the first and fourth layers of the laminated beam and the overall coordinate system of the laminated plate is 0°. The angle between the principal axis coordinate system of the second and third layers of the laminated beam and the overall coordinate system of the laminated plate is 90°, which is shown in figure 1. The sample adopts T300 epoxy material, and the material constant of the single layer is as follows: \( E_{11} = 131000 \text{MPa}, E_{22} = 9000 \text{MPa}, G_{12} = G_{13} = 54000 \text{MPa}, G_{23} = 45000 \text{MPa}, \mu_{12} = 0.3, \mu_{13} = \mu_{23} = 0.34 \).

By using Abaqus finite element analysis software, the modal analysis of composite cantilever beam is carried out by Block Lanczos solution method. The cantilever beam structure is divided into 20 elements. The plan view of its finite element model is shown in figure 2, and the displacement modal shape is determined by the displacement amplitude of 20 equidistant elements in the cantilever beam axis direction.
3.1. Research on Damage Identification Based on Displacement Modal Shape

The damage identification effect of modal shape parameters was studied by taking the four damage forms of fiber stretching, fiber compression, matrix cracking and matrix compression in the central Element (Element 10) as examples. As can be seen from figure 3, there is little difference between the first-order displacement mode curves of intact and damaged structures, and there is no significant difference between the first-order displacement mode curves of different damage forms. Therefore, the mode parameters cannot better identify the damage forms. At the same time, it can also be found that the first-order displacement mode shape curve does not have an obvious identification quantity at the damage location (Element 10) to characterize the structural damage, hence the mode shape parameters cannot accurately identify the damage location. Through the above analysis, it can be found that the displacement modal shape curve can not effectively identify the location of structural damage and the form of damage, which is also applicable to other displacement modal shapes.

3.2. Research on Single Damage Identification Based on Difference Accumulation Method

The damage identification characteristics of composite cantilever beams by differential accumulation method were studied when different types of damage occurred in the cantilever beams. Figure 3 shows that the identification effect of the difference accumulation method on the four damage forms of composite materials when the damage occurs in element 10 of the composite cantilever beam. As can be seen from figure 3, when the 10th element of the structure is damaged, the damage will cause mutation on the accumulated difference, and the mutation values generated by different damage forms are different in size, and the sequence of the mutation values is fiber stretching, fiber compression, matrix stretching and matrix compression respectively. Hence, the cumulative difference method can effectively identify the damage location and damage degree.
When the damage occurred in different positions of the cantilever beam, the damage identification characteristics of composite cantilever beam by differential accumulation method were studied. According to the distance between the damage position and the fixed end of the cantilever beam, four groups of simulation examples are prepared, namely, the nondestructive beam example, the damage example of element 4, the damage example of element 10, and the damage example of element 15. In order to control a single variable, the damage forms of the above examples all adopt the fiber fracture that has the most serious influence on the strength of the composite structure, and the calculation results of the four damage examples are shown in figure 5. According to figure 5, for the composite cantilever beam structure, under the same damage form, when the damage occurs at different positions, the abrupt change value of the accumulated difference is different, and the closer the damage element is to the fixed end of the cantilever beam, the greater the abrupt change value of the accumulated difference value is. Therefore, the damage identification sensitivity of the difference accumulation method gradually increases as the position of the damage gradually approaches the fixed end, which has an advantage for damage identification of the cantilever beam near the fixed end.

3.3 Research on Multi-damage Identification Based on Difference Accumulation Method

Through the study of the above simulation examples, the damage identification effect of the differential accumulation method for single-damage cantilever beam structure was verified, and the sensitivity characteristics of the differential accumulation method were studied. Through the analysis of the following multi-damage examples, the damage identification characteristics of the multi-damage cantilever beam structure by the difference accumulation method will be further studied.

When multiple damage occurs to the same cantilever beam, the damage identification characteristics of composite cantilever beam by differential accumulation method are studied. Taking a composite cantilever beam with three damages as an example, the damage identification characteristics of the difference accumulation method were studied when the fiber tensile damage occurred simultaneously in element 5, element 11 and element 16. The results are shown in figure 6. It can be seen from figure 6 that when a cantilever beam suffered three damage at the same time, the accumulated difference will mutate at each damage location. Therefore, the damage identification index has a good damage location effect on multi-damage structures. At the same time, it can also be
found that although the damage degree of the three elements is the same, the abrupt change of the accumulated difference value is different, and the nearer the damage is to the fixed end of the cantilever beam, the abrupt change of the accumulated difference value is more severe. This conclusion is the same as that in the case of single damage.

![Figure 6. Cumulative difference of concurrent fiber tensile damage of 3 elements](image)

4. Conclusion
1) The difference accumulation method proposed in this paper is a damage identification method that only needs the current modal shape of the structure, which is different from the damage identification method that requires both intact and damaged structures. This method is of progressive significance for health monitoring system to simplify the processing of modal shapes and reduce the storage space of modal shapes.

2) The difference accumulation method can accurately locate the damage of single damage and multi-damage structures at the same time, and the damage form of composite materials can also be better identified by analyzing the amplitude of the accumulated difference mutation.

3) For single-damage and multi-damage cantilever beam structures, the sensitivity of damage identification increases gradually as the damage position approaches the fixed end. This feature has high application value for cantilever beam structures that are prone to damage at the fixed end.

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