Composite Failure Detection in π-Joint Structure Using Fiber Bragg Grating Sensors

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Abstract. The use of composite structures in engineering applications has proliferated over the past few decades. This is mainly due to their distinct advantages of high structural performance, high corrosion resistance, high strength and weight ratio. They are however prone to fiber breakage, matrix cracking and delaminations which are often invisible. Although there are systems to detect such damage, the characterization of the damage is often much more difficult to achieve. A study is presented of the damage detection of a carbon fiber composite π-joint structure under bending loads using fiber Bragg grating sensor. Firstly, based on the general FEM software, the 3-D finite element model of composite π-joint is established, the failure process and every lamina failure load of composite π-joint were investigated by maximum stress criteria. Then, strain distributions belong the length of fiber Bragg grating were extracted, the reflection spectra of fiber Bragg grating have been calculated according to the strain distribution. Finally, to verify the numerical results, a test scheme was performed and the experimental spectra of fiber Bragg grating were recorded. The experimental results indicate that the failure sequence and the corresponding critical loads of failure were consistent with numerical predictions and the computational error of failure load is less 6.4%. Furthermore, it also verified the feasibility of the damage detection system.

Introduction

The use of composite in aerospace engineering applications has proliferated in recent years [1]. This is mainly due to their distinct advantages of high structural performance, high corrosion resistance, high strength / weight ratio and easy to shape. With the development of the composite technique, the integrated composite structures, which enable reduction in fastener and part counts and lead to the dramatic decrease of assemble cost and primary structural weight, are gradually used in aircraft structures [2][3][4]. The adhesive bonding joint, composed of two orthogonally placed parts meeting at a joint, such as L-joint, T joint, π-joint and so on, is an effective way to use integrated composite structures. For example, American F-35 Joint Strike Fighter used π-joints on the forward fuselage [3] European EF-2000 fighter wing are used in the curing of skin and vertical web structure [4]. These indicate that this technique may reduce the weight and improve the combat capability of the aircraft.

Damage initiates during service due to operational loading, aging, chemical attack, mechanical vibration and shocks [5][6]. Existing techniques, such as X-ray, ultrasonic C-scan and laser shearography have been applied to detect these damages [7]. However, it takes much time to inspect the composite joint structures by these techniques. Especially it can not realize online monitoring. Therefore, online monitoring of the damages in the composite joint structures is desired [8][9]. Fiber Bragg grating(FBG) sensor, as a new kind of sensor, has been widely applied in the field of structural health monitoring, for its light weight, small
diameter, resistance to electromagnetic radiation, corrosion resistance and so on \([10][11][12]\). This paper studied a kind real-time online monitoring system using fiber Bragg grating sensor, which used to monitor the failure of composite \(\pi\)-joint structure under bending loads.

1. Analysis on spectrum characteristics of FBG

For a FBG sensor, if it is subjected to an even strain, the shape of spectrum don’t change, we can obtain the strain value from the shift of maximum reflection wavelength \([13]\). If it is under uneven strain along the length of the grating, the spectrum shape of FBG will be not the same as before \([14]\), and we cannot get the value of the uneven strain directly by examine the maximum reflection wavelength, that is mainly because we can only get the average value of the strain of all points along the grating length. However, the structural form of composite \(\pi\)-joint is complicated. It is subjected to uneven strain when it is under bending load. And then, we analyze the spectrum characteristics of FBG when it is under uneven strain field.

Fiber gratings are produced by exposing a photosensitive fiber to a spatially varying pattern of ultraviolet intensity. Here we assume for that what results is a perturbation to the effective refractive index \(n_{\text{eff}}\) of the guided mode(s) of interest, described by \([14]\)

\[
\delta n_{\text{eff}} (z) = \delta n_{\text{eff}} (z) \left\{ 1 + \nu \cos \left[ \frac{2\pi}{\Lambda} z + \phi (z) \right] \right\}
\]

where, \(\delta n_{\text{eff}} (z)\) is the “dc” index change spatially averaged over a grating period, \(\nu\) is the fringe visibility of the index change, \(\Lambda\) is the grating period, and \(\phi (z)\) describes grating chirp, which may be caused by fabrication or a non-uniform strain field. In this paper, it means the chirp is caused by a non-uniform strain field. If this factor is attributed to the period parameters, the refractive index modulation can be written in

\[
\delta n_{\text{eff}} (z) = \delta n_{\text{eff}} (z) \left\{ 1 + \nu \cos \left[ \frac{2\pi}{\Lambda(z)} z \right] \right\}
\]

where, \(\Lambda(z)\) is the effective period of FBG when it is subjected a non-uniform strain.

When fiber Bragg grating is subjected to a non-uniform strain along its length, its effective refractive index and period will be changed, so the effective period of FBG can be describe by

\[
\Lambda (z) = \Lambda_0 \left[ 1 + (1 - p_e) \varepsilon (z) \right]
\]

where, \(\Lambda_0\) is the nominal period of FBG, \(p_e\) is elasto-optical coefficients of optical fiber, its value is equal to 0.26. From Eq. (1), (2) and (3), the grating chirp \(\phi (z)\) can be written as

\[
\phi (z) = -\frac{2\pi z}{\Lambda_0} \left[ \frac{(1 - p_e) \varepsilon (z)}{1 + (1 - p_e) \varepsilon (z)} \right]
\]

According to weakly guiding condition and coupled-mode theory, we can obtained the following simultaneous differential equations \([15]\)

\[
\frac{dR}{dz} = i \hat{\sigma} R (z) + i \kappa S (z)
\]

\[
\frac{dS}{dz} = -i \hat{\sigma} S (z) - i \kappa R (z)
\]

where, \(R\) and \(S\) are the amplitudes of the forward-propagating mode and the backward-propagating mode, respectively. In these equations, \(\hat{\sigma}\) is general “dc” self-coupling coefficient and \(\kappa\) is the “AC” coupling coefficient defined as
\[
\dot{\sigma} = \frac{2\pi}{\lambda} \frac{\delta n_{\text{eff}}}{\lambda} + 2\pi n_{\text{eff}} \left( \frac{1}{\lambda} - \frac{1}{\lambda_0} \right) \frac{1}{2} \frac{d\phi}{dz} 
\]

(7)

\[
\kappa = \frac{\pi}{\lambda} \sqrt{\delta n_{\text{eff}}} 
\]

(8)

In equation (7) \( \lambda_0 = 2n_{\text{eff}} \Lambda_0 \) is the designed wavelength which would be changed when FBG is subjected to various strain condition. The reflection coefficient of FBG is defined as

\[
\rho(z) = S(z) / R(z) 
\]

(9)

By substituting equation (9) into equation (5), we can obtained the following differential equation

\[
\frac{d\rho(z)}{dz} = -i\kappa - 2i\delta \rho(z) - ik\rho^2(z)
\]

(10)

The length of the grating is assumed to be \( L (L=10\text{mm}) \), so the limits of the grating is defined as \(-L/2 \leq z \leq L/2\). While the boundary conditions of FBG are \( R(-L/2) = 1 \) and \( S(L/2) = 0 \) [15]. Researches used transmission matrix method to solve equation (10) before. In this paper, Combine with equation (4), (7) and (8), we solve it by Runge-Kutta method. Thus the grating’s reflectivity \( r = |\rho|^2 \) can be obtained when the FBG is subjected to non-uniform strain.

2. Experimental specimen

In this paper, composite \( \pi \)-joint is taken as the research object. A composite \( \pi \)-joint consisting of a horizontal typical skin laminate, a vertical web, one “U” preform, one small horizontal preform and double “L” preform, in which the vertical web is bonded to two corners and one horizontal preform, was investigated as shown in Fig.1. The main dimension parameters of the \( \pi \)-joint are shown in Fig.2. The material of composite \( \pi \)-joint is carbon fiber, its properties are shown in Table 1.

![Fig.1 π-joint components schematic](image1.jpg)

![Fig.2 π-joint configuration dimension parameters (unit: mm)](image2.jpg)

<table>
<thead>
<tr>
<th>Table 1 Properties of material</th>
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<td><strong>Materials</strong></td>
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<td>Carbon fiber</td>
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3. Failure analysis of composite π-joint

In composite laminates, each lamina has two kinds of failure modes: matrix failure and fiber breakage. To the failed composite lamina, two modified stiffness models, full stiffness elimination model and partial stiffness elimination model, are used in general. In the first method, as long as one lamina is failed, regardless of their failure model, we assume that all stiffnesses of this lamina are disappeared, that is \( E_1 = 0 \), \( E_2 = 0 \), \( G_{12} = 0 \), but its thickness and location are not changed. In the second method, if the failure model is matrix failure, we assume that the values of \( E_2 \) and \( G_{12} \) are equal to zero, but \( E_1 \) remains the same. If the failure model is fiber breakage, the case is same to the assumption in the first method [16]. In this paper, we will use the first modified stiffness model, that is, full stiffness elimination model.

It is shown in literature [17] and [19] that “L” preform is the weakest part of the composite π-joint structure. Therefore, the failure process of the “L” preform is studied under bending load. Firstly, determined its initial failure lamina and modified its stiffness, then increased the load to find the second lamina. This process is repeated until all layers are failed. Using this gradually failure analysis method, we can obtain the failure sequence of “L” preform and corresponding critical load of each lamina. The calculating procedure is as following.

1. Build the finite element model of π-joint.
2. Initial load is applied to the finite element model of π-joint, then, the node stress of each lamina is analyzed through the finite element software.
3. The node stresses are put into the Tsai-Wu criterion equation to make out the damage index of each lamina. Take the lamina in which damage index is the biggest as the failed lamina, then, the critical load of failure is derived by maximum stress criterion.
4. According to the modified stiffness model, we can obtain the new stiffness of structure when one lamina is failed.
5. Repeat step 1-2 until all layers of the “L” preform are failed.

Based on the finite element (FE) analysis software ANSYS, for “U” perform, small horizontal preform and “L” perform, the FE models are set up with shell element, but to remain parts, the FE models are set up with solid element. Then, all parts are assembled to be a general structure. The Finite element model and FE mesh of the whole π-joint are given in Fig.3.

![Fig.3 Finite element model and mesh of π-joint](image)

The constraint conditions of π-joint should be decided by the experiment. Because of the complexity of composite π-joint, it is difficult to analyze. The numerical analysis methodology encompassed the following basis assumption: (1) Without considering the deformation, preload and friction force of the holding position; (2) The vertical displacements of the nodes on the holding position, in both forward and back sides of the
skin, are constrained. In this stage, the model does not contain FBG sensor. Therefore, the failure sequence, the corresponding critical loads which are shown in Table 2 and the strain distribution of the “L” preform will be obtained through the static analysis of the model, also can be extracted from the analysis.

| Table 2 Failure sequence and corresponding critical failure load of “L” preform |
|------------------|------------------|------------------|
| Failure sequence of “L” preform | 1 | 2 | 3 |
| Failure region   | 0° lamina | 45° lamina | -45°lamina |
| Critical failure load | 1514 N | 1548 N | 1593 N |

From the FEM analysis results, we can extract the strain distributions belong the length of fiber Bragg grating, as shown in fig.4. Thus, the reflection spectrums of fiber Bragg grating have been calculated according the strain distribution, which is show in fig.7 (a). During the calculation, the initial center wavelength of FBG is 1540nm. And other parameters are set below. The length (L), effective index (\(n_{\text{eff}}\)) and refractive index modulation (\(\delta n_{\text{eff}}\)) of FBG are 10mm, 1.45 an 0.0002 respectively.

![Fig.4 Strain distribution along the FBG length corresponding to different failure lamina of “L” preform](image)

4. Experiment and Discussion

Considering that the “L” preform is the weakest part of the composite π-joint structure, we arrange FBG sensor between the “L” preform and the small horizontal preform, Fig.5 shows the π-joint structure and the arrangement of FBG sensor in it. Testing of π-joint has been conducted at room temperature under a bending load. The experiment system is shown in Fig.6.
The joint was subjected to bending load on the web which position is 50mm from the web top and clamped on the ends of skin. The fiber Bragg grating was illuminated by an amplified spontaneous emission (ASE) light source (AQ4130, Ando Electric Co., Ltd.) and the reflection spectrum was obtained by using an optical spectrum analyzer (AQ6317, Ando Electric Co., Ltd.). During the loading process, the spectra and corresponding loads were recorded when the spectrum changed and abnormal sound issued. The results were shown in Fig.7 (b).

From Table 2, we can obtain the failure process of the π-joint theoretically. The onset of failure occurs on the 0° lamina of L perform, next is the 45° lamina of L preform and the ultimate failure occurs on the -45° lamina of L preform. The corresponding critical failure load is 1514N, 1548N and 1593N, respectively. Experimental results are given in Fig.7 (b). The comparison of the results of calculation and experiment showed that they had good concordance. The error of failure critical loads is less than 6.4%, which is in the range of...
permitted errors in the field of structure health monitoring research. Besides, compared the spectra in the different stage, though there was a slight difference between the measured and calculated spectra, the tendency of the change in the spectra was consistent. Therefore, we can judge the failure sequence and the corresponding critical loads of “L” preform in the π-joint structure by using the spectrum change of the FBG sensor.

5. Conclusion

The paper made use of the carbon fiber π-joint structure as research object, a kind real-time online monitoring system using fiber Bragg grating sensor was studied. Firstly, based on the general FEM software, the 3-D finite element model of composite π-joint is established, the failure process and every lamina failure load of composite π-joint were investigated. Then, strain distributions belong the length of fiber Bragg grating were extracted, the reflection spectra of fiber Bragg grating have been calculated according the strain distribution. Finally, to verify the numerical results, a test scheme was performed and the experimental spectra of fiber Bragg grating were recorded. The experimental results indicate that the failure sequence and the corresponding critical loads of failure were consistent with numerical predictions and the computational error of failure load is less 6.4%. Furthermore, it also verified the feasibility of the damage detection system and provided a foundation for the practical application of the FBG sensor in aerospace field.

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References