ESTIMATION OF PEEL STRESS AT THE OVERLAP END OF SINGLE-LAP JOINT BY USING EMBEDDED FBG

H. Murayama[1*], K. Kageyama[1], K. Uzawa[1], I. Ohsawa[1], K. Ohara[1], H. Igawa[2]
[1] School of Engineering, the University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan, [2] Japan Aerospace Exploration Agency, 6-3-1 Osawa, Mitaka-shi, Tokyo 181-0015, Japan
* Corresponding author (murayama@sys.t.u-tokyo.ac.jp)

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1 Introduction

The use of adhesive bonding in composites is recently increasing because it has advantages over mechanically fastened joints. Therefore, understanding the behavior of the adhesive joint is required for improving the reliability of a structure with bonding joints.

Analytical and numerical approaches to determine stress or strain distributions inside the adhesive and at the interfaces between the adhesive and the adherents have been proposed by many researchers [1-3]. On the other hand, although strain of the surface on the adherents could be measured and compared with analytical results, it is difficult to measure strain inside the adhesive and at the interfaces by conventional sensors, such as strain gauge.

As advanced sensing technologies, fiber-optic sensors which can be embedded inside the adhesive joints are attractive tools for providing a solution for this problem. Additionally, they have a feature to implement not only point sensing but also distributed sensing, so that they may measure the variation of the strain distribution inside the adhesive.

Recently, we have developed a distributed strain measurement system using long-length fiber Bragg grating (FBG) based on optical frequency domain reflectometry (OFDR) system [4]. It can measure a strain distribution with the high spatial resolution of less than 1 mm at an arbitrary position along the FBG [5]. So it enables us to measure locally fluctuating strain distribution precisely.

In this study, we embedded the long-length FBG whose length was about 100 mm into the adhesion layer of a single-lap joint and we could successfully measure the longitudinal strain distribution at the interface between the adhesive and the adherent along the FBG when the specimen was subjected to the tensile loads. In this test, we also found that the reflected spectrums around the overlap end of the single-lap joint were split, because there were large peel stresses which could cause the birefringence effect. In this paper, we propose the method to identify the magnitude of the peel stress by analyzing the reflected spectrums split due to the birefringence effect.

2 Sensing System with OFDR

2.1 FBG Sensor

FBG is an intrinsic devise with periodic perturbation of refractive index in the core of an optical fiber [6]. When spectrally broadband light is injected into the fiber with FBG, narrowband spectral component at a specified wavelength, called Bragg wavelength is reflected as shown in Fig.1.

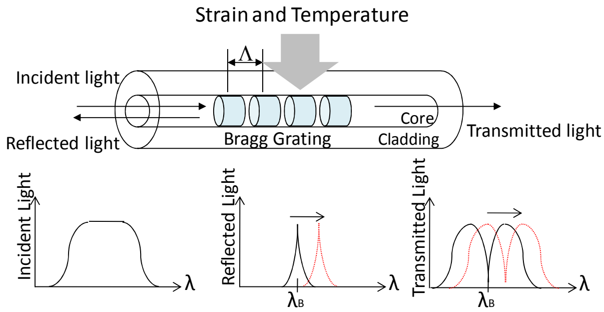

Fig.1. FBG sensor.

So FBG is usually used as a filter devise in the fiber-optic communication system. The Bragg wavelength λ_B is given by

$$\lambda_B = 2n_{eff}\Lambda, \tag{1}$$

where Λ is the pitch of the grating, and n_{eff} is the effective index of refraction of the core. When the pitch of FBG is mechanically changed by the applied strain, we can observe the wavelength shift in the reflected spectrum proportional to the change of the pitch. Therefore we can use FBG as a strain sensor, and strain of a structural member or inside a composite can be measured by monitoring the reflected light of FBG bonded on the surface or embedded into the laminate.

2.2 Sensing System Based on OFDR

The sensing system of this study consists of a wavelength tunable laser, photodiode detectors (D1, D2), broadband reflectors (R1, R2, R3), 3 dB couplers (C1, C2, C3), a long-length FBG whose length is about 100 mm and a computer with an A/D converter. The arrangement of the system is shown in Fig.2. This arrangement is similar to that of Ref. [7]. When an incident light swept for a prescribed span of wavelength is injected into the system, the light is split by the couplers and reflected by the reflectors and the FBG.

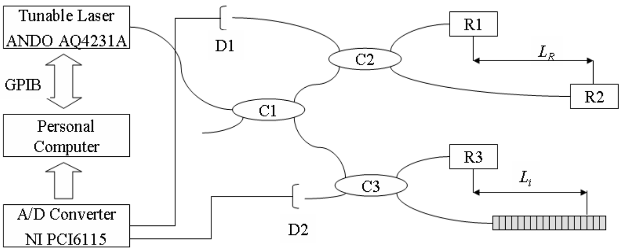

Fig.2. Sensing system with OFDR.

By using the signal of D1 as an external clock for A/D converter, we can sample the signal of D2 with the constant wavenumber interval, $\Delta k=\pi/n_{eff}L_R$. The signal of D2 is simply given by

$$D_2 \approx \sum_i R_i(k)\cos(2nL_ik), \tag{2}$$

where $R_i(k)$ is the spectrum reflected by i-th grating in the FBG, L_i is a path difference between reflector R3 and the i-th grating. Thus the signal D_2 is represented as the summation of interference signals of reflected lights from the reflector R3 and from each grating in the FBG.

The waveform of signal D_2 obtained from a FBG with the gauge length of 100 mm for uniform strain is shown in Fig.3. The signal D_2 is depending on the intensity of the reflected light including oscillating components with frequencies corresponding to the path difference L_i.

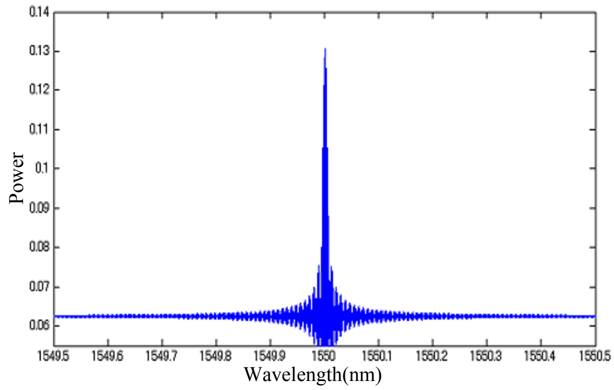

Fig.3. Waveform of singal D_2.

Then by applying Fourier transform analysis with a sliding window to the signal, we can separate the reflected spectra from each grating in the FBG as a spectrogram as shown in Fig.4. The horizontal axis represents wavelength of spectra, the vertical represents position and the color contrast represents the power of the spectra. In this spectrogram, we can see uniform reflection spectra along the FBG (1.00 m to 1.10 m). By determining the center wavelength of the spectra at each position in the spectrogram, we can map the strain profile along the long gauge FBG. In this study, we determined the center wavelength by calculating the center of the full width at half maximum (FWHM) of spectrum at each position in the spectrogram.

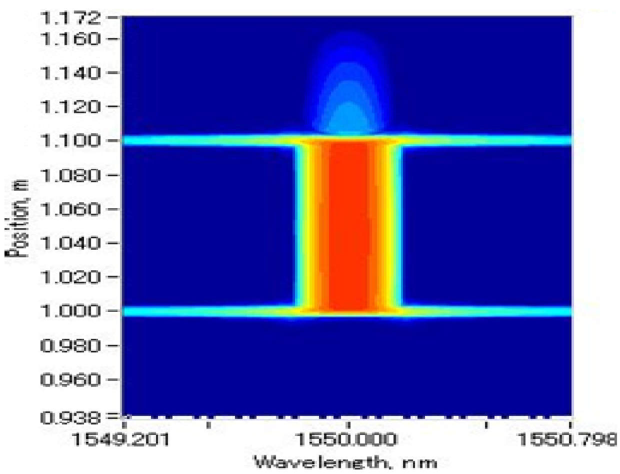

Fig.4. Spectrogram.

2.3 Birefringence effect

As shown in Fig.5, non-axisymmetric strain is applied to the optical fiber, and it can lead to birefringence effect. If birefringence effect occurs in FBG sensor, it is well known that the reflected spectrum will be split [8]. Therefore, in the end of the overlap, large loads applied diametrically might make such a reflected spectrum splitting because of the birefringence effect.

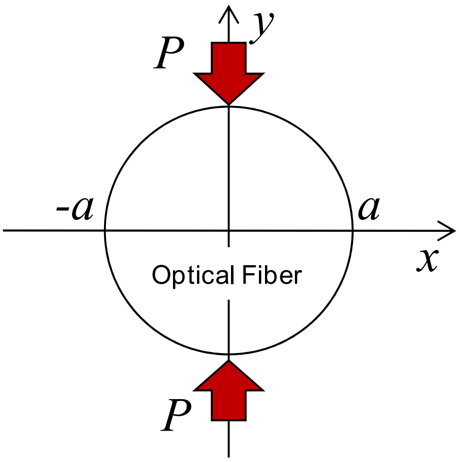

Fig.5. Optical fiber applied non-axisymmetric strain.

Stresses of the fiber core can be determined by Airy stress function, they are given by

$$\sigma_x^{core} = \frac{P}{\pi a}, \quad \sigma_y^{core} = -\frac{3P}{\pi a}. \tag{3}$$

In the case of plane strain condition, the relationship between the diametric load, P, and the wavelengths of the slow and fast modes, λ_{Bx} and λ_{By}, is shown in Fig.6.

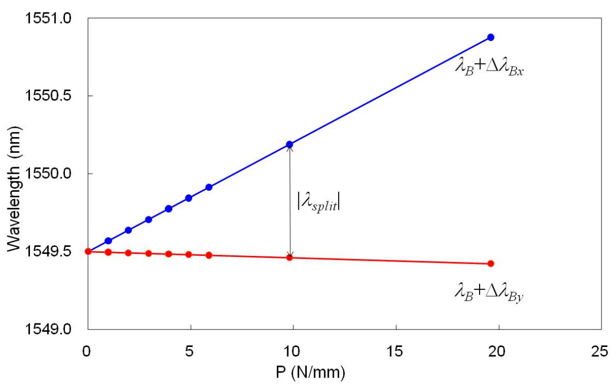

Fig.6. Wavelength shifts of the peaks

In this case, the applied load can be estimated by

$$P\textbf{[N/mm]} = 27.5\textbf{[N/mm/nm]} \times \left|\lambda_{split}\right|\textbf{[nm]}, \tag{4}$$

where $|\lambda_{split}|$ is the absolute difference between λ_{Bx} and λ_{By}.

3 Experiments

3.1 Specimen and Sensor Arrangement

Dimensions of the test specimen and the location of the FBG sensor are shown in Fig.6. The specimen is a single-lap joint of two aluminum plates adhered by epoxy adhesive. A long-length FBG sensor whose length and diameter were 90 mm and about 150 µm, respectively, was set on the V-shaped groove machined on the aluminum plate and bonded by the same epoxy as the adhesive. The grating of the region A (40 mm) was bonded on the left adherent to measure the strain distribution of the left adherent which was outside the adhered section. The region B (30 mm) was embedded inside the adhered section of the joint to measure strain distribution at the interface between the adhesive and the adherend. The region C (20 mm) was kept free to be used as reference part for temperature compensation.

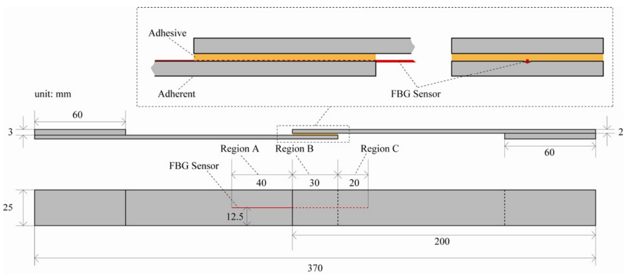

Fig.6. Dimensions of specimen and sensor location.

3.2 Split of Reflected Spectrum

Figure 7 shows the reflected spectrums near the overlap end of the single-lap joint at the load of 0 N and 1570 N. We can see that the reflected spectrum is split in 1570 N. From the calculated results using finite element analysis, we can find large peeling stress is applied to the both end of the overlap, especially the left end in the region B. In such a case, birefringence effect occurs in FBG sensor, and it is well known that the reflected spectrum will be split. Therefore, in the end of the overlap, large loads applied diametrically might make such a reflected spectrum splitting because of the birefringence effect. Figure 8 shows the wavelength of the two peaks in the reflected spectrum against the load. Each peak lineally shifts to be a longer wavelength in proportion to the tensile load and the proportionality coefficients differ from each other. Therefore, if we determine the relationship between the peel stress and the difference of the wavelengths of the two peaks, the magnitude of the peel stress can be estimated by analyzing the reflected spectrum. This relationship might be difference from the relationship given by Eq. (4), because it is supposed that the sensitivity of the embedded fiber to the peel stress is difference from that of the optical fiber in the condition shown in Fig.5. It can, however, be estimated by experiments or simulation with finite element models.

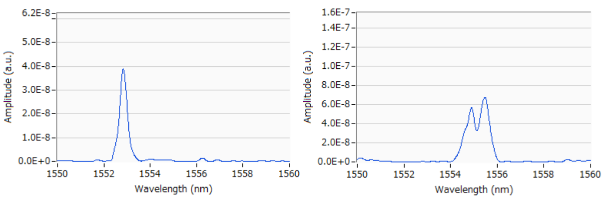

Fig.7. Reflected spectra (left: 0 N, right:1570 N)

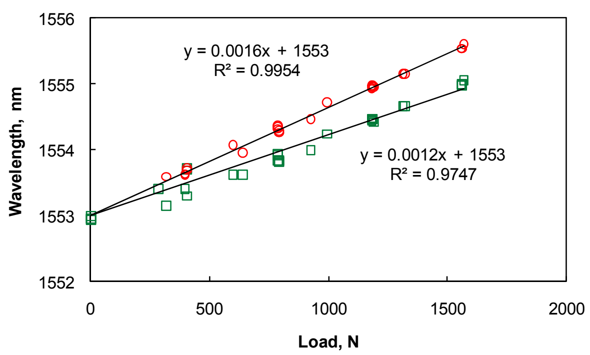

Fig.8. Wavelengths of the two peaks vs. the load.

4 Conclusions

In this study, we applied the fiber-optic distributed sensing system to monitoring the strain distributions inside the single-lap adhesive joint, using the embedded FBG at the interface between the adhesive and the adherent. By subjecting the single-lap joint to the static tensile loads, we found that the reflected spectrums around the overlap end of the single-lap joint were split, because there were large peel stresses which could cause the birefringence effect. We proposed the method to identify the magnitude of the peel stress by analyzing the reflected spectrums split due to the birefringence effect.

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