STRAIN MONITORING OF 6-M COMPOSITE WING STRUCTURE BY FIBER-OPTIC DISTRIBUTED SENSING SYSTEM WITH FBGS

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Abstract
Fiber-optic distributed sensors with the high spatial resolution are promising candidates for sensing elements for SHM system. The distributed sensing system based on OTDR can provide strain at an arbitrary position along long-length FBGs and can also measure strains of multiplexed FBG sensors. In this study, we applied this sensing system to strain monitoring of 6-m composite wing box made of CFRP in the load tests. We could successfully measure strain distributions by FBG sensor arrays to monitor the overall deformation of the wing box. The agreement between measured and calculated results is excellent. We could also measure the strain distributions precisely around stress concentration zones by the distributed sensing technique using long-length FBG. Strain data measured by FBG sensors would be used to estimate the load which was applied to the wing box in the test by inverse analysis technique.

1 Introduction
Fiber-optic distributed sensors that return a value of the measurand as a function of linear position along an optical fiber are promising candidates for sensing elements for structural health monitoring (SHM) system. Among them various distributed sensing techniques based on Brillouin scattering have been proposed for strain measurements [1-3]. Murayama *et al*. applied Brillouin optical time domain reflectometry (BOTDR) to strain monitoring of composite yacht hulls and at that time the spatial resolution and the accuracy were 1 m and ±30 με, respectively [4]. Recently Song *et al*. achieved the spatial resolution of 1.6 mm using Brillouin optical correlation domain analysis (BOCDA) [5]. However the accuracy for strain measurements had not been shown in the literature. While fiber Bragg grating (FBG) sensors with some interrogation systems are ordinarily employed for quasi-distributed strain measurements, they can be also applied to fully-distributed sensing [6,7].
Recently we have developed a distributed strain sensing system using long-length FBGs whose length is about 100 mm, based on optical frequency domain reflectometry (OFDR) [8]. We can identify the longitudinal strain at an arbitrary position along the FBG by using signal processing technology. The spatial resolution is less than 1 mm. This system was applied to strain monitoring inside the adhesive layer of single-lap joint by using embedded FBGs and it was proved that fiber-optic distributed sensors with the high spatial resolution can provide valuable information on strain/stress distributions that had not been ever measured directly, as well as damage and deterioration, in adhesively bonded joints [9]. The sensing technique based on OFDR can also be used to measure averaged strain at each FBG in multiplexed FBG

arrays [10]. In this study, the distributed strain monitoring by long-length FBG sensors and quasi-distributed strain monitoring by multiplexed FBG sensor arrays of a full-scale composite structure were demonstrated.
Civil Transport Team and Advanced Composite Technology Center of Japan Aerospace Exploration Agency (JAXA) are aiming at development of a low cost manufacturing technology for composite material structures. A composite wing box whose length is approximately 6 m was made by vacuum assisted resin transfer molding (VaRTM) and was put to a limit load test. In this study, we applied the distributed sensing system to the strain monitoring of this composite wing structure. Our aim firstly, is to monitor the overall deformation of the wing during a series of load tests by multiplexed FBG sensor arrays. Secondly, the aim is to measure the strain distributions of stress concentration zones, where for example the stiffness is varying discontinuously, by long-length FBG sensors.
We successfully equipped the composite wing structure with FBG sensors, of which the locations were based on the stress distribution calculated by finite element analysis (FEA). Totally 246 FBG sensors with 10 mm length, eight with 300 mm and six with 500 mm were bonded on either the inner or outer skins of the wing box.
We could successfully measure strain distributions by FBG sensor arrays to monitor the overall deformation of the wing box. The agreement between measured and calculated results is excellent. We could also measure the strain distributions precisely around stress concentration zones by the distributed sensing technique using long-length FBG. Strain data measured by FBG sensors would be used to estimate the load which was applied to the wing box in the test by inverse analysis technique and the results of the load estimation will be shown in the conference.

2 Distributed Sensing with OFDR

2.1 FBG sensors

FBG is an optical device that has a periodical refractive-index modulation, namely grating, in its core. When spectrally broadband light is injected into the FBG, this periodical refractive-index modulation selectively reflects light of a specified wavelength, and transmits the others. The reflected wavelength λ_B, called Bragg wavelength, is given by the following expression,

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

where n_{eff} is the effective index of refraction of the core and Λ is the pitch of the grating [11]. This formula tells us that the reflected wavelength is proportional to the periodicity of the grating. If strain is applied to the FBG, it causes a change in the grating periodicity, and therefore by observing the Bragg wavelength shift, the strain applied to the fiber can be calculated. Wavelength shift of 1 pm corresponds to a strain of about 1$\mu\varepsilon$.

2.2 Distributed measurement system based OFDR

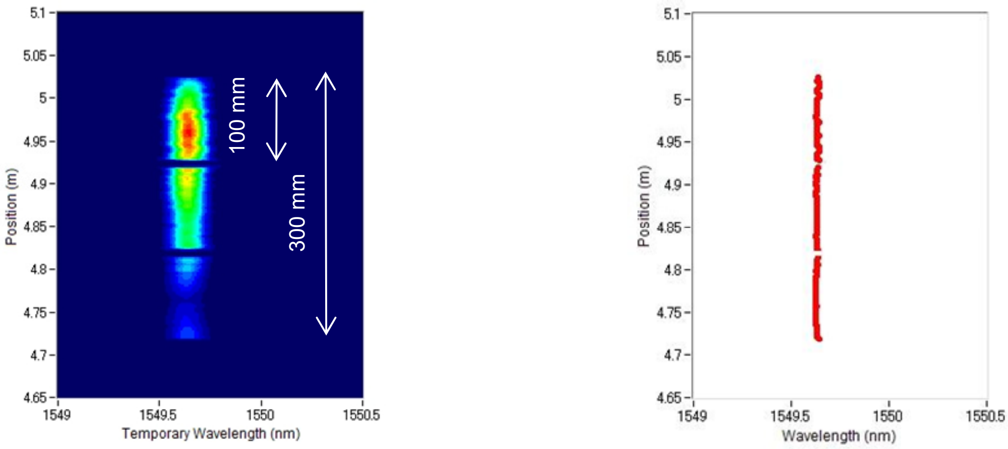
We have developed the distributed strain measurement system using FBG sensors [12]. In this measurement system, the reflected spectrum at an arbitrary position along FBG sensors can be calculated by analyzing the signal obtained from OFDR. The distribution of the reflected spectrum along the FBG sensors is called a spectrogram. We can determine the strain at a position along the FBG sensor by estimating the wavelength shift from the spectrogram.

2.2.1Distributed measurement by long-length FBG sensors

We can use FBG sensors with 100 mm in length, which is much longer than usual ones whose length is from 5 to 25 mm. It has been reported that it can measure strain distributions along the sensing fiber with the spatial resolution of less than 1 mm and enables us to determine strain fluctuation of a stress concentration area precisely by using these long-length FBG sensors [8,9]. Figure 1(a) shows the spectrogram obtained by three long-length FBGs serially cascaded at about 5 mm intervals. In this spectrogram, we can see uniform reflection spectra along the FBG (4.72 m to 5.02 m). By determining the center wavelength of the spectra at each position in the spectrogram, we can map the strain profile along the long-length FBG as shown in Fig. 1(b).

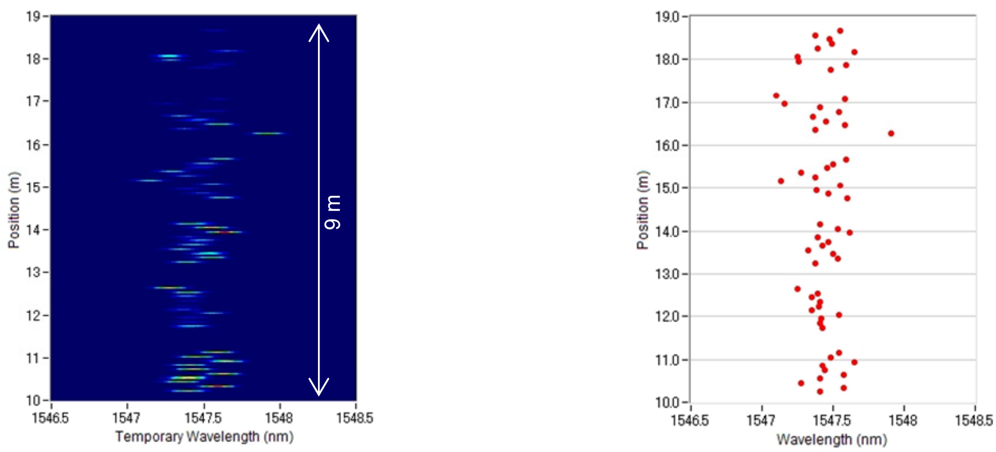
2.2.2 Quasi-distributed measurement by multiplexed FBG sensor arrays

In addition, FBG sensors with usual length can also be used for quasi-distributed sensing. We confirmed that 60 FBG sensors with 10 mm in length, allocated along an optical fiber with an interval of 100 mm, could measure strain individually at each position. Figure 2(a) shows the spectrogram obtained by a 60-FBG sensor array. By observing the center wavelength shift of each FBG sensor, the overall strain profile along the fiber could be plotted as shown in Figure 2(b).



(a) Spectrogram. (b) Center wavelength distribution.

Figure 1. Distributed measurement by long-length FBG sensor.



(a) Spectrogram. (b) Center wavelength distribution.

Figure 2. Quasi-distributed measurement by a 60-FBG sensor array.

3 Strain Monitoring in Load Test

3.1 Measurement system

The layout of the sensing system we used in this study is shown in Fig. 3. It consists of a wavelength tunable laser, two photodiode detectors (D1, D2), three broadband reflectors (R1, R2, R3), three 3dB couplers (C1, C2, C3), 16 channels of fibers with FBG sensors, a channel selector, and a desktop computer with an A/D converter.

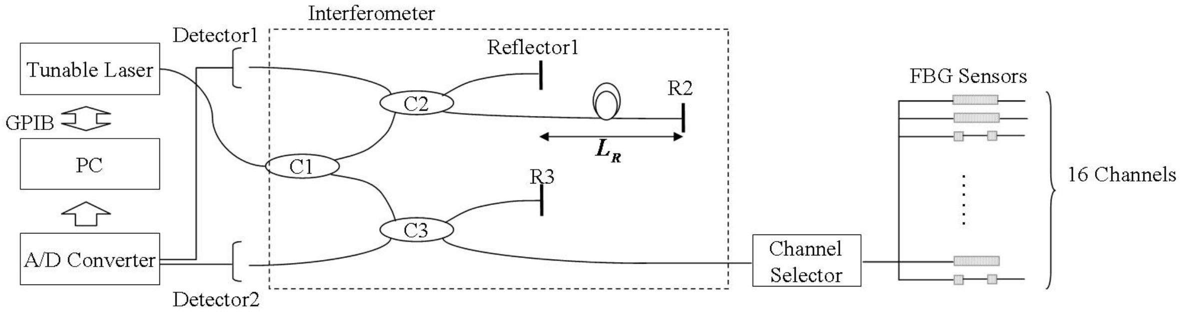


Figure 3. Measurement system.

3.2 Composite wing box with FBGs

Figures 4 and 5 show the composite wing box and its inner structure. The length was 6 m and the width at the root was 1.4 m. Our aim firstly, is to monitor the overall deformation of the wing during a series of load tests by multiplexed FBG sensor arrays. Secondly, the aim is to measure the strain distributions of stress concentration zones, where for example the stiffness is varying discontinuously, by long-length FBG sensors. As shown in Fig. 6, we equipped the wing box with seven FBG arrays (A-1:A-7), eight long-length FBGs with 300 mm gauge length (B-1:B-8), six long-length FBGs with 500 mm gauge length (B-9:B-14). Each array had about 30 or 40 FBGs with 10 mm in length and FBGs were arrayed in a 100 mm pitch along the fiber. Table 1 shows the configuration of each line including the assignment for the channel selector.

Figure 4. Composite wing box.

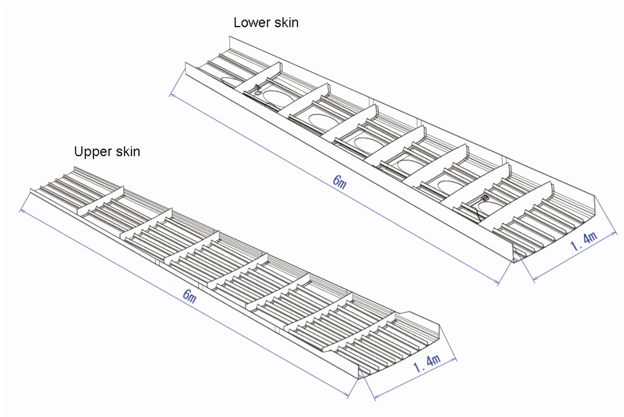
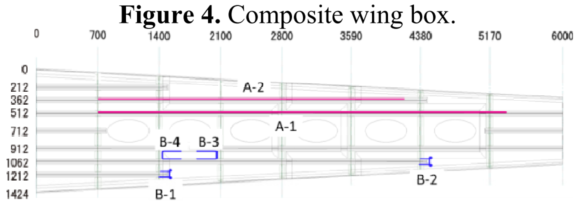
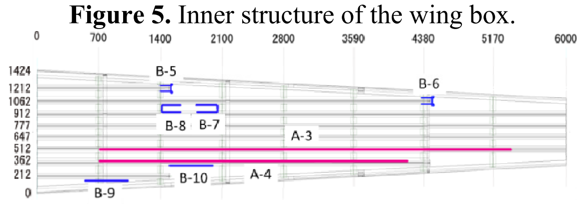


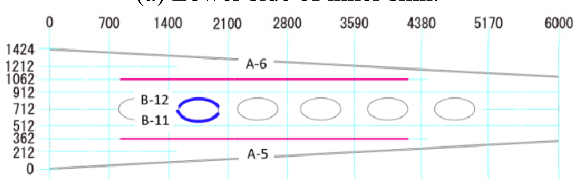
Figure 5. Inner structure of the wing box.



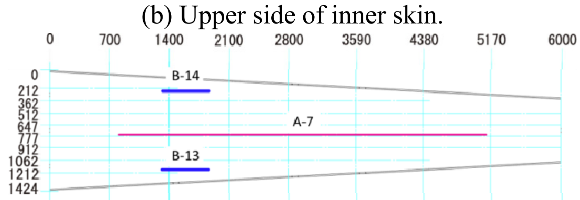
(a) Lower side of inner skin.



(b) Upper side of inner skin.



(c) Lower side of outer skin.



(d) Upper side of outer skin.

Figure 6. FBG arrays and long-length FBGs in the wing box.

Ch	FBG line	Sensor Configuration	Side	Skin	Others
1	A-1	10 mm FBG × 42	Lower	Inner skin	Stringer flange
2	A-2	10 mm FBG × 31	Lower	Inner skin	Stringer flange
3	A-3	10 mm FBG × 42	Upper	Inner skin	Stringer flange
4	A-4	10 mm FBG × 42	Upper	Inner skin	Stringer flange
5	A-5	10 mm FBG × 30	Lower	Outer skin	Stringer flange
6	A-6	10 mm FBG × 30	Lower	Outer skin	Stringer flange
7	A-7	10 mm FBG × 40	Upper	Outer skin	Stringer center
8	B-1	300 mm FBG	Lower	Inner skin	Stringer run-out
9	B-2	300 mm FBG	Lower	Inner skin	Stringer run-out
10	B-3, B-4	300 mm FBG × 2	Lower	Inner skin	Box framed by stringers and ribs
11	B-6	300 mm FBG	Upper	Inner skin	Stringer run-out
12	B-7, B-8	300 mm FBG × 2	Upper	Inner skin	Box framed by stringers and ribs
13	B-9	500 mm FBG	Upper	Inner skin	Stringer web surface
14	B-10	500 mm FBG	Upper	Inner skin	Stringer web surface
15	B-11, B-12	500 mm FBG × 2	Lower	Outer skin	Around maintenance hole
16	B-13, B-14	500 mm FBG × 2	Upper	Outer skin	Outside of stringer

Table 1. Configurations of FBG sensors.

3.3Measuremetn results in load test

The wing box was subjected to static load tests. The test equipment is shown in Fig. 7. The bending load was applied to the structure at 16 points and up to the design limit load. Strain data was acquisitioned when applied load was stable at a ratio of the limit load.

We made the finite element model of the wing box as shown in Fig. 8 to compare strains measured by FBGs with those of FEA by ANSYS.

We could successfully measure strain by all FBGs installed to the wing box. Figure 9 shows the measured results by A-1 at 0%, 20%, 40%, 60%, 80% and 100% of the limit load. The horizontal axis represents the position along y axis in the Fig. 8 and the origin is at the root of the wing. The solid circles and lines are measured and calculated strains, respectively. We can know the overall deformation easily by observing the measured results. Since A-1 was bonded in the longitudinal direction on the inner skin of the lower side, tensile strains were measured along A-1 and strain around the maintenance holes shown in Fig. 6 (a) was increased because of stiffness decrease. The agreement between the measured strain and calculated one is excellent. Figure 7 shows the strain distributions measured along B-1. The horizontal axis represents the position along the sensing fiber and the origin is at an end of FBG. In this case, the spatial resolution was about 1 mm. Since B-1 was around the tip of a stringer where stiffness was changing locally, we can find that strain was varying largely. It is expected that damage, such as delamination between the skin and the stringer, can be detected by observing the distinctive strain distribution.

4 LOAD IDENTIFICATION BY INVERSE ANALYSIS

We have developed the estimation technique of the distributed loads on a plate structure based on strain distributions measured by strain sensors on the surface [13]. In this technique, we are using finite element model in order to enable integrated and organized operation of design and in-flight load prediction. In the conference, we will report the results of the load estimation based on the measured strains by inverse analysis.

Figure 7. Test equipment.

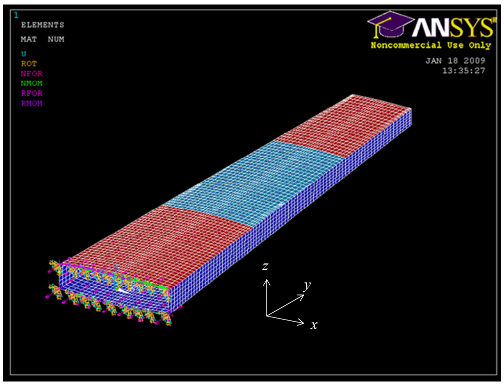


Figure 8. Finite element model.

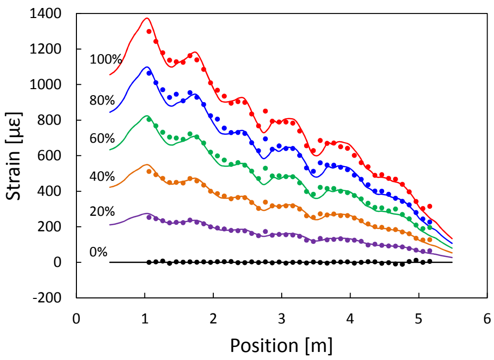


Figure 9. Strain distributions measured by A-1.

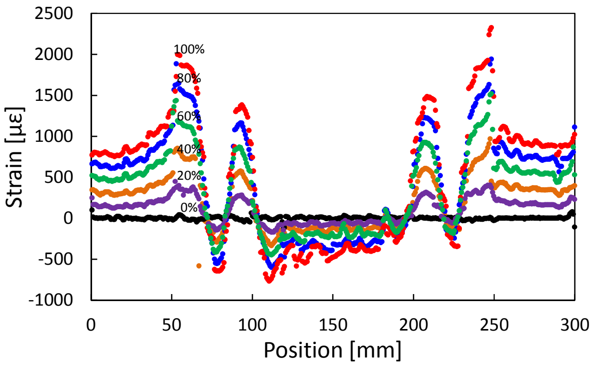


Figure 10. Strain distributions measured by B-1.

5 CONCLUTIONS

We applied the fiber-optic distributed sensors with the multiplexed FBG arrays and the long-length FBGs to monitor the strain distributions in the composite wing box whose length was 6 m. We succeeded in measuring the overall deformation of the wing box and the strain distributions at the stress concentration zones of interest by the FBG arrays and the long-length FBGs, respectively, in the load tests. We could know the overall deformation easily by observing the strain distributions measured by the FBG arrays. By the long-length FBGs, we could measure a distinctive strain distribution around the tip of the stringer with high spatial resolution. In the conference, we will also show that the applied load can be estimated by inverse analysis based on the measured strain data. Consequently, we can say that the distributed sensing system is very helpful to develop the integrated SHM system to detect damage and monitor the operational condition.

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