RECENT DEVELOPMENT OF STRUCTURAL HEALTH MONITORING TECHNOLOGIES FOR AIRCRAFT COMPOSITE STRUCTURES

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Abstract

Advanced composites including carbon fiber reinforced plastic (CFRP) are extensively being used in recent aircraft structures due to a strong demand for high efficiency and reasonable affordability. However, inspection and maintenance of CFRP structures are of concern to the safety of new aircraft. The damage in operation can be more complicated in CFRP structures than in conventional metallic ones. Efficient inspection and maintenance procedure of aircraft CFRP structures has been highly demanded using structural health monitoring (SHM) technologies under development.

In Japan, we have been developing optical fiber based SHM technologies in recent industry-university collaboration programs. After some important fundamental developments, such as small-diameter optical fiber sensors for embedment in CFRP structures without introducing any deterioration, we are now applying to sub-component structure prototypes. This presentation provides some recent development of optical fiber based SHM technologies for near-future aircraft composite structures.

1 Introduction

SHM technologies have been studied extensively in order to assess the safety and the durability of the structures [1]. In addition, for weight saving of airplanes, CFRP laminates are extensively being used for the primary structures. However, the maintenance cost of the structures may increase because of the complicated fracture process of the CFRP laminates. A new technological innovation to reduce the maintenance cost is a health monitoring or management system. At present, optical fiber sensors are most promising among all [2, 3]. This is because optical fibers have enough flexibility, strength and heat-resistance to be embedded easily into composite laminates.

A most potential candidate for the sensing device is an optical fiber Bragg grating (FBG) sensor [4]. FBG sensors are very sensitive to non-uniform strain distribution along the entire length of the grating, which deforms the reflection spectrum from the FBG sensors. Taking advantage of the sensitivity, microscopic damages that cause non-uniform strain distribution in CFRP laminates can be detected.

When the optical fiber sensors are embedded into composite materials, however, there is a possibility of degradation in mechanical properties of host materials. Hence, the authors and Hitachi Cable, Ltd. have recently developed small-diameter optical fiber and its fiber Bragg grating (FBG) sensor that are suitable for embedment inside a lamina of composite laminates without strength reduction [5].

In the following, a brief summary is presented for some previous studies on the small-diameter FBG sensors for damage monitoring and SHM of composite structures. Then, some recent results in the current projects are presented on optical fiber based SHM for aerospace composite structures.

2 Damage Detection by Small-Diameter FBG Sensors

2.1 Development of Small-Diameter Optical Fibers and FBG Sensors

The small diameter optical fibers (both single-mode and multi-mode) were developed and FBG sensors were fabricated with these optical fibers (Fig. 1). The optical fiber is with 40 μm in cladding diameter and 52 μm in polyimide coating diameter, which is easily embedded within one CFRP ply of typically 125 μm in thickness. Such optical fibers have both mechanical and optical properties similar to those of conventional optical fibers with 125 μm in cladding diameter and do not cause any reduction in strength of composites when embedded parallel to reinforcing fibers in laminates [5]. When a small-diameter optical fiber is embedded inside a lamina, resin-rich regions cannot be found around the fiber, as shown in Fig. 2. The polyimide coating relieves the stress concentration around the cladding with a proper combination of the stiffness and the thickness. The coating is also highly compatible with epoxy or other high-temperature polymer matrix of CFRP composites under high-temperature exposure during fabrication and also in high-temperature use.

Then, FBG sensors were also successfully developed with these single-mode small-diameter optical fibers, where periodic gratings with approximately 0.53 μm in space were inscribed in the gage section (typically 10 mm in length). When a broadband light is introduced from one end of the fiber, a narrow-band spectrum with a sharp wavelength peak corresponding to the grating spacing is obtained if uniform strain within the gage section can be assumed. FBG sensors are usually used to measure strain and/or temperature through the shift of the wavelength peak [4].

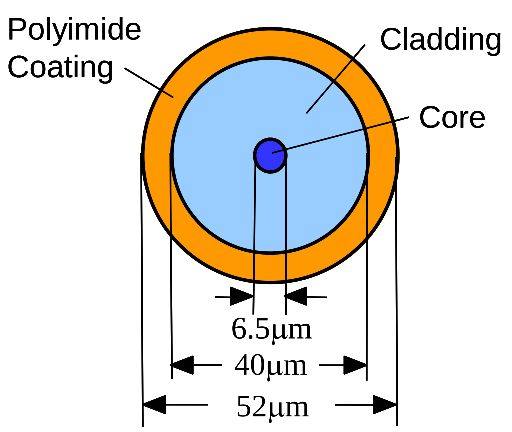

Fig. 1. Small-diameter optical fiber

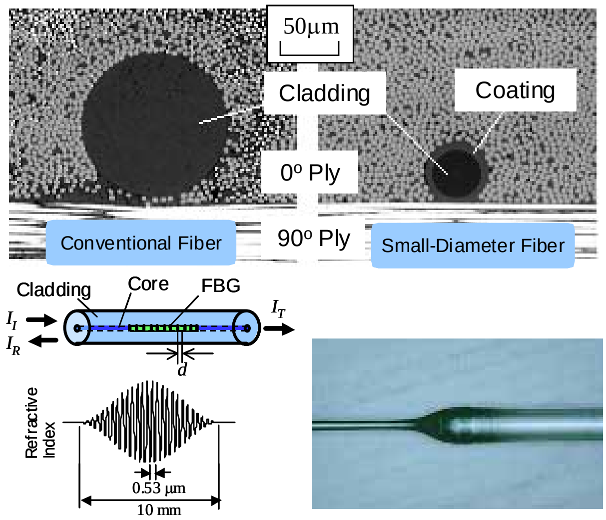

Fig. 2. Conventional and small-diameter optical fibers embedded in a CFRP lamina and small-diameter FBG sensors with fiber connection to conventional optical fibers.

2.2 Damage Detection by FBG Sensors

FBG sensors are very sensitive to non-uniform strain distribution along the entire length of the grating, which deforms the reflection spectrum from the FBG sensors (Fig. 3). Taking advantage of this sensitivity, microscopic damages that cause non-uniform strain distribution in CFRP laminates can be detected. After the monitoring methodology was established for cross-ply laminates [6, 7], transverse cracks were monitored in general quasi-isotropic laminates [8]. When an FBG sensor was embedded in the -45^o ply to detect transverse cracks in the adjacent 90^o ply of CFRP quasi-isotropic laminate $[45/0/-45/90]_s$ (Fig. 4), a non-uniform strain distribution due to the initiation and evolution of transverse cracks caused the wavelength distribution in the reflected light (Fig. 5). While there were no

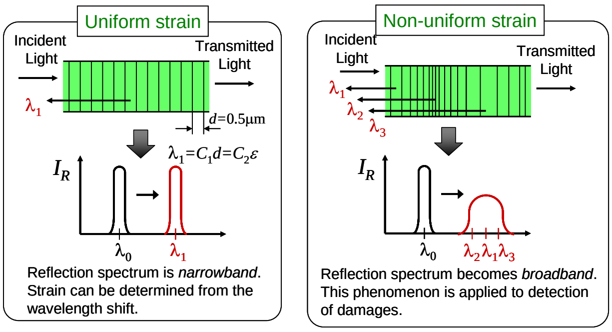

Fig. 3. Response of FBG sensors to uniform and non-uniform strain distribution

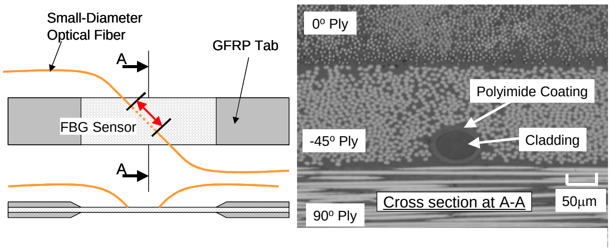

Fig. 4. A small-diameter FBG sensor embedded in the –45^{o} ply for detection of transverse cracks in the adjacent 90^{o} ply of quasi-isotropic $[45/0/-45/90]_s$ laminate.

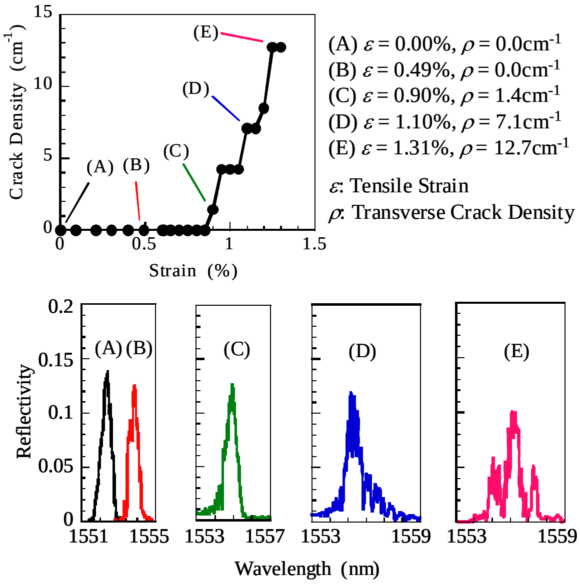

Fig. 5: Change in wavelength distribution of reflected light from the FBG sensor due to the evolution of transverse cracks.

transverse cracks, the spectrum kept its shape and the center wavelength shifted corresponding to the applied strain. With increasing transverse crack density, the shape of the reflection spectrum was distorted; the intensity of the highest peak became small, some peaks appeared around it, and the spectrum became broad. These experimental observations could be well explained by the theoretical prediction using the calculated strain distribution and the fiber optic theory [6-8]. The location of transverse cracks in CFRP cross-ply laminates could be also obtained when a chirped FBG sensor with gradual change in grating period along the gage length was used [9]. The crack location can be well correlated with the wavelength in the spectrum.

The same principal can be applied to the detection of delamination or disbond in bondlines, which is the most important damage for structural design of composite laminates [10-13]. Figure 6 shows the $[45/-45/0/90]_s$ CFRP laminate specimen with an embedded FBG sensor. The experimental results are shown in Fig. 7 for detection of free-edge delamination [11]. It should be noted that small-diameter optical fibers can be embedded in the laminates and penetrate the surface of the laminates to the outside without introducing any significant defect. The free-edge delamination grew alternatively at 0/90 and 90/90 interfaces under tension-tension fatigue loading. An initial single peak in the reflection spectrum was separated into two peaks, and the peak at longer wavelength grew as the edge delamination grew. The two peaks at shorter and longer wavelengths in the reflection spectrum correspond to the strain levels of the bonded and delaminated areas, respectively. This change in the reflection spectrum was found to be well predicted by the theoretical prediction. This technique can be also applied to other types of delamination detection around stress-concentrated regions such as rivet holes. Multiple-mode damages including transverse cracks, delamination and splitting were also identified through an inverse analysis of the reflection spectrum in notched CFRP laminates [14, 15] and in holed CFRP laminates [16-18]. Debonding between honeycomb core and CFRP facesheets was also monitored using a small-

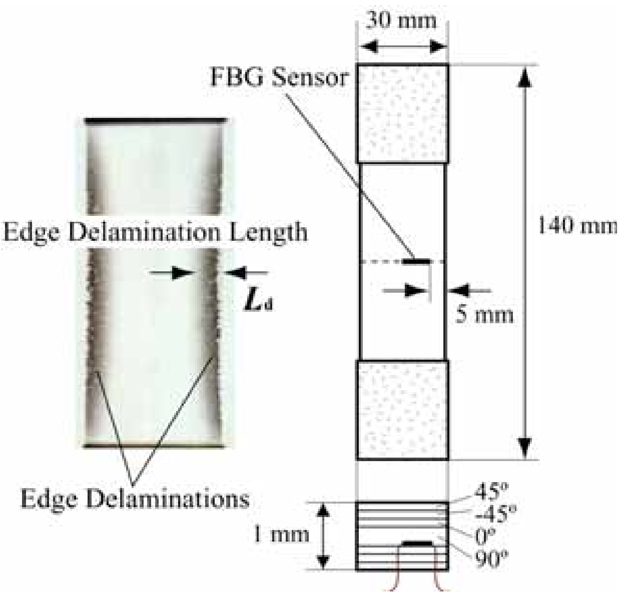

Fig. 6. Schematic of $[45/-45/0/90]_s$ edge delamination specimen with an embedded FBG sensor.

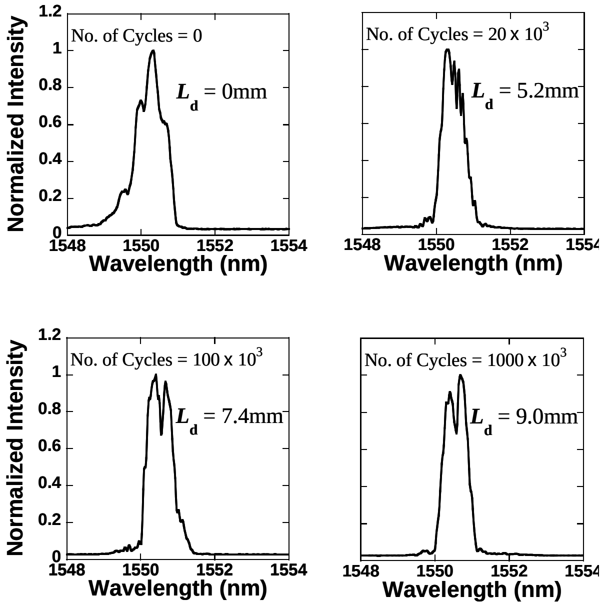

Fig. 7. Change in wavelength distribution of reflected light from the FBG sensor due to the edge delamination growth.

diameter FBG or distributed sensor embedded in adhesive layer [19-21].

FBG sensors can also monitor the axial thermal residual stress during the fabrication process of CFRP laminates. However, the reflection spectra are normally distorted after the fabrication of laminates, because of non-axisymmetric thermal residual stresses due to the embedment [22]. This distortion of the spectrum will lead to misreading in the measurement. In order to study the effect of the thermal residual stress, the reflection spectrum was measured during the fabrication process and well correlated with the theoretical prediction [23, 24].

In addition, the following fundamental studies were also conducted for applications of small-diameter FBG sensors: (1) effects of coating on the damage detection by FBG sensors [25], (2) temperature-compensated strain measurement using an FBG sensor [26], and (3) a combined damage monitoring and suppression system of CFRP laminates using FBG sensors and SMA (shape memory alloy) foil actuators [27, 28].

2.3 Damage Detection in Stiffened Composite Fuselage Structure

In the "R&D for Smart Material/Structure System (SMSS)" project (October 1998 to March 2003) as one of the Academic Institutions Centered Program supported by NEDO (New Energy and Industrial Technology Development Organization) Japan, two demonstrators were manufactured. One was aimed at Damage Detection and Suppression, and the other was at Noise and Vibration Reduction. These were cylindrical fuselages made of composite structures, whose length was 3 m and diameter was 1.5 m [29, 30].

The Damage Detection and Suppression Demonstrator (Fig. 8) was rigidly supported at one end and subjected to the upward shear load up to approximately 240 kN at the other end by hydraulic actuators, resulting in approximately 3,600 $\mu\varepsilon$ strain at maximum at the gage section of both upper and lower panels. The internal pressure up to 75 kPa was also applied in the pressurization stage. Several load-unload cycles were applied to the Demonstrator in order to measure the response of the structure under loading and to confirm the repeatability of the data. The following six themes were selected for demonstration (Fig. 9): (1) real time detection of

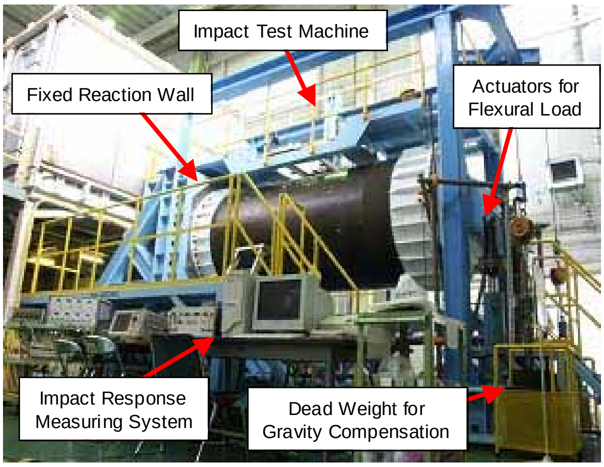

Fig. 8. Final assembly of the Damage Detection and Suppression Demonstrator

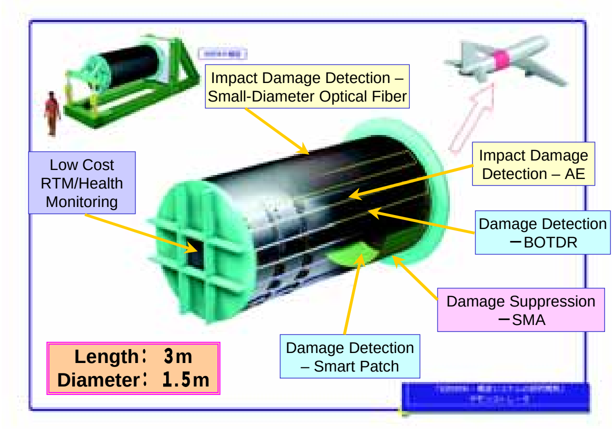

Fig. 9. Selected themes in Damage Detection and Suppression Demonstrator Test

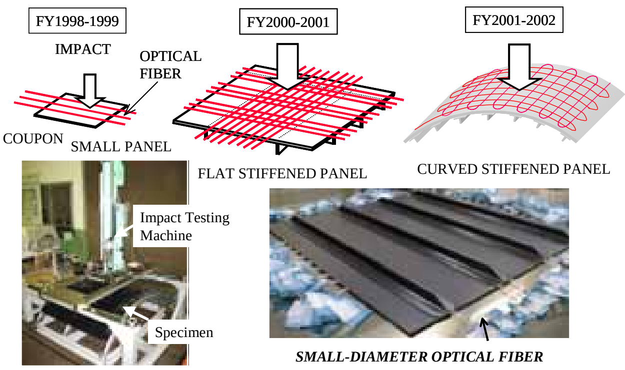

Fig. 10. Impact test specimens from coupons to stiffened flat and curved panels with embedded small-diameter optical fibers

impact damage with embedded small-diameter optical fiber sensors, (2) real time impact detection with integrated acoustic emission sensor network system, (3) strain distribution measurement using distributed BOTDR (Brillion Optical Time Domain Reflectmetry) technique, (4) damage suppression using embedded SMA foils, (5) maximum strain memory sensors by electric conductivity change in CFRP patch, and (6) smart manufacturing of low-cost sensor integrated panel by resin transfer molding.

Development of real time detection of impact damage with embedded small-diameter optical fiber sensors was conducted as a collaborative work between the University of Tokyo and Kawasaki Heavy Industries. Monitoring of the impact load on composite laminates was successfully made with embedded multi-mode small-diameter optical fibers [31, 32]. The bending loss was observed only during impact loading. The maximum magnitude of optical loss was found to be proportional to that of the impact load. Several small-diameter FBG sensors were also used to obtain the impact location through the dynamic strain measurement. Figure 10 shows the impact test specimens from flat coupons to stiffened flat and curved panels with embedded small-diameter optical fibers.

In the upper panel of the Damage Detection and Suppression Demonstrator in Fig. 8, the small-diameter optical fiber sensors were embedded in order to detect impact-induced damages (Fig. 11) [32]. The fiber connecters had been well designed to be embedded so that the fabricated CFRP panel could be trimmed at the edges after the manufacturing for practical use (Fig. 12). The small-diameter FBG sensors were used to obtain the impact location through the dynamic strain measurement, and multi-mode small-diameter optical fibers were embedded to judge the occurrence of the impact-induced damages using the optical loss due to bending. The algorism of impact load and damage evaluation and visualization system is shown in Fig. 13. Then, a novel impact detection and localization system was also developed as shown in Fig. 14. This system could successfully detect the impact locations and impact-induced damages.

The authors are also applying small-diameter FBG sensors to other composite

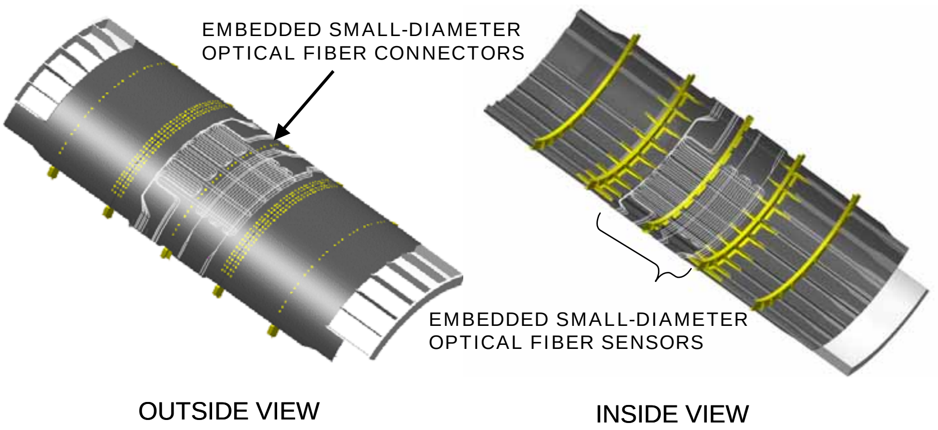

Fig. 11 Schematic of arrangement of embedded small-diameter optical fibers in the upper panel.

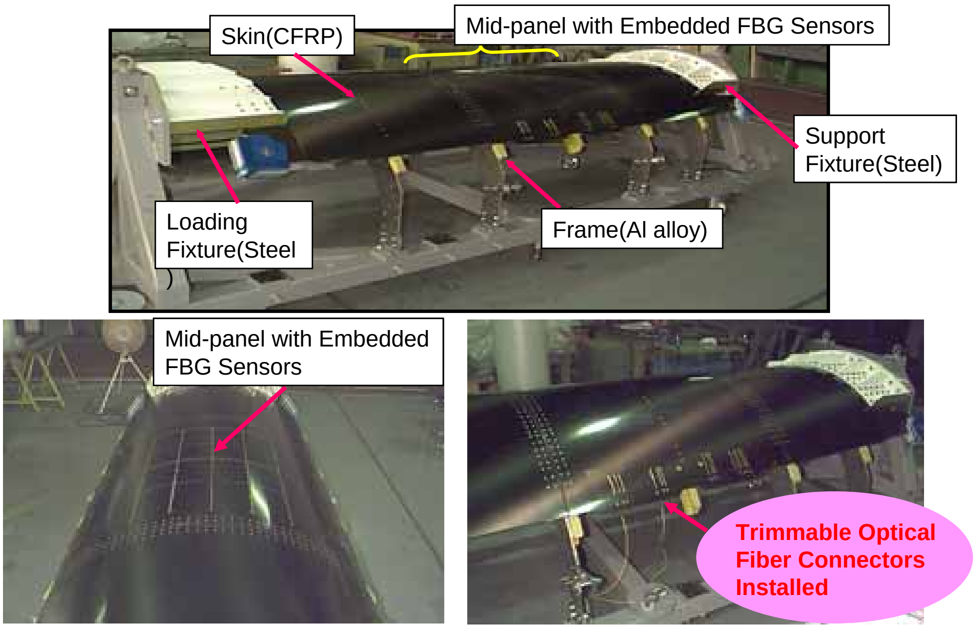

Fig. 12. Upper panel with embedded small-diameter optical fibers and trimmable connectors.

structures. Real time strain monitoring of composite LH_2 cryogenic tank during the flight operation was successfully conducted using a developed onboard FBG demodulator mounted on a reusable launch vehicle [33].

3 Recent ACS-SIDE Project

3.1 Summary

The current ACS-SIDE (Structural Integrity Diagnosis and Evaluation of Advanced Composite Structures) project was established in 2003 as a five-year program by RIMCOF (Research Institute of Metals and Composites for Future Industries) and funded by METI (Ministry of Economy, Trade and Industries), Japan. The main goal of the project is to establish the following three structural health monitoring technologies for prototype applications in advanced aircraft composite structures, that is, (1) PZT/FBG hybrid sensing system for bond-line monitoring in CFRP box structures (Fuji Heavy Industries, Hitachi Cable Ltd., The University of Tokyo, Tohoku University, AIST), (2) Highly reliable advanced grid structures (HRAGS) (Mitsubishi Electric Co., The University of Tokyo), and (3) Distributed strain sensing using Brillouin optical

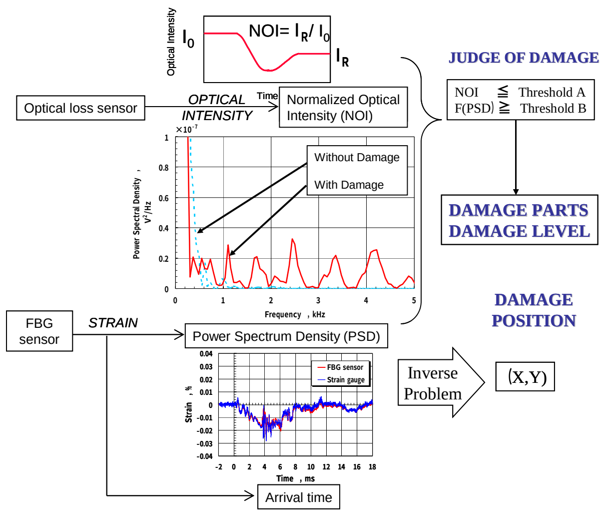

Fig. 13 Algorism of impact load and damage evaluation/visualization system

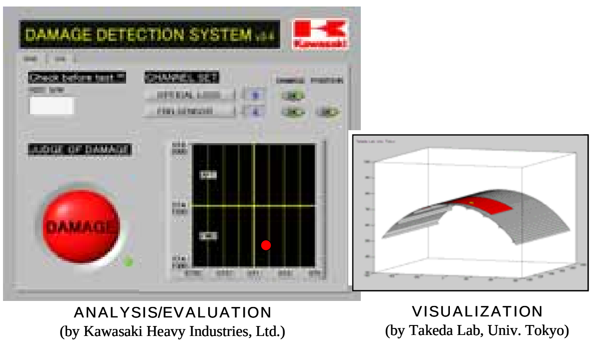

Fig. 14. A developed impact detection and localization system. The system judged a delamination at the impact region.

correlation domain analysis (Mitsubishi Heavy Industries). These systems are highly demanded to assure the safety and reliability of advanced composite structures and to reduce the maintenance cost as well.

3.2 PZT/FBG hybrid sensing system for bond-line monitoring in CFRP box structures

A new hybrid and active sensing system with PZT actuators and FBG sensors has been developed by our group. The main focus is laid on the bond-line monitoring (debonding at inaccessible bonded areas) in CFRP box structures. Such structures can be realized only with a reliable SHM system. Lamb waves

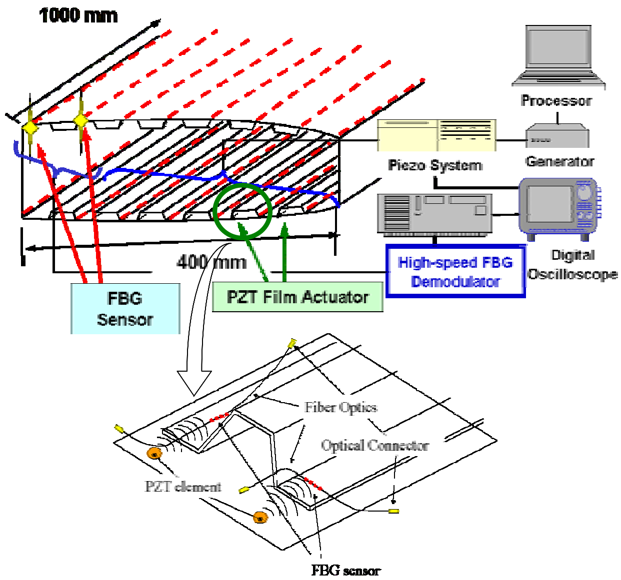

Fig. 15. Lamb wave detection in CFRP box structures with high-speed optical wavelength interrogation system using an AWG filter

generated by actuators can travel in some distance and are influenced by damaged or debonded regions. Then, these Lamb waves are measured by a newly developed high-speed optical wavelength interrogation system using an AWG (arrayed waveguide grating) filter (Fig. 15) [34]. Small-diameter FBG sensors were successfully embedded in the bond lines of typically 125 μm in thickness without strength reduction.

Figure 16 shows a fatigue test with our hybrid and active sensing system installed. Gradual growth of debonding at critical regions or hot spots was measured by conventional ultrasonic inspection and the corresponding Lamb waves were continuously monitored during the test. Handling of small-diameter FBG sensors was highly improved by introducing pre-installed optical connectors. The optimiza-tion study was conducted on the placement of PZT actuators and FBG sensors. Optical properties of small-diameter FBG sensors were improved so that the attenuation due to micro-bending was minimized. Change of detected Lamb waves could be observed as the debonding grew as shown in Fig. 17. Before the debonding was introduced, two main modes appeared around 20 μs and 45 μs. With increase

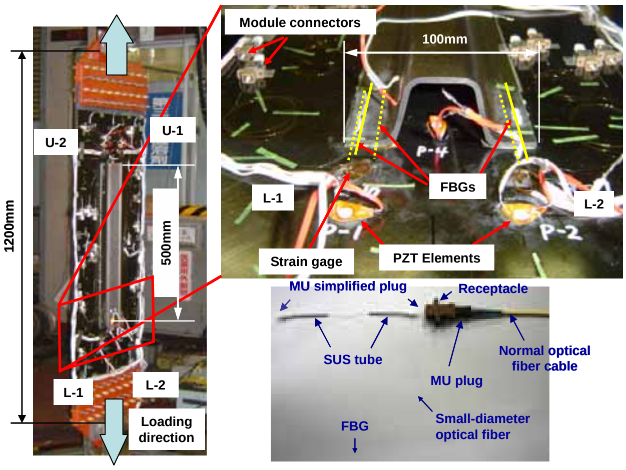

Fig. 16. Fatigue test of a CFRP box structure with the hybrid and active sensing system. Pre-installed optical connectors were installed.

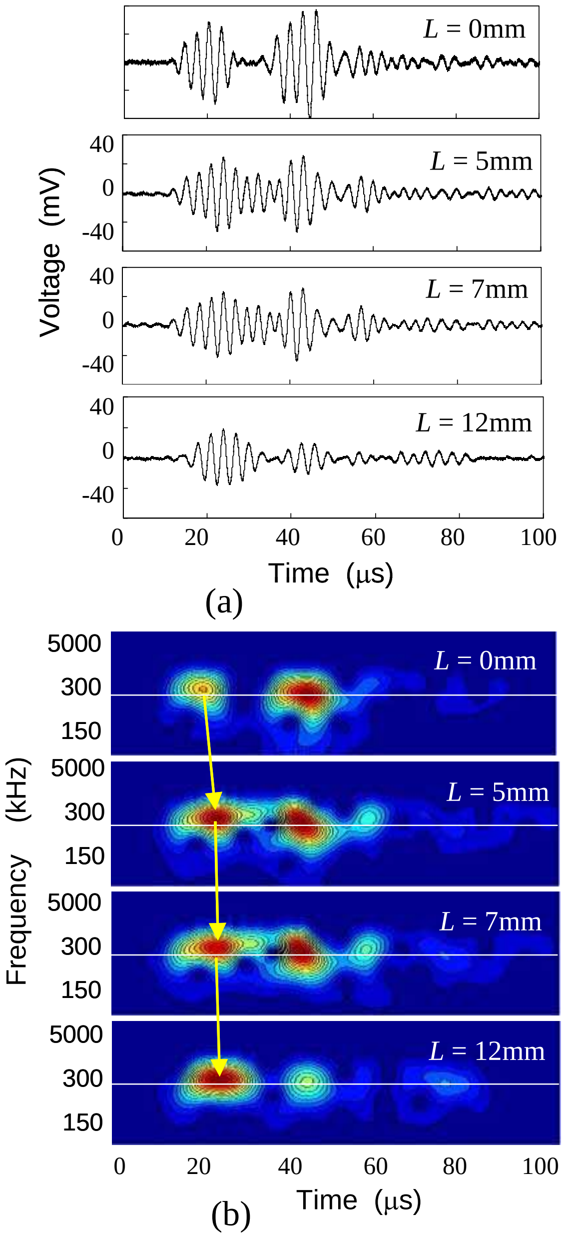

Fig. 17. Change of detected Lamb waves with growing debonding (a). Wavelet transform can distinguish the change in the waveform more clearly (b)

in the debonding length *L*, another mode appeared between the two modes, and the amplitude of the slower mode became smaller than that the faster mode. Wavelet transform applied to the received waveforms makes us distinguish the change in the waveform more clearly [35]. Two parameters have been introduced to distinguish the waveform change qualitatively (Fig. 18), that is, damage index *DI* and correlation coefficient *c*. The *DI* value provides the difference in the distribution of wavelet coefficients between the standard data and the compared data. The *c* value denotes the correlation coefficient of wave envelopes of the standard data and the compared data. The delamination growth can be identified using both parameters. The details can be found in Refs. [36, 37].

3.3 Highly reliable advanced grid structures (HRAGS)

A grid structure made of CFRP unidirectional composites, named as an advanced grid structure (AGS), has specific characteristics such as simplicity of stress path / damage feature and fail-safe structural redundancy. We are proposing the HRAGS system equipped with a SHM system utilizing FBG sensors embedded in every rib of AGS so that the size and the intensity of operational or accidental damages can be evaluated through the strain measurement of every rib. A recent advanced 6-axis controlled tape placement machine can be utilized to place CFRP unidirectional tapes and optical fibers with FBG sensors (Fig. 19). Recent high-speed optical switch can be also used to scan all the strain data from a number of FBG sensors [38].

Figure 20 shows an example of the HRAGS system output. This specimen has 39

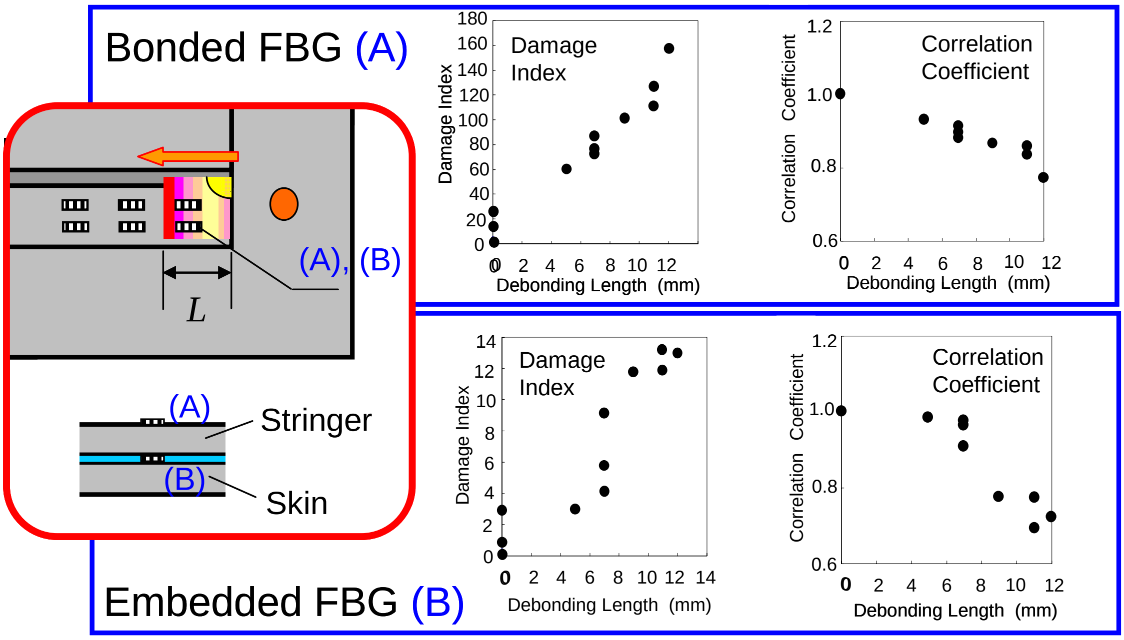

Fig. 18. Damage index *DI* and correlation coefficient *c* as functions of debonding length.

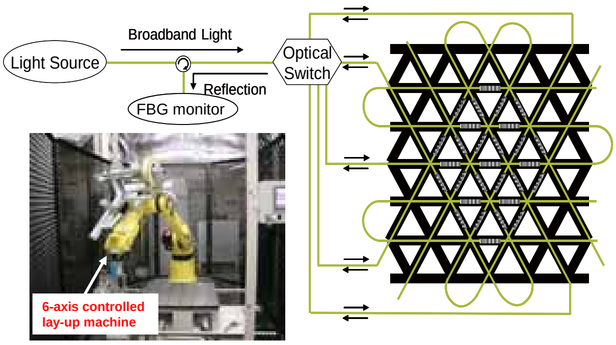

Fig. 19. HRAGS system and CFRP tape and optical fiber placement

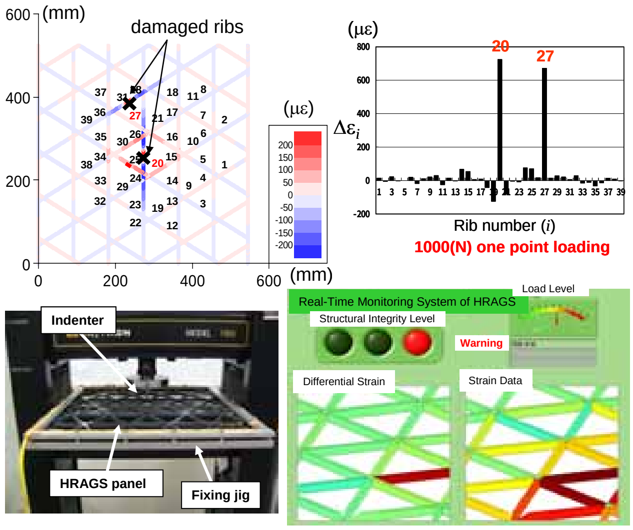

Fig. 20. HRAGS system output. The 20th and 27th ribs were partially notched. A user-friendly and robust statistical damage recognition system for SHM was established.

FBG sensors multiplexed into seven optical fibers attached on lower surfaces of ribs. At first, the specimen was loaded on one nodal point up to a certain load (1000N) and all the strains $\varepsilon^{\text{intact}}$ were measured from the FBG output. Then, the specimen was unloaded and the 20th and 27th ribs were partially notched. Afterward, it was loaded again up to 1000N and strains $\varepsilon^{\text{damage}}$ were measured under the same boundary conditions. Finally, the change in strains (differential strain) $\Delta\varepsilon = \varepsilon^{\text{damage}} - \varepsilon^{\text{intact}}$ was calculated. Although the differential strain $\Delta\varepsilon$ was found a good parameter to distinguish the damage location, a more user-friendly and robust procedure to determine the damage location was required for use in practical aircraft operating conditions. So, a statistical damage recognition system for SHM was established for this purpose [39].

3.4 Distributed strain sensing using Brillouin optical correlation domain analysis

The BOTDR is most popular method of the distributed optical fiber sensing system to measure the strain distribution along an optical fiber, but the special resolution has been limited up to 1 meter in length. The measurement along the whole optical fiber length took typically 20-30 minutes. Hotate et al. have been developing a novel distributed stain measurement technique called BOCDA (Brillouin correlation domain analysis) with high spatial resolution and dynamic measurement capability [40, 41]. The development of a prototype BOCDA system has been conducted which operates with 50 mm in spatial resolution and 2.7 Hz in sampling speed.

Comparison of strain distribution is shown in Fig. 21 between BOCDA and electrical strain gages in buckling tests of stiffened panels. A high special resolution was well demonstrated. The high-speed sampling at a certain point in an optical fiber was also demonstrated as shown in Fig. 22. Then, a demonstration flight test was conducted to obtain in-flight data and to understand some problems for use under practical flight conditions [42].

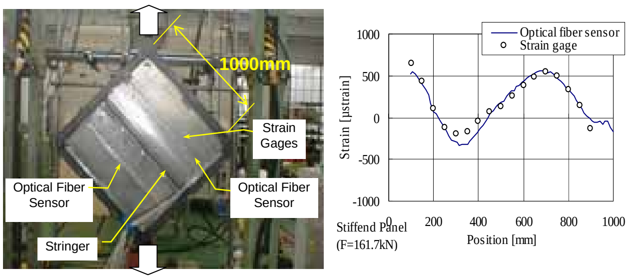

Fig. 21. Comparison of strain distribution between BOCDA and electrical strain gages in buckling tests of stiffened panels.

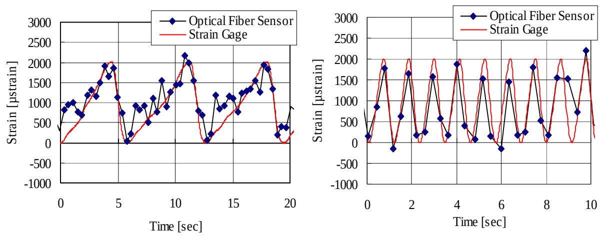

Fig. 22. High-speed sampling at a certain point in an optical fiber using BOCDA system.

4 Conclusions

Optical fiber sensors including FBG are promising as tools for SHM of aerospace composite structures as found in this review. Especially, small-diameter optical fiber and its FBG sensors are attractive for embedment in composite laminates. More extensive studies are necessary to certify them for use in real aerospace composite structures.

Some recent results in the current ACS-SIDE project were also presented on optical fiber based SHM for some feasible applications in aerospace composite structures, which include (1) PZT/FBG hybrid sensing system for bond-line monitoring in CFRP box structures, (2) Highly reliable advanced grid structures (HRAGS), and (3) Distributed strain sensing using Brillouin optical correlation base analysis (BOCDA). These techniques are necessary to assure the safety and reliability of advanced composite structures and to reduce the maintenance cost as well for practical use. Further continuing efforts are necessary for implementing them in real aerospace composite structures.

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