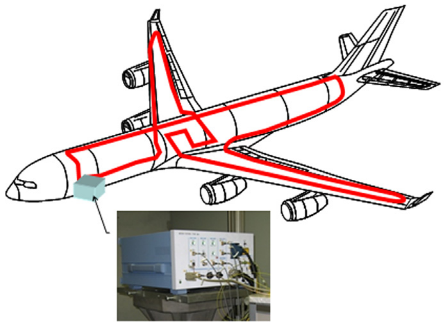
Development of a BOCDA-SHM System to Reduce Airplane Operating Costs



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Mitsubishi Heavy Industries, Ltd. (MHI) has developed a structural health monitoring (SHM) system for aircraft structures, using Brillouin optical correlation domain analysis (BOCDA). This includes an aircraft-mountable BOCDA measuring device, whose accuracy has been verified in flight tests. This paper outlines the current status of the BOCDA-SHM system, and provides a durability evaluation of the sensor installation part and a reliability analysis of the damage diagnosis, which were conducted as a part of our efforts to enhance the overall reliability of the system.

1. Introduction

In recent years, airlines have increased their demands for health monitoring of aircraft structures in order to reduce aircraft operating costs. A SHM system is expected to meet their demands, since it facilitates a reduction in operating costs by shortening the period required for aircraft structural inspections. Among the various SHM systems, BOCDA-SHM system detects structural damage and measures structural life by recording and analyzing variations in the strain distribution of the overall aircraft structure, or the load history data for each operation.[1]

The basic concept of applying BOCDA measurements to aircraft structural health monitoring is illustrated in **Figure 1**.

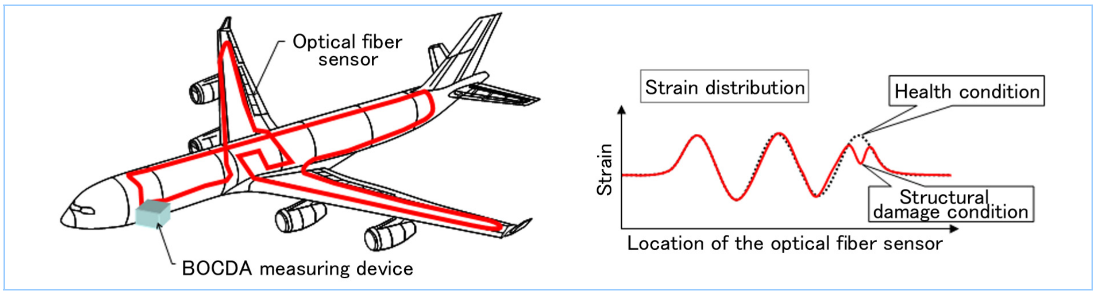

Figure 1 Application concept of the BOCDA-SHM system

BOCDA can measure the strain distribution and dynamic strain at an arbitrary point on an optical fiber. By placing optical fibers throughout an aircraft structure, damage can be diagnosed from distributed strain variations, and structural life can be measured from the load history of the structure. We built a prototype of an aircraft-mounted BOCDA measuring device, and have demonstrated its accuracy in a business jet operating environment.[2] To apply an SHM system that monitors structural health during operation, the reliability of the overall system and the trustworthiness of its diagnosis must first be ensured. This paper describes a durability evaluation of the sensor installation part for an aircraft BOCDA-SHM system, as well as the development status of the diagnostic technology for assessing structural damage.

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2. Development of the BOCDA-SHM system

2.1 Evaluation of sensor system durability

The durability of the SHM system can be ensured by confirming the durability of the measurement devices and sensor installation part under operating conditions. Accordingly, we evaluated the durability of an optical fiber sensor installation on a structural surface in an aircraft operating environment. The evaluation included the effects of major environmental factors, such as temperature, pressure, humidity, and lubricants. The environmental conditions for this evaluation are listed in **Table 1**.

The test specimen for the evaluation was a carbon fiber-reinforced plastic (CFRP) plate (used in aircraft structures), to which an optical fiber was bonded with epoxy adhesive, and protected with fuel tank sealant. The optical fiber sensor had a diameter of 125 μm, and was coated with polyimid resin. We applied a tension load to this optical fiber to evaluate the durability of the installation part. The applied tension was 4 N, corresponding to a step-like strain change of 8000 μstrain. **Figure 2** illustrates the test procedure. Each simulated environmental condition listed in Table 1 was applied to the sensor installation part, and the adhesion strength of the optical fiber was evaluated. The results of this evaluation verify that the adhesive strength of the optical fiber is adequate under the conditions listed in the table, and thus the sensor installation part is durable in an actual operating environment.

Table 1 Environmental conditions for durability evaluation of a sensor installation part

Test Item	Environmental conditions
High temperature environment	+110±5°C, air
Low temperature environment	-65±2°C, air
Temperature cycle	-65−110°C, air
High pressure environment	200±10kPa
Low pressure environment	11.6±10kPa
Operating oil environment	+70±2°C, skydrol immersion
Fuel environment	+50±2°C, jet-A immersion
Humidity environment	+70±2°C, 90±5%R. H.

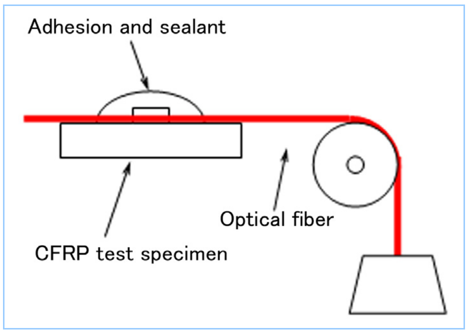

Figure 2 Test procedure for evaluating optical fiber adhesiveness

2.2 Adhesive delamination damage detection algorithm

The BOCDA-SHM system must evaluate a massive amount of data at a high spatial resolution to measure the strain distribution on an optical fiber sensor (with a typical length of several hundred meters) installed on an aircraft structure, and detect damage. To handle the large quantity of data efficiently, it was necessary to develop a diagnostic algorithm that automatically detects the portion of the strain variation associated with structural damage.

We therefore developed an algorithm that diagnoses delamination expansion of an adhesive member from the output of the BOCDA measurement system. We adopted the Mahalanobis–Taguchi (MT) method to identify an abnormality in the large quantity of multi-dimensional data generated by the BOCDA measurements. The MT method defines the Mahalanobis distance (MD) as the relative distance between an evaluation criterion and the measured data of a diagnosis target, and evaluates a deviation from normal conditions (i.e., an abnormality) by uniformly evaluating the MD. When using this procedure, the unit space (an aggregation of data defined as normal) is first specified, and then the MD (the distance from the unit space) is calculated from various parameters in measured data during operation. A structural abnormality is diagnosed from the size of the MD. Hence, this process does not require the modeling (i.e., model equations) of an a priori predicted multivariate quantity, and can be used for wide-range determination and monitoring of various conditions of the diagnosis target.[3]

Our developed algorithm for detecting adhesive delamination damage employs the strain distribution and the distance-directed wavelet-transformed results as a diagnostic parameter. Structural conditions are evaluated by calculating the MD from diagnostic parameters during operation, after first specifying the unit space in terms of diagnostic parameters under healthy conditions.

We conducted an adhesive delamination test on a specimen that imitated a composite reinforced panel, in order to evaluate the damage detection characteristics of this algorithm. The test specimen was 1,000 mm long, 400 mm wide, and approximately 1.5 mm (8-ply) thick, and had a strap (in the form of a stringer) that was 400 mm long, 50 mm wide, and approximately 1.5 mm (8-ply) thick secondarily bonded to its center. The optical fiber sensor, which was over 700 mm long, was installed 5 mm from and parallel to the strap (**Figure 3**).

Strain variation was evaluated from BOCDA measurements by applying a tension load to the panel. The BOCDA measurements were taken with 30 mm spatial resolution. Adhesive delamination expansion occurred at a tension of around 130 kN, and a variation of the strain distribution was observed in the vicinity of 0.2 m from the origin of measurements (**Figure 4**). We calculated the MD distribution by applying our developed MT diagnostic algorithm to this variation of the strain distribution. The calculated MD distribution is shown in **Figure 5**. The results indicate that the variation was detectable, since an increment in the MD value was observed at the locations where the delamination expansion occurred.

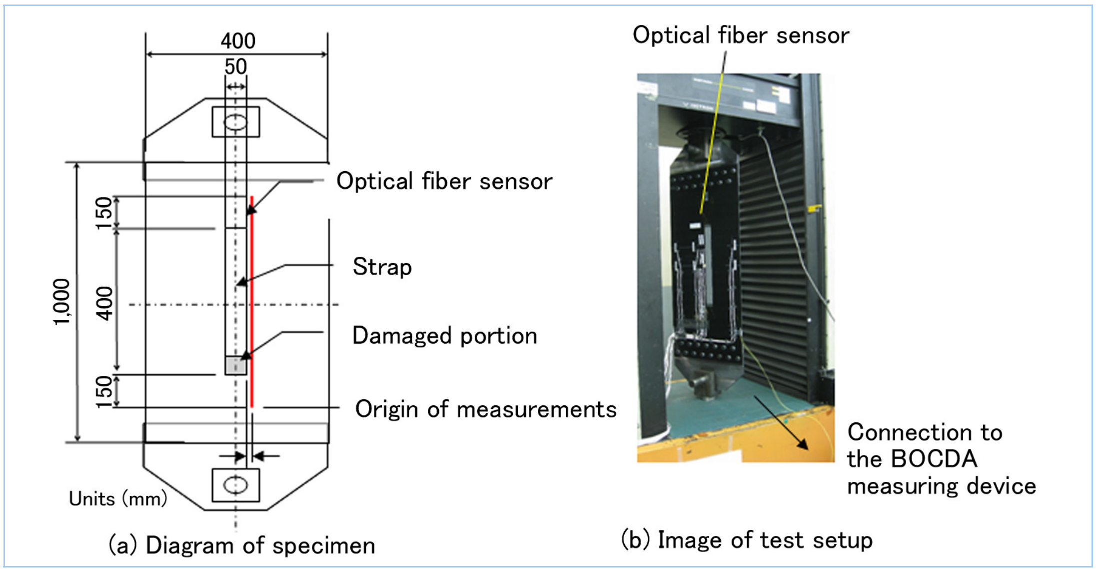

Figure 3 Overview of the test specimen for evaluating adhesive delamination detection

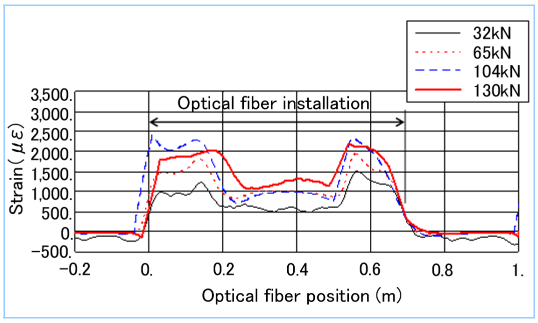

Figure 4 Variations of strain distribution associated with adhesive delamination damage expansion

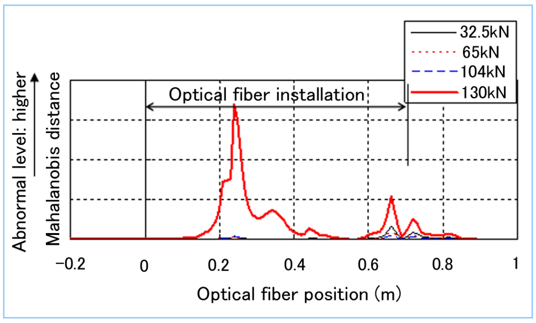

Figure 5 Results of applying the adhesive delamination damage detection algorithm

2.3 Development of a damage detection algorithm

The optical fiber sensors used in the BOCDA-SHM system can be embedded in CFRP materials, and offer the potential for detecting damage inside the CFRP. Accordingly, we embedded an optical fiber in a CFRP material to evaluate the detectability of delamination damage.

Figure 6 shows an overview of the test specimen for evaluating delamination damage detection. The specimen was 350 mm long, 200 mm wide, and approximately 1.5 mm (8-ply) thick, and artificial delamination damage was installed on the central layer of the plate. An optical fiber sensor approximately 600 mm long was embedded in the same layer as the artificial delamination, and was drawn out from the edge of the CFRP.

We inserted a metal blade with a thickness of 1 mm in the artificially created delamination to cause the delamination to expand gradually, and took BOCDA measurements at a spatial resolution of 30 mm. Figure 6 depicts the gradually expanding delamination fronts A, B, and C as dotted lines. The Brillouin frequency shift (BFS) corresponding to the strain distribution, and the Brillouin gain spectrum (BGS) at each measurement point were measured for the evaluation. The BGS indicates the condition of the measurement point; the spectrum tends to be narrower when the strain distribution is uniform within the spatial resolution (a precipitous peak), and wider when the strain distribution fluctuates within the spatial resolution (a mild peak). The BOCDA measurement results are shown in **Figure 7**. The BFS variation in the vicinity of 0.2 m, associated with the expansion of delamination damage, is shown in Figure 7(a). The BGS at the corresponding position is shown in Figure 7(b). The shape of the BGS changed with the expansion of delamination damage. Figure 7(b) indicates that the residual strain created during CFRP curing was released in the vicinity of the delamination damage front, where the distribution became non-uniform. However, uniformity was restored beyond the area of delamination damage. The expansion of damage inside a CFRP material involves the release of residual strain, and results in a non-uniform strain distribution for an embedded optical fiber.

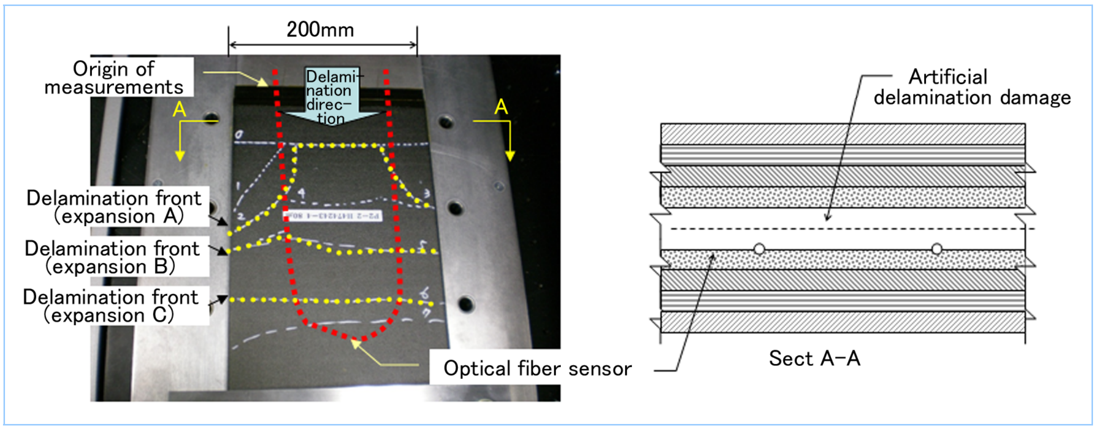

Figure 6 Overview of the test specimen for evaluating delamination damage detection

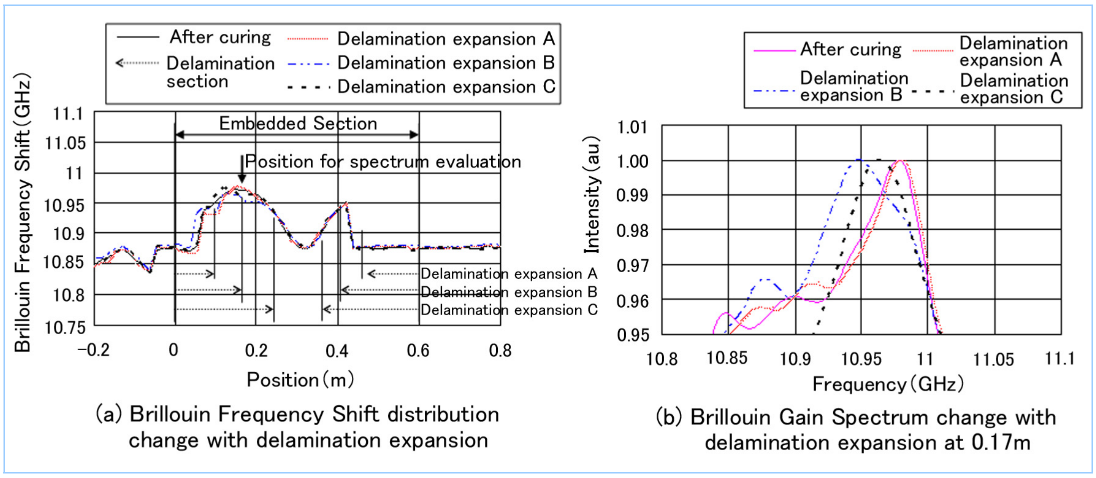

Figure 7 Measurement results of the delamination damage detection test

To evaluate the conditions of such delamination quantitatively, we developed a diagnostic algorithm based on the MT method, using the BGS profile as a parameter. In this diagnostic algorithm, the BGS half value width, center frequency of the half value, 3/4 value width, and center frequency of the 3/4 value are adopted as evaluation parameters. The MD distributions of the crack fronts A and C, calculated by the MT diagnostic algorithm, are shown in **Figure 8**. The figure reveals that the MD value increased with the expansion of delamination at the delaminated location or delamination front, and thus an abnormality (i.e., structural damage) can be detected. However, the MD value also increased at a point where a sensor was not embedded, due to disturbance in the vicinity of the measurement, and approximately 60 mm of distance error was detected between the actual delamination point and the point where the MD increased. Improved stability of damage detection and improved location accuracy remain challenges for future research.

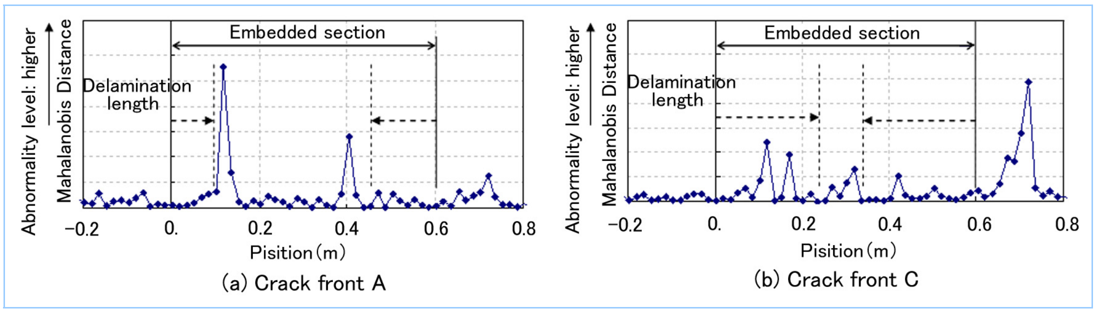

Figure 8 Results of applying the delamination damage detection algorithm

3. Conclusion

In this paper, we outlined the results of an optical fiber sensor durability test and the development status of a diagnostic algorithm, as a part of our efforts to develop a health monitoring system for the overall structures of actual aircraft. We ensured that the sensor installation part is durable in an aircraft operating environment, and devised an MT-based algorithm for diagnosing the delamination and adhesive delamination that are typical damage conditions in an aircraft structure. In light of these achievements, we are planning to downsize the aircraft structural health monitoring device, evaluate the damage diagnosis possibilities quantitatively, and reduce the application cost of the sensor system.

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References

1. Hotate K. et al., Distributed fiber Brillouin strain sensing by correlation-based continuous-wave technique -cm-order spatial resolution and dynamic strain measurement, SPIE Photonics Asia, Shanghai, Vol. 4920-51 (2002) p. 299-310
2. Yari, T. et al., Monitoring Aircraft Structural Health Using Optical Fiber Sensors, Mitsubishi Heavy Industries Technical Review Vol. 45 No. 4 (2008)
3. Takeshita T. et al., A property of the Probability distribution of the Estimator of the Mahalanobis Distance, J76-D-II 1, p. 59-64(1993)