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Impact damage detection system using small-diameter optical-fiber sensors embedded in CFRP laminate structures

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Abstract—The mechanical properties of composites subjected to out-of-plane impact decrease markedly from even barely visible damage. In this study, three damage detection technologies are explained: (1) Technologies for the arrangement of embedded small-diameter optical fibers that have no serious effect on the mechanical properties of composites; (2) Technologies for the egress of the optical fibers using 'the embedded connector for smart structures' that can be trimmed without damaging the optical fibers; and (3) Technologies for a damage detection system that has data acquisition and analysis functions, evaluates the initiation and the position of damage, and visualizes damage information. We conducted an impact test using the composite airframe demonstrator. FBG sensors are embedded in the upper panel of the 1.5 m diameter, 3 m long stiffened cylindrical composite structure for strain measurement, and optical fibers are embedded for optical loss measurement. Damage detection in composite structures using the developed damage detection system was demonstrated.

Keywords: Health monitoring; impact damage; stiffened panel; composites; optical-fiber sensor; FBG sensor.

1. INTRODUCTION

Carbon fiber reinforced plastic (CFRP) composites have been used extensively for light weight airframe structures because of their high specific strength and stiffness. As shown in Fig. 1, because of the serious decrease in composites caused by damage, compression after impact (CAI) strength is regarded as an important

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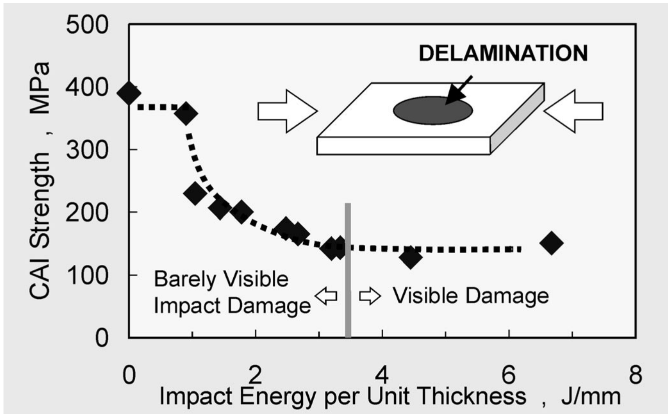


Figure 1. Relationship between CAI strength and impact energy.

design criterion. As a damaged part should be inspected in detail by traditional non-destructive inspection (NDI) methods, such as ultrasonic C-scan or soft X-ray, the part has to be removed from operational airframe structures usually at great expense in both labor and down-time. The objective of this study, which has taken five years [1], is the development of technology to detect barely visible impact damage (BVID) in composite structures by using embedded optical-fiber sensors. The system developed can be used for in-flight damage detection as well as for on-ground damage detection. This technology can be expected to provide cost reduction for inspection and associated work. In this paper, both the developed technologies and demonstration of damage detection using a composite airframe structure are explained.

2. TECHNOLOGIES DEVELOPED FOR DAMAGE DETECTION

Some basic technologies were developed for composite structure damage detection. The four main technologies explained in this section are (1) the method of damage detection, (2) the designed arrangement for embedded small-diameter optical-fiber sensors, (3) the connectors for smart structures, and (4) the analysis, evaluation, and visualization system.

2.1. Method of damage detection

In this study, optical-fiber sensors are used to detect damage in composite structures. ‘Small-diameter optical fibers’ (40 μm in-cladding diameter [2]) were specially used. This small diameter is very important because, as shown in Fig. 2, conventional optical fibers, such as communication fibers, normally have a 125 μm in-cladding diameter, i.e. the same as the thickness of a CFRP prepreg. Small-diameter optical fibers can be embedded within a CFRP prepreg without deteriorating the mechanical properties of composites. Here, the core diameters of small-

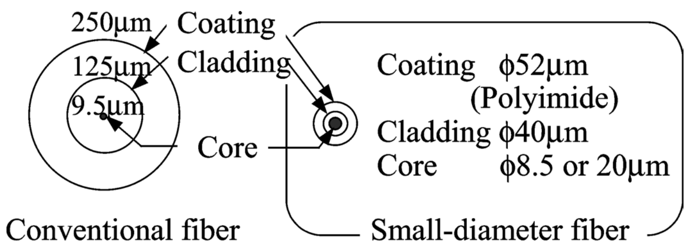


Figure 2. Comparison of small-diameter optical fiber with conventional optical fiber. (a) By measuring optical intensity. (b) By measuring strain responses.

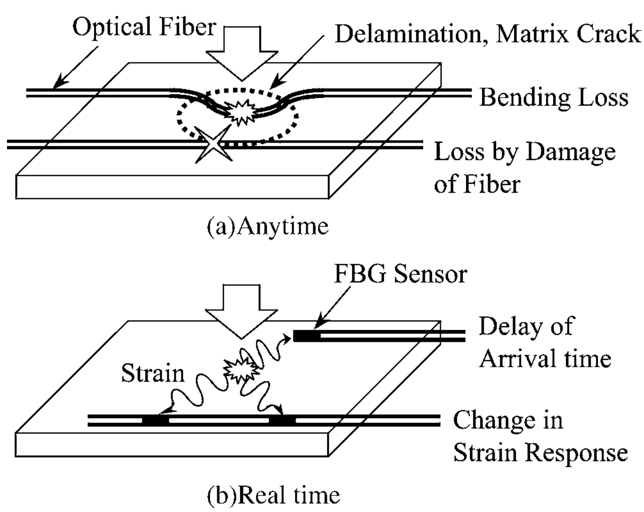


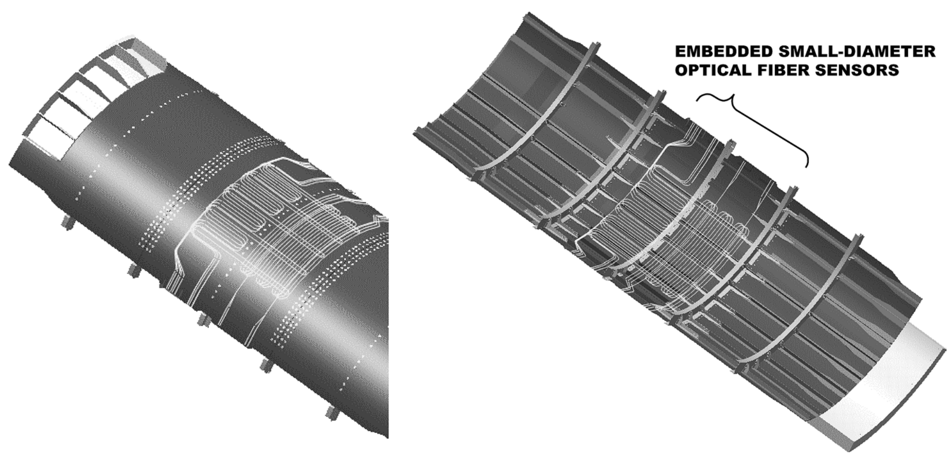
Figure 3. Damage detection method. (a) External view. (b) Internal view.

diameter optical fibers are 8.5 μm for single-mode fibers or 20 μm for multi-mode fibers.

Figure 3 depicts two methods of damage detection using the small-diameter optical-fiber sensors. The first is the method of measuring the optical intensity of multi-mode type optical fibers, as shown in Fig. 3a. Incident light enters from one end of an optical fiber, passes through the damage-detection sensing area, and comes out from the other end. If the optical fiber is subjected to damage or local bending or deformation by impact damage, such as delamination or matrix cracking, the optical intensity of optical fiber decreases. Damage initiation can be judged from the degree of the optical loss. It is not necessary to measure the optical intensity in real-time in this method. The other method is to use single-mode type FBG sensors. As shown in Fig. 3b, the sensors can measure the strain induced by impact events. Damage initiation can also be judged from the change in strain responses, and the damage position can be detected using the differences of arrival times of the strain at each sensor.

2.2. Arrangement design for embedded small-diameter optical-fiber sensors

How should we arrange the optical-fiber sensors to be embedded in practical airframe structures? Table 1 lists the main design items. For a curved, stiffened panel, a skin and a stringer have different damage characteristics. For instance, impact damage in composites tends to appear from the middle of the thickness to the backside of the skin subjected to an impact load. As a result, optical-fiber sensors need to be embedded in the skin, stringer and interlaminar region between the skin and stringer. The damage distribution in a planar area is important for determining the embedded optical-fiber interval. The optical characteristics and multiplex system must also be considered. Finally, care should be taken in locating fasteners and developing assembly-handling procedures to ensure the embedded optical fibers are not cut.



(a) Outside view (b) Inside view

Figure 4. Designed arrangement of embedded optical-fiber sensors. (a) Edge of skin. (b) Edge of stringer. (c) Detail of (b).

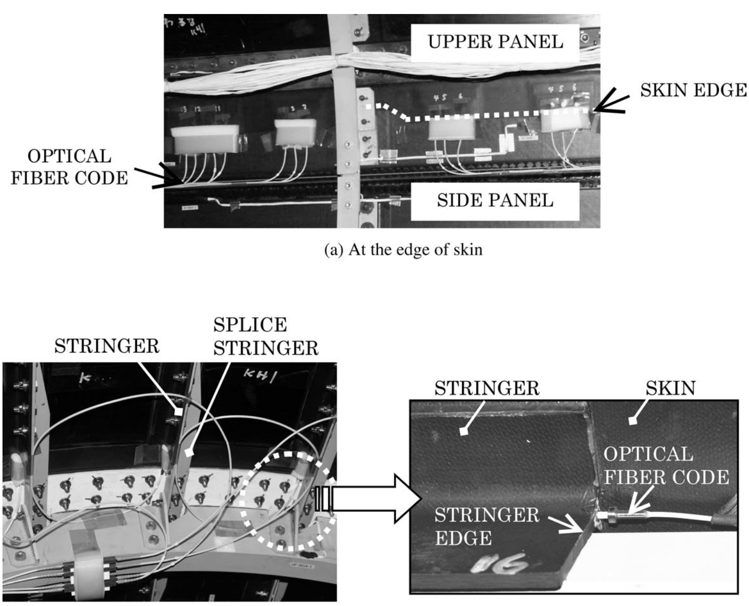
Table 1.
Main design items arranging optical-fiber sensors

Design item	Investigation item
Parts with embedded sensors	• Damage characteristics for composite structure
Interlaminar position of embedded sensors	• Ply distribution of damage
Interval of arranged sensors	• Plane distribution of damage • Optical characteristics
Proper quantity of sensors	• Multiplex system • Optical characteristics
Egress location of sensors	• Skin/stringer, fasteners • Handling for assembly

The designed embedded optical-fiber sensor arrangement in a curved, stiffened panel is shown in Fig. 4. The embedded fibers are 16 small-diameter optical fibers and four small-diameter FBG sensors. This 3 m long panel consists of three small panels with nine blade-type stringers and five frames. Each small panel is joined using splice plates and splice stringers. As a part of simulating an airframe structure fuselage, this panel was assembled with other panels by single-lap (longitudinal) splicing. Fastener holes are therefore drilled at the lap splice segment without cutting the embedded optical fibers.

2.3. Connectors for smart structures

Embedded optical-fiber sensors egress the laminate/CFRP structure to connect with a measurement system. However, at the level of structural element specimens, the embedded fibers were egressed directly from the specimens. This egress method has a serious problem in that the handling from manufacturing to assembly is difficult and trimming after the curing of composite structures is impossible. Therefore, 'the embedded connector for smart structures' was developed. This connector is embeddable in composites, trimmable after curing and connectable with optical-fiber cords or cables. Figure 5 illustrates the connection with optical-fiber cords. As shown in Fig. 5a, there is a part of the lap splice between an upper panel and a side panel. Optical-fiber cords can be connected to the edges of the skin of an upper panel. Figure 5b depicts the connection of optical-fiber cords to the edges of



(a) At the edge of skin

(b) At the edge of stringer

(c) Detail of (b)

Figure 5. Connection of embedded connectors for smart structures with optical-fiber cord.

stringers. Figure 5c presents detail of part of the connection. In this study, optical-fiber cords could be easily attached or removed.

2.4. Analysis, evaluation and visualization system

The optical signal data (optical intensity and strain) are analyzed and evaluated to identify damage incidents, specify the position/part damaged, and estimate the damage level. The information is displayed on a graphical screen to indicate the result of damage detection. The methods of analysis and evaluation are shown in Fig. 6. For damage detection, as mentioned in Section 2.1, two optical-fiber sensor measuring methods are used. Measured optical intensity is normalized by equation (1). The value of the normalized optical intensity (NOI) is compared with threshold A. An NOI $\leqslant$ A indicates a 'damage incident'. Damage is also detected from the power spectrum density (PSD) of the strain responses measured by FBG sensors when F(PSD) $\geqslant$ threshold B. The area and level of the damage can be determined by correlating the received data to the sensor arrangement. Moreover, since the arrival time of a strain wave at each FBG sensor differs, the position (x, y) of the damage can be specified by solving the inverse problem for the time lag function of equation (2).

$$\mathrm{NOI} = \frac{I_R}{I_0}, \tag{1}$$

I_0 reference optical intensity before damage, I_R residual optical intensity after damage.

Objective function:

$$\underset{x,y}{\mathrm{Min}}\,\mathrm{F}\left[\left(\frac{\mathrm{d}S_{ij}}{\mathrm{d}t_{ij}} - \mathrm{V}\right)^2\right], \quad i \neq j, \tag{2}$$

i, j serial number of FBG sensors, dS difference of the distance S between FBG sensor and damage position (x, y), dt difference of the arrival time at each FBG sensor, V velocity of strain wave in a composite demonstrator.

The analysis, evaluation, and visualization system, which is included in the damage detection system, was developed using the algorithm mentioned above. As shown in Fig. 7, the system has a graphical screen/interface. The main screen (on the left) displays the data measured by the optical-fiber sensors, and the data is analyzed and evaluated. The color of indicator (1) changes to red as new damage is detected. The X–Y graph (2) can indicate the damage point. Here STAxxx and STyy mean the position of frames and stringers, respectively. Using damage initiation and position information, correlated to the arrangement of embedded optical-fiber sensors, the position of the damage parts included in the damaged area can also be indicated on a 3D structural model. An example of the visualization of the damage in a skin and a stringer is shown in the 3D model on the right of Fig. 7. The point of view for the model can be easily changed using a mouse, and the information can be understood visually. (The 3D model was developed at the University of Tokyo.)

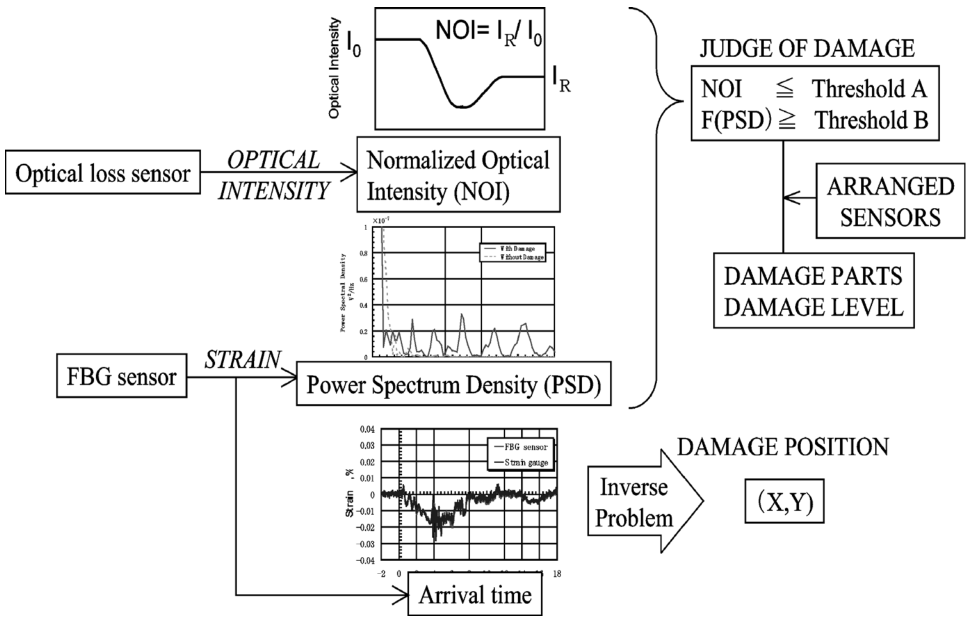


Figure 6. Damage detection analysis and evaluation.

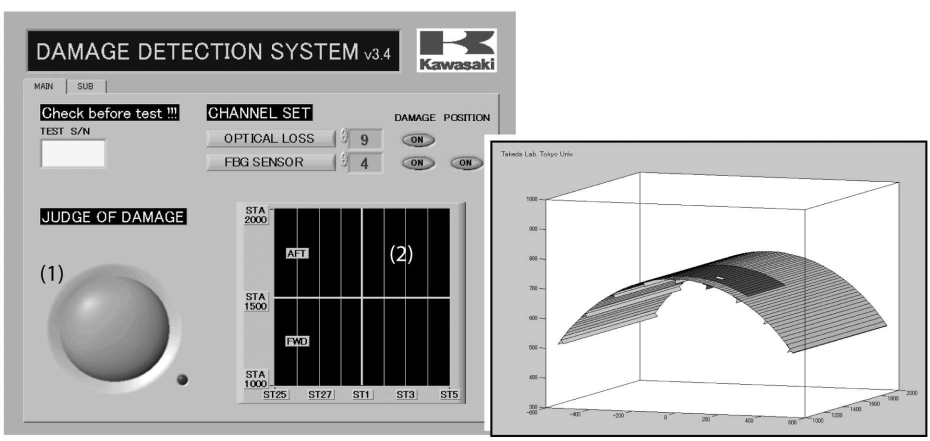


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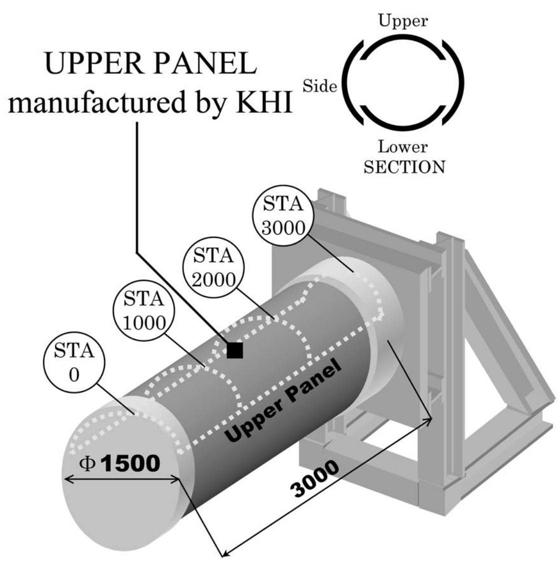
Figure 7. Damage detection system main screen. (a) Photograph of demonstrator. (b) Sketch of demonstrator.

3. DEMONSTRATION TEST

3.1. Specimens for impact test

As shown in Fig. 8a, the impact test for the demonstration of damage detection after bending and pressure tests was conducted using a 1.5 m diameter and 3 m long demonstrator. The composite demonstrator, assembled with a single lap splice, consists of the upper panel, left and right side panels, and lower panel. The specimen

(a) Photograph of demonstrator



(b) Sketch of demonstrator

Figure 8. Full view of demonstrator.

is supported as shown in Fig. 8b. The sensing area of the optical-fiber sensors is the mid-part of the upper panel, from STA1000 to STA2000. The area has a skin with three frames and five stringers. Ten impact positions on a mid-bay skin, the flange and the center of a stringer are shown in Fig. 9. Impact damage can be

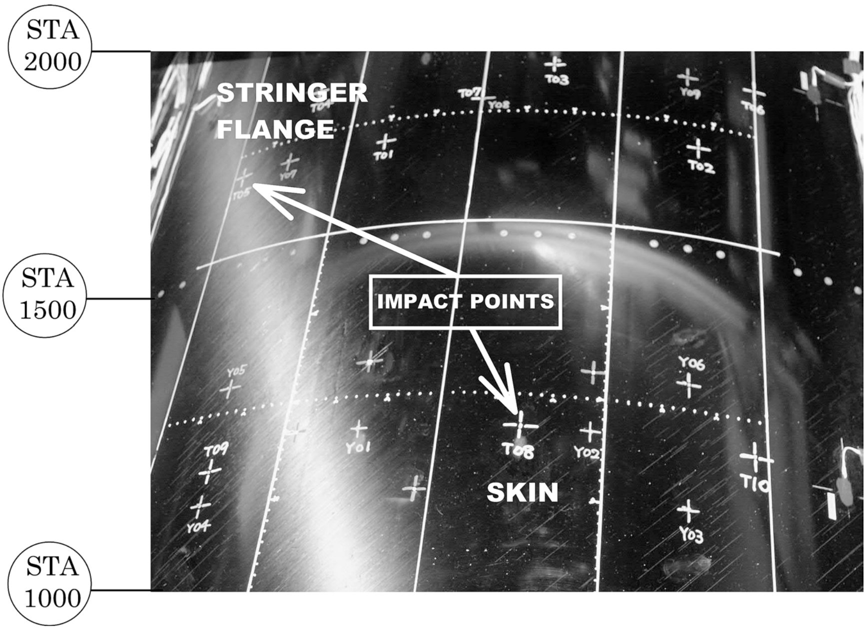


Figure 9. Impact points on the upper panel.

induced by dropping a 55 N impactor from an impact test machine installed above the demonstrator (Fig. 8a). In this study, the impactor was dropped from heights of 0.19 m to 0.56 m.

3.2. Damage detection system

Figure 10 depicts the impact damage detection system (DDS). The DDS consists of the measurement system and the analysis, evaluation, and visualization system. The optical intensity measured by the optical detector and the strain measured by the FBG sensor system are stored in a digital data recorder. At the same time, the impact load measured by an impact test system is acquired. The damage to the composite is detected by the analysis, evaluation, and visualization system.

3.3. Result of damage detection

Damage in all of the tests induced by barely visible damage in a composite could be detected. First, typical responses of optical intensity and strain measured by the optical-fiber sensors with an impact load are shown in Fig. 11. In this case, the BVID occurs in the composite at approximately 3 ms after impact. As the impact load is increased, the response of normalized optical intensity changes. We found that the intensity is reduced to zero by the initiation of damage. The strain response also changes after impact, and changes rapidly after the initiation of damage.

Using data like these, damage was detected by DDS. Two typical examples of the damage detection results are described below.

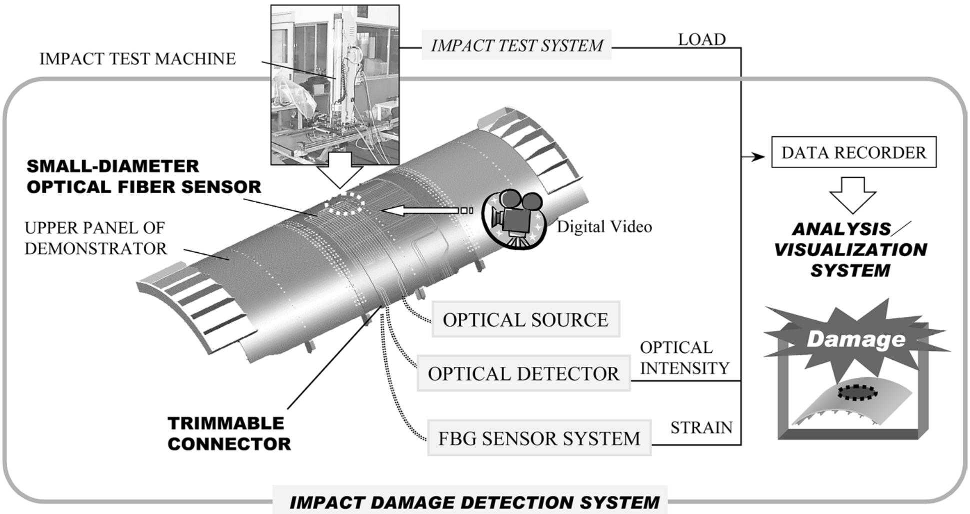


Figure 10. Impact damage detection system and impact test system.

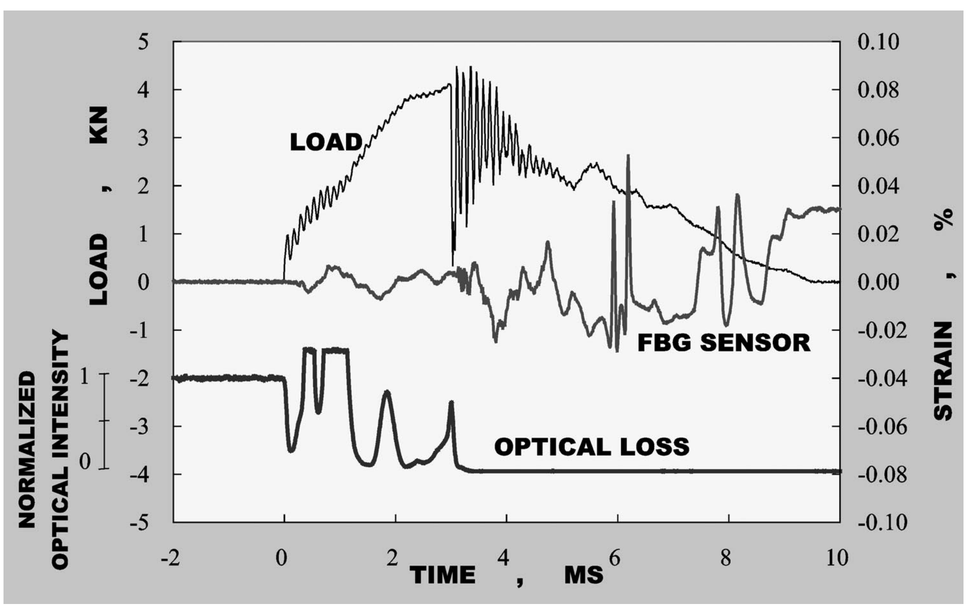
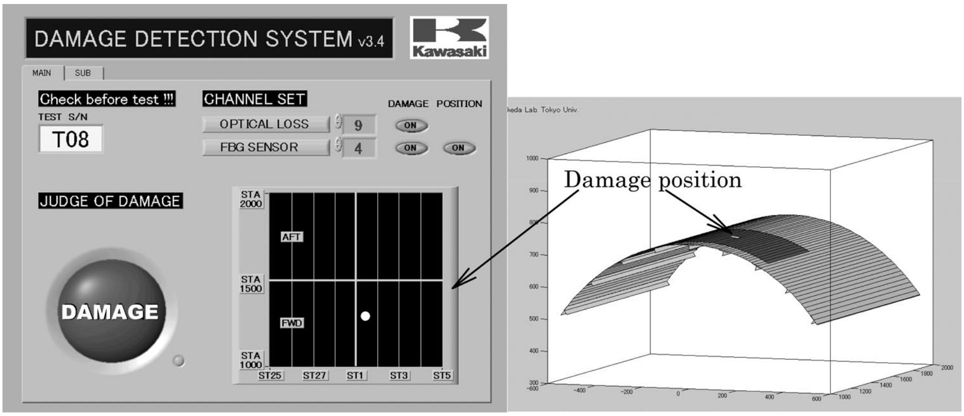


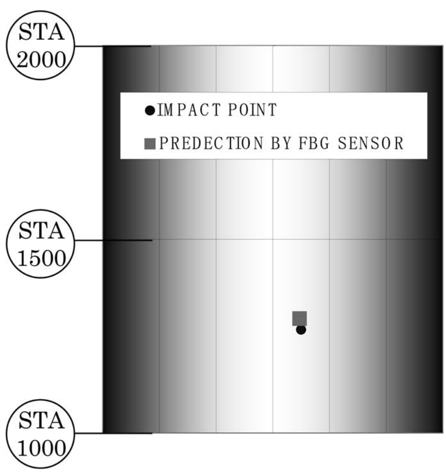
Figure 11. Typical example of the responses measured by optical-fiber sensors. (a) Result 1. (b) Accuracy of a predicted point.

(a) Result 1

Skin damage was initiated by the impact load on a mid-bay skin. The 900 mm^2 damage area measured by ultrasonic scan is 'barely visible impact damage' since the dent depth on the impact surface is 0.4 mm. The initiation and the part/position of the damage were evaluated by DDS as shown in Fig. 12a. DDS judges there



(a) Result 1



(b) Accuracy of a predicted point

Figure 12. Result 1 — Damage detection of a mid-bay skin subjected to impact load.

is damage in a mid-bay skin between STA1000 to STA1500. We confirmed that the damage position, predicted using the data of FBG sensors, agreed well with the impact position as shown in Fig. 12b.

(b) Result 2

Damage was initiated in an interlaminar region between the skin and a stringer by an impact load on a stringer flange. The 450 mm^2 damage area is barely visible impact damage since the dent depth on the impact surface is 0.0 mm. The initiation and the part damaged were evaluated by DDS as shown in Fig. 13. In this case, the damage position was not evaluated since the FBG sensors were not covering

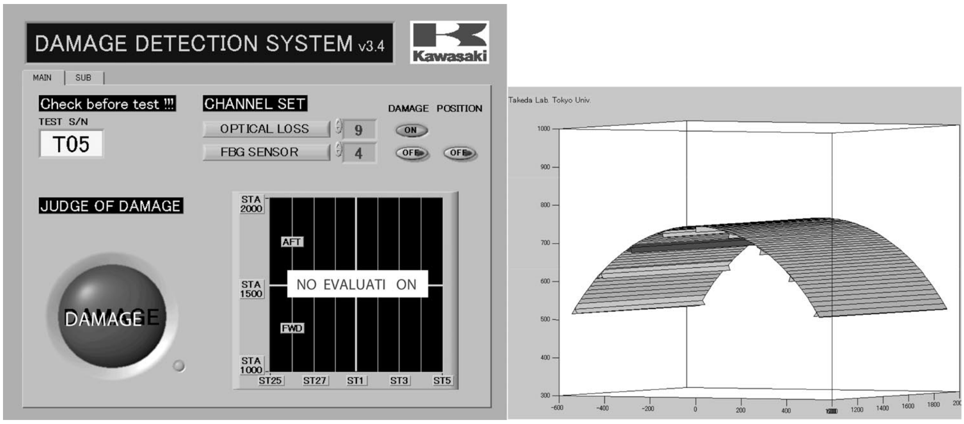


Figure 13. Result 2 — Damage detection of a stringer flange subjected to impact load.

the sensing area from STA1500 to STA2000. DDS judged there was damage in a stringer.

4. CONCLUSIONS

We confirmed from the demonstrator test that barely visible damage in the skin, stringer or interlaminar region between the skin and stringer could be detected by the damage detection system developed. The basic technologies of the composite structure damage detection system were demonstrated using embedded small-diameter optical-fiber sensors. For practical use, more development of the following technologies is necessary.

- Practical sensor technologies: Evaluation of environment resistance, durability and reliability.
- Practical optical-fiber installation technologies: Simple handling procedures, similar to that those of prepregs.

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REFERENCES

1. H. Tsutsui, A. Kawamata, J. Kimoto, T. Sanda and N. Takeda, Impact damage detection of curved stiffened composite panels using wavy embedded small-diameter optical fibers, in: *Smart*

Structures and Materials 2002: Industrial and Commercial Applications of Smart Structures Technologies, Vol. 4698, A.-M. R. Mcgowan (Ed.), pp. 454–461. SPIE, San Diego (2002).

2. K. Satori, Y. Ikeda, Y. Kurosawa, A. Hongo and N. Takeda, Development of small-diameter optical fiber sensors for damage detection in composite laminates, in: *Smart Structures and Materials 2000: Sensory Phenomena and Measurement Instrumentation for Smart Structures and Materials*, Vol. 3986, R. O. Claus and W. B. Spillman, Jr. (Eds), pp. 104–111. SPIE, Newport Beach (2000).