Novel distributed sensing optical fibres in composite cylinders for impact damage detection

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Abstract

Impact damage detection is one of the big issues for getting the reliability of composite structures. Many researches were performed to develop impact damage detection techniques by continuous real time monitoring. However, this real time monitoring has several disadvantages such as continuous operation of the detection system, and sometimes missing the impact events. Therefore, we are trying to develop a periodic inspection system for impact damage detection of composite structures using fiber optic BOCDA (Brillouin optical correlation domain analysis) sensor with a sensing optical fiber. By applying a distributed sensing optical fiber embedded in a composite cylinder with filament winding process, this long distributed sensing optical fiber can detect the impact damages from the residual strain changes measured by fiber optic BOCDA sensor. In this study, three kinds of optical fibers, which are a single-mode fiber, a polyimide coated fiber, and an aluminum coated optical fiber, were prepared to measure the residual strain change. The residual strain magnitude of the aluminum coated optical fiber was bigger than other fibers at the same impact energy level. However, the single-mode optical fiber was also shown the residual strain detection capability. After investigating the residual strain measurement, three composite cylinders having the sensing optical fibers were fabricated and tested by a drop weight impact machine. Several damages in composite cylinders were generated by these tests. The location and severity of these damages were well detected from the residual strain changes measured by fiber optic BOCDA sensor. After all, it can be concluded that this distributed sensing technique can be used to detect the location and severity of composite damages after impact events.

1. Introduction

Composite materials have been extensively applied to modern aircrafts such as Boeing and Airbus. As the use of composites increases, it is important to keep the structures safe. Composite materials are mostly used in the form of sheet materials, which often cause damages that is difficult to visually recognize when subjected to external impacts. Therefore, it is very essential to detect such barely visible impact damages in order to secure the reliability of composite structures. Many researches have studied to develop impact damage detection techniques by continuous real time monitoring[1,2]. Piezo-sensor based detection researches were a major stream on this field[3~5]. An acoustic emission technique is used to detect damages by detecting small displacements using piezo-transducers propagating through the materials when materials are broken[6]. Also,
a guided lamb wave technique uses active exciting wave and detecting the received waveform change by damages[1]. These techniques use the fast wave signals and data processing to identify damage location and levels. Fiber Bragg grating (FBG) based optical fiber sensors have been successfully used as discrete sensors to detect such impact damages [7~12]. However, FBG sensors should be operated in a real-time continuous measurement condition, and also, signal processing using these discrete sensing data is necessary to find the location and severity of impact. If the impact traces of composite structures can be detected by measuring the residual strain of sensing optical fibers embedded in the structures, this measurement would give two major advantages. First is able to operate the detection system periodically which does not need to power on at all times. The second is the detection performance of cumulative damages caused by multiple impacts. However, no attempts to detect the residual strain have ever been conducted, except for our previous experiment [13,14]. This was the first trial to measure residual strain obtained from optical fiber bonded on composite plate. Therefore, we are trying to develop a periodic inspection technique for impact damage detection of composite structures using embedded sensing optical fibers with fiber optic BOCDA(Brillouin optical correlation domain analysis) sensor.

2. Concept of impact trace detection

Composite materials are usually considered as perfect elastic material. So the composite materials recover to their initial shapes when the materials experience low velocity impact. Therefore, impact damage, especially barely visible impact damage, could not be detected by sensors without real time measurement at the instant of impact. However, if some portion of the strain caused by impact remains in the sensors, the impact trace can be detected by these sensors as the residual strain. Furthermore, if these sensors are distributed on the whole surface of composite materials, impact traces of the composite structure can be detected with the positional information. Damage detection after the impact event is shown in Figure 1 (a), using the sensing optical fiber wound on the composite cylinder. If a low-speed impact is applied to the outside of the cylinder, deformation occurs in the composite cylinder at that position and the local residual strain distribution due to the damage changes after the impact body has disappeared. However, since the sensing fiber is passing through this position, Figure 1 (b), it is possible to detect the residual strain at the impact position. This residual strain information can provide impact location and size information of the damage. Such a damage detection method is a useful method to detect damages by the sensor after impact events.

![Figure 1. Damage detection concept of a composite cylinder after impact using fiber optic BOCDA sensor](image)
3. Composite cylinders with sensing optical fibers

In order to study the sensing characteristics of optical fibers embedded in composite cylinders, 3 kinds of fibers are prepared; an aluminium-coated optical fiber, a polyimide-coated optical fiber, and a standard single mode optical fiber (acrylate-coated optical fiber) as shown in Figure 2. These fibers are embedded in composite cylinders each.

Composite cylinders are fabricated with T700 carbon tapes by filament winding process as shown in Figure 3. The stacking sequence of these cylinders is $[90^\circ_1 / OF / 90^\circ_1 / + - 20^\circ / 90^\circ_3 / + - 20^\circ / 90^\circ_3 / + - 20^\circ_2 / EPDM]$. EPDM is a rubber pad wrapped around a cylinder mandrel with Ethylene Propylene Terpolymers. OF refers to the sensing fiber and is wound and buried between the hoop layers of 90 degrees. The 90-degree layer is 12 mm in pitch when wrapped around one turn, so the sensing fiber is also wound at this interval. The reason for putting a 90-layer carbon tape layer after winding the sensing fiber is to protect the sensing fiber. The size of the cylinder is 260 mm in diameter, 4.6 mm in thickness, and 1,924 mm in length. The length of the sensing optical fiber when it is wound one turn is about 816 mm. The sensing fiber was
wound about 1.8 m around the cylinder. Thus, the total length of the sensing fiber is 816 x 150/1000 = 122 m. When these composite cylinders were cured in an oven, a portion of the optical fiber tip was protected in a plastic bag. The composite cylinder was manufactured through a general curing process, maintaining at 85 and 150 degrees for 6 hours each.

4. Implementation of fiber optic BOCDA sensor

The distributed strain measurement technique is necessary to implement this impact damage detection of composite materials. This distributed strain should be measured at the condition of a few centimeter distance resolution to localize the impact. A fiber optic BOCDA sensor is applied to measure this distributed strain, and the residual strain after impact is detected using a sensing optical fiber. Fiber optic BOCDA sensor can give Brillouin frequency, $\Delta \nu_B$, at every part of sensing optical fiber. This Brillouin frequency is linearly related with strain, $\Delta \varepsilon$, as a simple equation (1). When a single mode fiber is used as a sensing fiber, the strain conversion coefficient, $C_\varepsilon$, is about 0.05 MHz/micro-strain.

$$\Delta \nu_B = C_\varepsilon \Delta \varepsilon$$ (1)

In order to get the local strain information in a sensing optical fiber line, the phase of light source is modulated and also the probe light and the pump light are correlated at some localized length of the optical fiber shown in Figure 4. So, the localized correlated strain information can be obtained at that position by the BOCDA sensor.

5. Impact experiments

A drop weight impact machine was prepared to make some damages on the composite cylinders. This machine was composed of an impactor holder with a load cell, a
pneumatic break system, and a supporting jig. An impact tip was prepared as the shape of hemisphere followed by ASTM test method. A diameter and a tip length in a hemisphere impactor were 1.2 and 0.5 cm. The crosshead with the impactor was held and dropped using an electromagnet holder. The crosshead was clamped using a pneumatic break system after impact to prevent the second impact.

![Figure 5. Impact test machine: (a) machine, (b) crosshead, and (c) half circular support](image)

Impacts were given at the several points on the cylinders. For three groups from the left of the cylinder in Figure 6, the energy levels of 40, 20, and 10 J in order were to be applied using a hemisphere impactor. The cylinder was rigidly clamped with two half circle supports and holders in Figure 5 (b). Impact test was performed at each 10 cm section of the composite cylinder and this section was isolated by two circular clamping supports as shown in Figure 5 (c). Therefore, the effect of each impact was confined between two circular clamping boundaries. In this impact experiment, the cylinder was considered to contain solid contents and so inside pressure in the cylinder was supposed to be low.

![Figure 6. Impact positions on the composite cylinder with an embedded sensing optical fiber](image)

6. Test results

In order to detect the damages, the residual strain of composite cylinders should be measured before and after impacts. If the residual strain is uniformly distributed in the sensing optical fiber before impacts, then it is not necessary to measure the strain before
impacts. However, the initial residual strain is not uniform because the tension of the sensing optical fiber is not uniform during the winding process and also the composite material have its non-uniform residual strain. In Figure 7, the residual strain change was shown through the sensing fiber length[15]. The aluminium coated fiber showed the biggest residual strain value at the same impact energy, 40 J. However, in the case of single mode fiber, the strain was also shown to be able to detect the impact damage. It would be concluded that these all sensing fibers can be used to detect the impact damages of the composite cylinder.

![Figure 7. Residual strain distribution in the sensing optical fibers embedded in composite cylinders][15]

In figure 8, the impact damage information was displayed by drawing the residual strain change through the sensing optical fiber (polyimide coated optical fiber). In this figure, the energy level and location of impacts were well shown. After all, this distributed sensing technique can be used to detect the location and severity of composite damages after impact events.

![Figure 8. Impacts on the composite cylinder with an embedded sensing optical fiber](image)
7. Conclusions

A periodic inspection system for impact damage detection of composite structures was tried to be implemented using fiber optic BOCDA (Brillouin optical correlation domain analysis) sensor with novel sensing optical fibers embedded in composite cylinders. Three kinds of optical fibers, which are a single-mode fiber, a polyimide coated fiber, and an aluminum coated optical fiber, were prepared to measure the residual strain change. The residual strain magnitude of the aluminum coated optical fiber was mostly bigger than other fibers at the same impact energy level. However, the single-mode optical fiber was also shown the residual strain detection capability. After investigating the residual strain measurement, three composite cylinders having the sensing optical fibers were tested by a drop weight impact machine. The location and severity of these damages were well detected from the residual strain changes measured by fiber optic BOCDA sensor. Therefore, it would be concluded that this distributed sensing technique can be used to inspect composite structures periodically.

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References and footnotes