Hierarchical Sensing System Combining Optical Fiber Network and Distributed Built-In CVM Sensors: Delamination Monitoring of CFRP Structure

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ABSTRACT

This study develops a novel delamination monitoring system by extending our previous approach for monitoring surface-cracks in a large-scale composite structure. In the new system, numerous thin glass capillaries are stitched into a CFRP laminate, and internal pressure in the built-in capillary sensors, based on comparative vacuum monitoring (CVM), is maintained as a vacuum. When delamination is induced, the capillary sensors located within the delaminated area are breached, and air flows into the capillaries. The consequent pressure change within the capillary is then converted into axial strain in a surface-mounted optical fiber through a transducing mechanism, which is connected to the capillary. By monitoring the strain distribution along the optical fiber, it is possible to identify a transducing mechanism in which the pressure change occurred and thus to specify the location of the delamination. This study begins by establishing a sensor deploying/embedding method by replacing stitching yarns of dry carbon fabrics with capillary sensors. Finally, the hierarchical fiber-optic system is validated in a plate specimen.

INTRODUCTION

Optical fiber sensors have attracted considerable amount of attention in structural health monitoring (SHM) field, since they are small, lightweight, immune to electromagnetic interference, environmentally stable, and have very little signal loss over extremely long distances. Previous researches have successfully demonstrated

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that fiber-optic-based systems are highly sensitive to wide-ranging damage modes in CFRP. However, when the conventional fiber-optic-based systems are applied to large-scale structures for monitoring randomly induced damage such as impact damage, they are unsatisfactory in the following three properties; robustness, repairability, and monitorable area. Specifically, a failure at only one point on a sensing optical fiber leads to a breakdown of the entire sensing network. And once the optical fiber is disconnected, the damaged part needs to be repaired. However, it is very difficult to access and reconnect the damaged fiber. Furthermore, the fiber-optic sensing obtains basically one-dimensional strain (temperature) distribution along the thin fiber. Hence damage, far away from the sensing fiber, cannot be detected, since it induces no significant strain (temperature) change in the fiber.

To overcome these drawbacks, the authors have proposed a hierarchical fiber-optic-based sensing system analogous to the nervous system in vertebrates [1]. In the hierarchical system, several kinds of specialized devices are hierarchically combined to form a sensing network. Specifically, numerous three-dimensionally structured sensor devices are distributed throughout the whole structural area and connected with an optical fiber network (which is not embedded into the structure) through transducing mechanisms. The distributed "sensory nerve cell" devices detect damage, and the fiber-optic "spinal cord" network gathers the damage signals and transmits the information to a measuring instrument. It is important to note that conventional systems utilize optical fiber sensors to both detect damage and transmit damage information. In the hierarchical system, however, the devices are specialized, as nerve cells of natural life forms became specialized in evolutionary history, and the distributed devices and the optical fiber network separately bear these two functions. In our previous study [1], a hierarchal impact damage detection system was developed with surface-crack sensing devices based on comparative vacuum monitoring (CVM), which was originally developed by Structural Monitoring Systems Ltd. in Australia [2]. Barely visible impact damage (BVID) in a CFRP skin-stringer fuselage demonstrator was successfully detected (Fig. 1), clearly confirming that the hierarchical system has better repairability, higher robustness, and a wider monitorable area compared to existing fiber-optic-based systems.

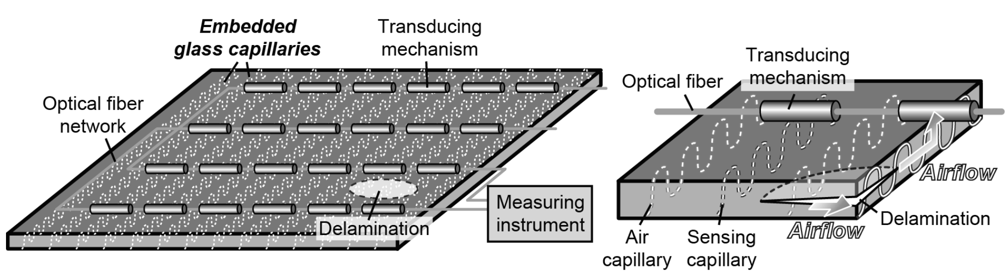
However, since the developed system utilized the surface-crack sensing devices,

Figure 1. Hierarchical surface-crack monitoring system deployed on CFRP fuselage panel.

the system could not detect internal damage such as delamination, which is strongly linked to structural strength reduction. Furthermore, since numerous fragile devices were mounted on the structural surfaces (Fig. 1), the system may not be acceptable in practical manufacturing/assembly processes and subsequent operation. Furthermore, it is difficult to ensure reliability of the surface devices after long-term environmental exposure. Thus this study advances the hierarchical system by developing embeddable CVM sensor devices. We begin by illustrating a schematic of the advanced system and then establish a novel sensor embedding/extracting method, which is compatible with existing composites manufacturing techniques. Finally, the hierarchical fiber-optic system is validated in a delamination detection test using a plate specimen.

HIERARCHICAL DELAMINATION DETECTION SYSTEM

Figure 2 illustrates the schematic of the hierarchical delamination detection system based on CVM. The principle behind CVM is that a vacuum contained in a small volume is extremely sensitive to any leakage. It basically uses an elastomeric surface sensor with fine channels that detects surface cracks by monitoring internal pressure variation in the channels. In this study, however, numerous thin glass capillaries are woven or stitched into a CFRP laminate, and the built-in capillaries are divided into "sensing capillaries" and "air capillaries." The interval between the capillaries is determined by the unacceptable damage size. Internal pressure in the sensing capillaries is maintained as a vacuum, and the air capillaries are open to the atmosphere. When delamination is induced, capillaries located within the delaminated area are breached, and air from the air capillary flows into the sensing capillary. It is important to note that the capillaries are made of brittle glass and are embedded in through-thickness direction, the capillary are highly sensitive to cracks propagating in the in-plane direction, and are reliably breached when delamination occurs. The consequent pressure change within the sensing capillaries is then converted into axial strain in the surface-mounted optical fiber through the transducing mechanism, which is connected to the sensing capillaries. The strain distribution along the optical fiber is monitored by using a distributed strain measurement system (e.g., a Brillouin-based system). Therefore, one can easily identify the transducing mechanism and sensing capillary where the pressure change occurred and thus locate the delamination. It is important to note that the CVM-based sensor is simple, lightweight, low-cost, flexible



(a) *(b)*

Figure 2. Hierarchical delamination detection system.
(a) Overall view. (b) Sensor mechanism in delaminated area.

enough to be applied to complex structures, requires small amounts of energy to operate (i.e., only for vacuuming), and involves no electrical excitation. Thus the CVM is highly suitable to be combined with optical fibers in the hierarchical sensing system.

EMBEDDING AND EXTRACTING CAPILLARY SENSOR

In order to realize the hierarchical delamination detection, we need to establish a capillary embedding/extraction technique. A common composite material with objects in the through-thickness direction would be a composite made with stitched dry fabrics and resin transfer molding (RTM). If some of the stitching in dry fabrics could be replaced with glass capillaries, the capillaries could be instantly used as sensor devices after curing of the structure. Figure 3 illustrates the new sensor embedding/extracting procedure. Since the glass capillaries are initially stitched or woven in the dry fabrics, there is no need to embed additional sensors during or after the laminate lay-up process. After curing, the edge of the panel is trimmed and the capillaries are extracted. The panel has the surface "sacrificial layer", which does not bear load, and the glass capillaries partially go through the sacrificial layer. By slightly machining the panel

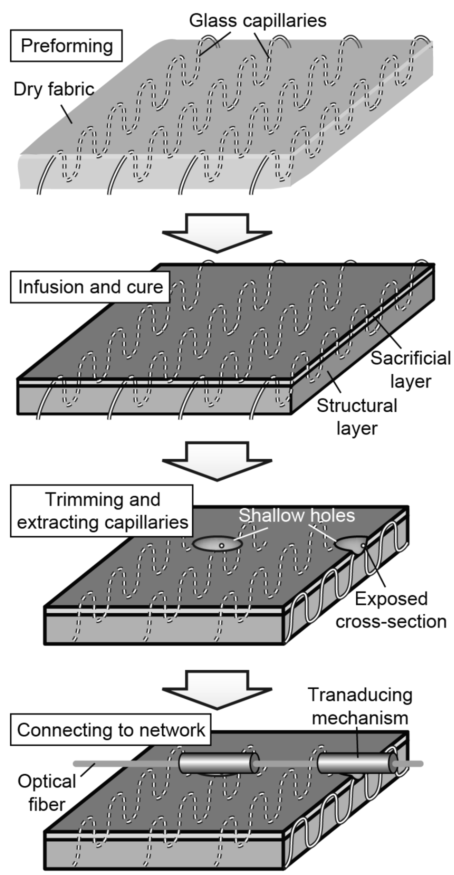


Figure 3. Sensor embedding/extracting procedure.

surface, one can expose the cross-sections of necessary capillaries without damaging the carbon fiber structural layer, and then connect them to the transducing mechanisms. These procedures are compatible with existing composite manufacturing techniques and can be applied to large-scale composite structures with complex shapes. As for the mechanical properties of the capillary-integrated composite panels, it is reasonable to think that strength reduction due to the sensor integration is minimal, since the embedded capillaries, replacing some of the original stitches, do not change the fabric structure itself significantly.

In order to validate the proposed procedure, a verification test was conducted. This study employed "capillary columns" for the sensing devices. A capillary column is a long and thin tube used mostly in gas chromatography as a gas separator. Figure 4 shows the cross-section of a capillary column utilized (inner diameter 100μm, outer diameter 200μm, GL Sciences Inc.). The tube is made of glass and the outside is coated with a polyimide resin, providing mechanical strength. Ideally, the capillary columns are automatically introduced into dry fabrics during preforming. In this study, however, the capillary sensors are manually stitched into fabrics after layup. The fabric utilized was a carbon non-crimp fabric (NCF) manufactured by SAERTEX GmbH & Co. (quasi-isotropic, 4mm thick), and the surface sacrificial plies (unidirectional glass fabric $[0_3]$, 0.5mm thick) were added on the both surfaces of the carbon fabric. After stitching the capillary columns, an epoxy resin (XNR6809 /XNH6809, Nagase ChemteX Co.) was infused into the specimen on a single-side aluminum mold using vacuum assisted resin transfer molding (VARTM). The saturated specimen was finally cured in an oven at 120^{o}C. Figure 5 shows a picture of the cured specimen. The surface is flat and smooth, and one can see the embedded glass capillaries going through the

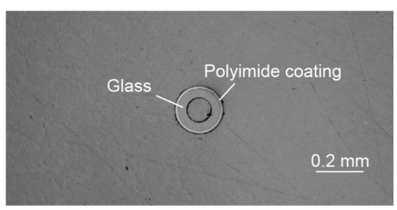


Figure 4. Cross-section of capillary column utilized for hollow sensing device.

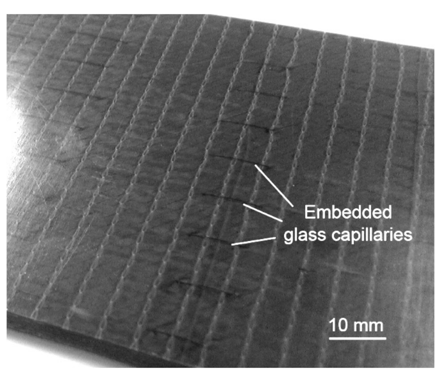


Figure 5. Surface of cured specimen.

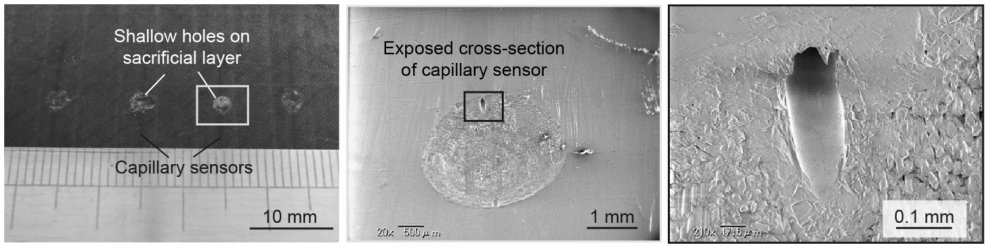


Figure 6. Extracted glass capillary.

transparent sacrificial layer consisting of glass fiber fabrics. Finally, the embedded capillaries were extracted by manually drilling shallow conical holes (cone angle 135^o) on the surface sacrificial layer. Figure 6 presents a picture of the specimen surface, and SEM images of the conical hole and the cross-section of the embedded capillary. The hole-diameter was about 3mm and one can see the cross-section of the capillary is clearly exposed, maintaining the original hollow shape to be reliably connected with the transducing mechanism.

Thus, the proposed sensor integration method was successfully validated. Even though an automatic procedure needs to be developed to integrate the capillary columns into dry fabrics, the experiment clearly demonstrated that glass-made capillary columns can be embedded in through-thickness direction of CFRP laminates, and that the embedded sensors can be reliably extracted from the sacrificial layer with a method compatible with existing composite manufacturing techniques.

DEMONSTRATION OF HIERARCHICAL FIBER-OPTIC DELAMINATION DETECTION SYSTEM

Materials and Methods

Finally, the hierarchical fiber-optic delamination detection system was validated. Figure 7 presents a photograph of the specimen (4mm-thick quasi-isotropic NCF CFRP laminates with 0.5mm-thick surface sacrificial layers on the both surfaces, 190×190×5mm^3). Eighteen glass capillaries were embedded in the specimen at even interval of 1cm. Ten of them were used as the sensing capillaries, and the rest as the air capillaries. Two transducing mechanisms *A* and *B* were attached on the specimen back surface, and five sensing capillaries were extracted and connected to each transducing mechanism through connecting sealants. An optical fiber (Heatop 300, Totoku Electric Co., Ltd) was fixed inside the transducing mechanism through pressure-sensitive movable parts, and the internal pressure increase (decrease) in the transducing mechanism is quickly and sensitively converted into the strain increase (decrease) in the optical fiber fixed inside [1]. Furthermore, a check valve (VA3582 VL610-101, Vernay Laboratories, Inc.) was attached to each transducing mechanism for removing air. It is important to note that the connecting sealants between the sensor devices and the transducing mechanisms were extremely soft. Hence, strain induced in the CFRP laminate does not affect the strain of the optical fiber fixed inside the transducing

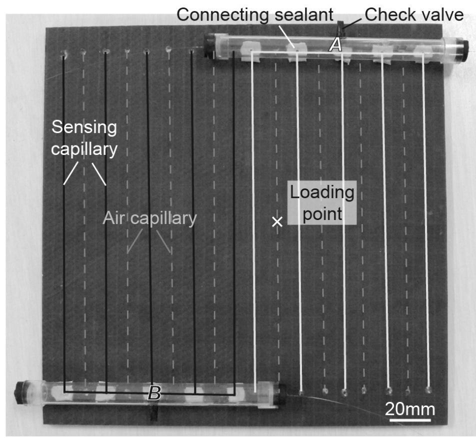


Figure 7. Specimen back surface. Load is applied to front surface.

mechanism, and the fixed optical fiber responds only to the internal pressure change of the transducing mechanism.

First, the four edges of the CFRP specimen were simply supported, and the sensor system attached to the back surface was evacuated. The strain distribution along the optical fiber was measured before and after the evacuation by a Brillouin-based distributed strain measurement system (NBX-7020, 2cm spatial resolution, 1cm sampling interval). Next, indentation loading-unloading tests with constant speed of 1.0 mm/min were conducted by gradually increasing the maximum indentation displacement up to 3mm. The measurement time of NBX-7020 was about one minute, and dynamic strain measurement while the internal pressure changed in the transducing mechanism was difficult. Hence, static strain measurement was conducted after each unloading.

Results

Figure 8 compares the strain distribution obtained from the optical fiber before and after the evacuation. The fixed parts within transducing mechanisms *A* and *B* are highlighted. In order to sensitively monitor the internal pressure change induced by delamination, the optical fiber was fixed in a state of tension. Since handmade, simple equipment was used to apply the tensile pre-strain to the optical fibers, the peak strain values before vacuuming did not match. When air inside the sensor systems was completely removed via the check valves, the strain in the fixed parts decreased by about 300με. A preliminary test confirmed that when the transducing mechanism was refilled with air, the strain immediately recovered the values before vacuuming. Hence, when the delamination is induced and air flows into the evacuated transducing mechanism, the strain will increase to the initial value. Figure 9 shows the strain distribution along the optical fiber obtained in the subsequent indentation tests. The strain distribution did not change in the first two tests. After the third test (3mm indentation), however, the strain increased about 300με at the transducing mechanism of sensor unit A (Fig. (a)). Meanwhile sensor B stayed the same, indicating that the delamination was limited to the area monitored by sensor A. Hence one can easily

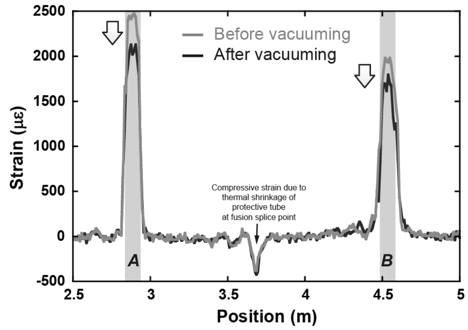


Figure 8. Strain distribution before and after vacuuming.

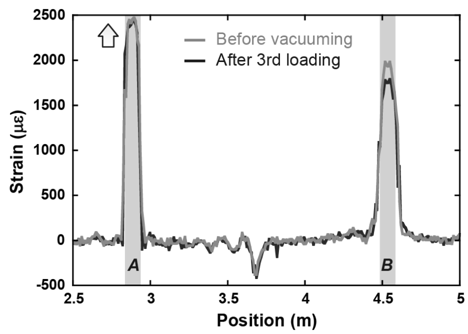


Figure 9. Strain change due to delamination.

identify the delaminated area based on the quite simple damage signal (i.e., strain recovery). If the internal pressure increase rate is dynamically obtained by a faster fiber-optic measurement system, one will be able to estimate the distance of the delamination from the transducing mechanism and thus identify the delamination position within the sensor.

CONCLUSIONS

This study developed a hierarchical fiber-optic-based delamination detection system. A novel sensor deploying/embedding method was first established by replacing stitching yarns of dry carbon fabrics with the capillary sensors. Finally, the hierarchical fiber-optic system was validated in a plate specimen.

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