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EXTENDED HIERARCHICAL FIBER-OPTIC-BASED SYSTEM FOR SENSING-HEALING OF COMPOSITE DELAMINATION

Shu Minakuchi, Denghao Sun, Nobuo Takeda

The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa-shi, Chiba 277-8561, JAPAN

minakuchi@smart.k.u-tokyo.ac.jp

ABSTRACT

This study demonstrates the first autonomous sensing-healing system applicable to large-scale composite structures. The microvascular self-healing system is combined with our hierarchical fiber-optic-based sensing system. The hierarchical system is a fluid distribution system with a local pressure monitoring function, and the combined system offers the ability to sense/heal composite delamination, and also to self-diagnose the system condition.

KEYWORDS : *Composite structures,delamination, optical fiber, self-healing*

1. INTRODUCTION

Inspired by biological systems having the ability to heal after being wounded, a wide variety of self-healing materials has been proposed and demonstrated during the last two decades [1]. In the structural composites field, microvascular systems to mitigate resin-dominated damage have recently attracted a considerable amount of attention [2-4]. When a crack or delamination breaches embedded vasculatures in a composite material, reactive fluids (i.e., healing agents) flow from the breached points into the cracked region, repairing the damage. One of the advantages of this system is that the vascular network connected to a reservoir can deliver sufficient volume of the healing agents to completely fill the damage, which is difficult to achieve with the other approaches (e.g., microencapsulation [1]). It has been demonstrated that vascular systems can almost fully recover the strength of aerospace-grade composite laminates with moderate impact damage [4], and thus have a great potential to change the current damage tolerance design philosophy, which could lead to more lightweight and efficient composite structures. Meanwhile, several researchers have recently addressed the potential ability of integrated sensing/healing systems [5-7]. The integrated systems are expected to increase the efficiency and reliability of self-healing systems, and enhance the performance and adaptability of the host materials. Especially, Norris et al. successfully demonstrated a microvascular-based integrated system in structural composite materials [7]. Furthermore, they presented new storage methods for healing agents that can expand the choice of potential healing chemistries.

These recent remarkable advancement in self-healing materials and integrated sensing-healing systems has been achieved through intensive research activities focusing on local sensing/healing mechanisms (e.g., mechanical interactions between sensing/healing devices and damage, chemical reaction of healing agents within damage, and strength recovery of small coupon specimens). Following this, system engineering approaches to design the system architecture and manage the whole of the scaled-up complex system are urgently needed to make a jump from autonomous sensing-healing composite materials to the practical smart structures. This study demonstrates the first autonomous sensing-healing system applicable to large-scale composite structures. As proposed in Ref [6], the microvascular self-healing concept is combined with our hierarchical fiber-optic-based sensing system (Fig. 1). The hierarchical system is a fluid distribution system with a local pressure monitoring function, and the combined system offers the ability to

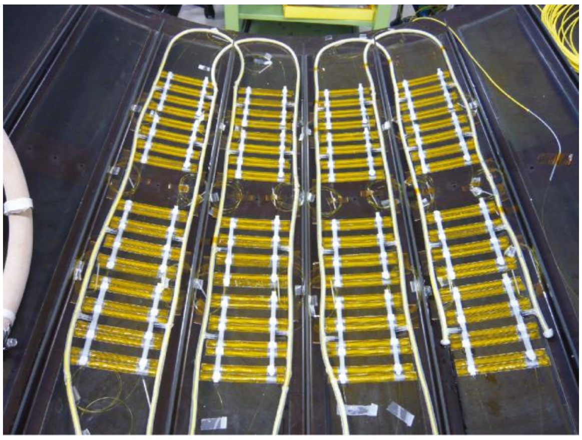

Figure 1: Hierarchical system deployed on back-surface of CFRP fuselage structure for impact damage detection [8]. Hierarchical system has wider monitorable area, higher robustness and better repairability compared to conventional fiber-optic-based systems.

sense/heal composite delamination, and also to self-diagnose the system condition. This study begins by describing the basic concept of the combined system. The hierarchical system is validated in a plate specimen. It is important to note that previous studies have successfully demonstrated that complete filling of damage with healing agents followed by cure leads to almost full recovery of degraded strength of the host material. Hence, this study focuses on phenomena before cure of healing agents (i.e., sensing and infiltration of damage). Specifically, we utilized water-based viscous liquid instead of a healing agent (i.e., resin).

2. OVERVIEW OF COMBINED SYSTEM FOR AUTONOMOUS SENSING-HEALING OF COMPOSITE DELAMINATION

2.1 Hierarchical fiber-optic-based system [6, 8]

Optical fiber sensors have attracted considerable amount of attention in the structural health monitoring field, since they are small, lightweight, immune to electromagnetic interference, environmentally stable, and have very little signal loss over extremely long distances. The hierarchical fiber-optic-based system is analogous to the nervous system in vertebrates, which evolved by specializing neural cells. The system hierarchically combines several kinds of specialized devices to form a sensor 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 fiber-optic-based systems utilize optical fiber sensors to both detect damage and transmit the damage information. In the hierarchical system, however, the devices are specialized, and the distributed devices and the optical fiber network separately bear these two functions. Owing to this specialization, the hierarchical system has better repairability, higher robustness, and a wider monitorable area compared to conventional fiber-optic-based systems [8]. Based on this concept, the authors developed a surface-crack detection system using comparative vacuum monitoring (CVM), and barely visible impact damage in a CFRP skin-stringer fuselage demonstrator was successfully detected (Fig. 1). The system was then extended to an internal-damage (i.e., delamination) detection system by replacing the surface-crack sensors with embeddable devices (i.e., woven-in glass capillaries) [6].

2.2 Combined sensing-healing system

This study further advances the hierarchical system by combining it with self-healing. Figure 2 depicts the schematic of the combined system. It should be noted that the combined system in this study employs Vaporization of Sacrificial Components (VaSC) recently reported [3]. This is because vascular channels manufactured by VaSC have much higher damage sensitivity compared to glass capillaries. First, sacrificial fibers (catalyst-impregnated polylactide (PLA) fibers) are woven into the dry fabric. The interval of sacrificial fibers is determined by unacceptable damage size. After the resin infusion and cure, the sacrificial fibers are removed by heating the panel to vaporize PLA, yielding empty channels in the panel. The cross-sections of empty channels are then exposed to the panel surface. The panel has the surface sacrificial layer [6], which is normally glass fiber reinforced plastic (GFRP) and does not bear load, and the channels partially go through the

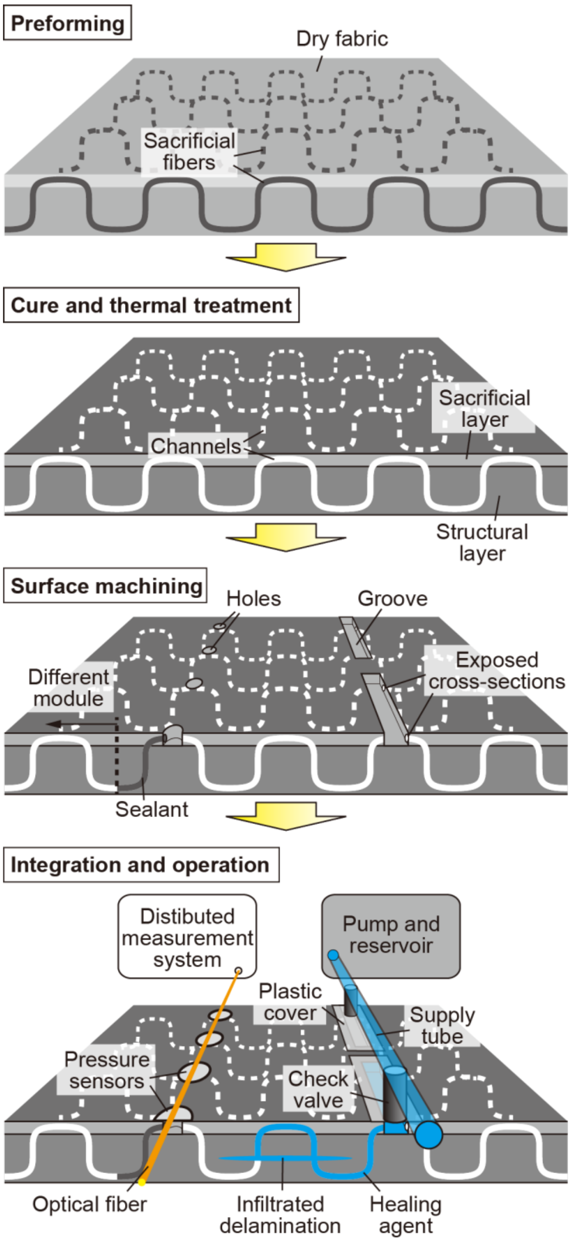

Figure 2: Schematic of combined system.

sacrificial layer. By slightly machining the panel surface, one can expose the cross-sections of necessary channels without damaging the structural layer (e.g., carbon fiber reinforced plastic (CFRP)). Furthermore, by closing the exposed cross-sections with sealant, one can divide a long channel into short segments. Several channel segments are united through a surface groove to be one vascular module, and then connected to the main supply tube through a check valve. Meanwhile, shallow holes are created on the other side of the vascular modules, and the fiber-optic-based pressure sensors are installed. The size of the module determines the spatial resolution of the sensing system.

First, pressurized air is injected into the channels from the supply tube or an additional air supply tube, and a pressurized healing agent then circulates in the supply tube. The pressure of the healing agent is lower than the pressure in the channels, so the healing agent does not flow into the channels through the check valves. When delamination is induced, channels located in the delaminated area are breached, and the pressure in the damaged vascular module drops as the pressurized air leaks into the delamination. Note that pressure decreases only in the damaged module since the check valve isolate the local pressure reduction. The healing agent then flows into the breached channels and damage, initiating healing. At the same time, the pressure sensors detect the pressure reduction in the breached channels. Strain of the optical fiber changes in the damaged module, and thus one can easily identify the damaged module by monitoring the strain distribution along the optical fiber using a distributed sensing system.

It is important to note that the hierarchical system can minimize channel volume within structures, and thus the degradation of the mechanical property is minimal. The supply vessel with large diameter, which may be said to correspond to an artery, is attached to the structural back-surface and not embedded. Only thin channels branching from the main supply tube, which may correspond to capillary blood vessels, are embedded. Furthermore, it is possible to reduce the diameter of the channels. Considering laminar liquid flow in a constant circular capillary (length l and inner diameter d), the mass flow rate Q is given by the Hagen-Poiseuille equation

$$Q = \frac{\pi\rho\,\Delta P d^{4}}{128\,\mu l} \tag{1}$$

where ΔP is the pressure drop across the channel, ρ and μ are the density and viscosity of liquid. When a quite long channel is required to cover a large structural area (i.e., l is very large), one needs to significantly increase the diameter of the channel d or the power of the pressurizing system ΔP to supply sufficient amount of the healing agent Q to an arbitrary damage area along the channel, which has detrimental effects on the structural performance. In contrast, the hierarchical system consists of numerous short channels (i.e., l is small) and the healing agent locally flows in the damaged module. Hence, it is possible to reduce the channel diameter and the power of the pressurizing system. Furthermore, when one point on a long channel is breached or blocked for any reason including damage or a manufacturing defect, the channel cannot supply the healing agent to the area over the point since the internal pressure drops to almost zero at the breached point, leading to the partial loss of its healing function. In the hierarchical system, however, the effect of the breach is limited in the damaged module since the check valve isolates the pressure change and the healing agent is transferred through the supply tube to the other modules. It is also important to note that the fiber-optic-based pressure sensor continuously monitors the pressure change after the system installation. Hence, the system can detect the blockage or leakage of the embedded channels before and during the operation, which significantly increases the reliability of the healing system. The proposed system has several advantages arising from its hierarchical nature.

3. SYSTEM DEMONSTRATION

3.1 Materials and Methods

Figure 3 presents the back-surface of the specimen equipped with the combined sensing/healing system. The materials utilized for the laminate were a unidirectional glass fabric (UF-E300, SP. Systems, ply thickness 0.3mm), PLA monofilament fibers (Unitika, Ltd., diameter 200µm), and an epoxy resin (XNR6813/XNH6813, Nagase ChemteX Co., Tg = 210°C). First, the PLA fibers were treated with tin(II) oxalate (SnOx) to decrease their depolymerization temperature in reference to the recently reported method [3]. The fibers were immersed in a stirred solution composed of 50ml trifluoroethanol (Wako Pure Chemical Industries, Ltd.), 25ml water, and 6g SnOx (Wako Pure Chemical Industries, Ltd.). After the chemical treating of 24h, the fibers were dried in an oven. The treated PLA fibers were then manually stitched into a stacked glass fabric ($[0/90_6/0]$), and additional two plies were stacked on the both surfaces of the specimens, resulting in the final stacking sequence of $[0_3/90_3]_S$ (thickness: 3.5mm). The epoxy resin was infused into the fabric on a flat single-sided aluminum mold using vacuum assisted resin transfer molding (VaRTM), and the saturated fabric was cured in an oven at 120°C for 2 hours. After this 1st cure, the specimen was heated at 180°C for 12h to reach the full cure (2nd cure) and to vaporize the embedded PLA fibers. The fiber-optic-based pressure sensors were installed on the left side. First, shallow holes (diameter 10mm, depth 0.9mm) connected to the embedded channels were created using a milling machine. The created holes were then covered with acrylic substrates (diameter 20mm, thickness 1mm) using airtight tapes (KTD-19, 3M Company), and a polyimide-coated optical fiber (HEATOP300, Totoku Electric Co., Ltd., diameter 150mm) was bonded on the plastic covers using an epoxy resin. When the internal pressure of the sensor increases, the acrylic cover deforms upward, inducing tensile strain in the optical fiber. In contrast, when delamination occurs and the pressure drops as air leaks into the damage, the strain of the optical fiber locally decreases in the sensor connected to the channels breached by the delamination. Thus, one can easily locate the delamination by monitoring the strain distribution along the optical fiber. The supply tube was attached on the right side of the specimen. Two grooves (width 1mm, depth 0.9mm) were cut on the surface using a milling machine, constructing two vascular modules, each of which consists of four embedded channels connected by one groove. After covered by acrylic substrates, the grooves were connected to the supply tube (diameter 3mm) through miniature stainless-steel check valves (CCPI5510014SE, The Lee Company, diameter 2.5mm, height 5 mm). The weight of each module was less than 10g.

The verification test began by evaluating the sealing performance of the system by pressurizing the supply tube and the channels with air. Strain distribution along the optical fiber was monitored using a distributed measurement system (OBR4600, Luna Technologies, spatial

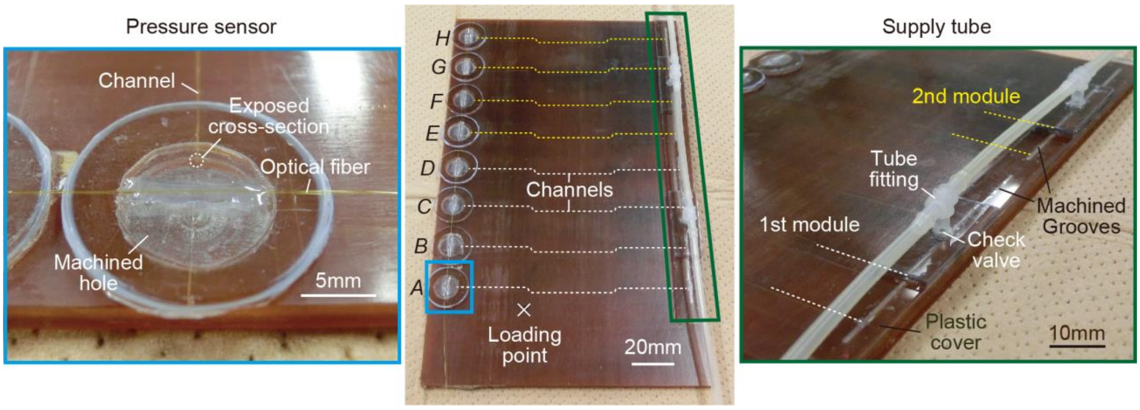

Figure 3: Back-surface of specimen equipped with combined sensing/healing system.

resolution 2mm, sampling interval 1mm) to confirm the validity of the pressure sensors. An experimental liquid composed of water and hydroxypropyl cellulose (viscosity 0.1Pa·s) was then injected into the supply tube and channels using an air pump (gauge pressure 0.1MPa). This viscosity was determined in reference to an epoxy resin healing agent (RT151, ResinTech, Ltd., mixed viscosity of 0.1Pa·s at 23°C [7]). Quasi-static indentation (loading speed 1mm/min) was applied to the specimen using a hemispherical steel indenter (diameter 12.7mm) attached to material testing system (AG-50kN, Shimadzu Co.), breaching the channel connected to the sensor *A* (Fig. 3). Since OBR is a static measurement system, a fiber Bragg grating (FBG) sensor (Technica S. A., diameter 150μm, gage length 1mm) was additionally bonded on the sensor *A* and connected to an optical sensing interrogator (sm125, Micron Optics, Inc., sampling 1Hz) to monitor the dynamic strain change during the loading test. It is important to note that pressurized air was not injected into the channels, as proposed in Section 2. Alternatively, the pressurized liquid was utilized to see the moment of the channel breaching and to correlate it with the FBG strain response.

3.2 Results

Figure 4 presents the strain distribution along the optical fiber after pressurizing. The strain increased by more than 1000με at each sensor due to the internal pressure increase, confirming the validity of the sensors. The compressive strain between the sensors is due to the release of initial tensile strain introduced during the bonding process of the optical fiber. In the sensor *G*, however, the strain did not increase by pressurizing. The channel connected to the sensor *G* was visually checked, and it was found that the channel was partially blocked by a small amount of PLA that did not vaporize probably due to the insufficient chemical treatment. In this way, the pressure sensors monitor the system condition and inform us the defects. When all the pressure sensors do not respond to pressurizing (i.e., strain does not increase), the supply tube could have the trouble. In case that one vascular module is not responsive, a check valve within the module would be problematic. Based on the information obtained, we can take immediate action to recover the system.

Figure 5 presents the indentation load curve, the strain change in the FBG, and the photographs of the specimen taken from the back surface. The strain increased by 200με immediately after pressurizing the liquid, since air in the groove and channels was compressed by the injected liquid and flowed into the pressure sensors. The strain then gradually increased as the liquid reached the sensor and air in the sensor was compressed. The indentation load was applied to the specimen 6min after the injection. The bending crack occurred at the 1st load drop. Delamination then initiated from the loading point a the 2nd load drop (*a* in Fig. 5), and another bending crack was introduced at the 3rd load drop. During these damage events, the viscous liquid continuously flowed into the sensor and the FBG strain kept increasing. When delamination breached the channel, however, the liquid immediately leaked into the delamination (*b* in Fig. 5).

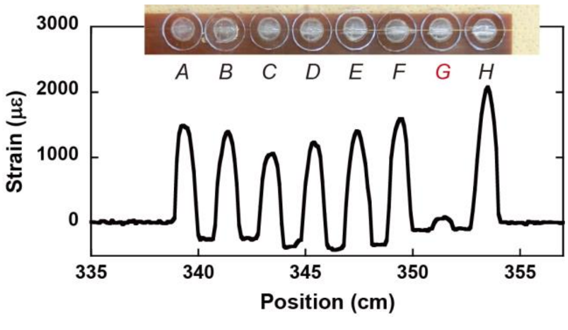

Figure 4: Strain distribution along optical fiber after pressurizing.
Strain of sensor *G* did not increase due to channel blockage.

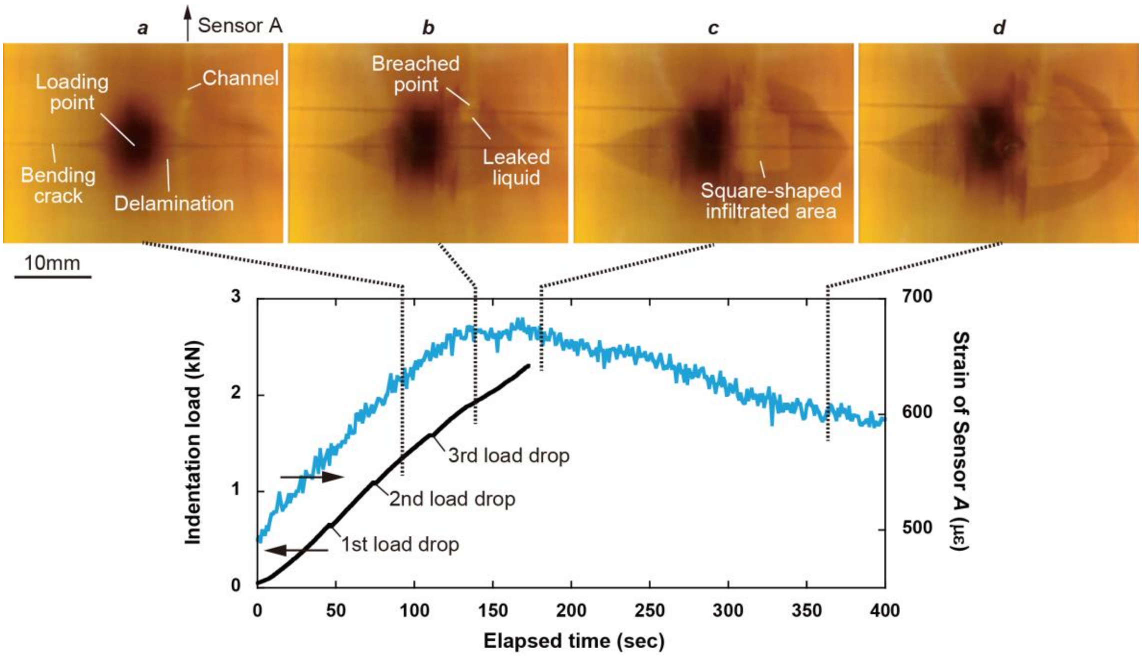

Figure 5: Results of demonstration test. Strain of sensor *A* began to decrease when delamination breached channel.

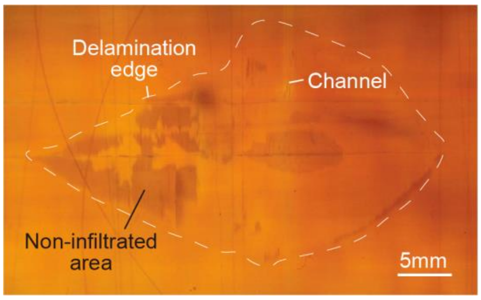

Figure 6: Photograph of specimen after test.

The strain in the optical fiber sensor stopped to increase at the moment of the channel breaching, successfully detecting the delamination. The strain then gradually decreased as the liquid in the sensor flowed backward into the delamination and the pressure in the sensor dropped. First, the liquid flowed toward the center of the delamination (*c* in Fig. 5). However, the flow front gradually extended toward the edge of the delamination (*d* in Fig. 5), and the hierarchical system finally filled the one half of the delamination by the liquid (Fig. 6).

Thus, the demonstration test successfully verified the proposed hierarchical system. The delamination was detected from the strain change in the optical fiber, and the system filled the damage by the viscous liquid simulating a healing agent. Furthermore, the potential ability of the system to self-diagnose its own condition was demonstrated. It should be noted that strain change in the optical fiber was rather slow since the viscous liquid was injected into the channels to see the moment of the channel breaching. The viscous liquid flowed slowly in the thin channels, and thus the pressure change in the sensor was not fast. In a practical application, it is preferable to pressurize channels with air and circulate a healing agent within the supply tube, as proposed in

Section 2. This not only expands the choice of potential healing chemistries [7], but also improves the response speed of the sensing system.

4. CONCLUSIONS

This study demonstrated the first autonomous sensing-healing system applicable to large-scale composite structures. The microvascular self-healing system was combined with our hierarchical fiber-optic-based sensing system. The delamination was detected from the strain change in the optical fiber, and the system filled the damage by the viscous liquid simulating a healing agent. Furthermore, the potential ability of the system to self-diagnose its own condition was demonstrated.

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