

# Microvascular-based Hierarchical System for Sensing-Healing of Delamination in Composite Structures

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## ABSTRACT

Our previous study proposed a hierarchical sensing-healing system combining a microvascular self-healing material and our fluid distribution system with local pressure monitoring. The combined system could increase efficiency and reliability of the healing. In this study, the sensing/healing performance was evaluated using a compression after impact (CAI) test of a composite stiffened panel. Even though further optimization of the healing resin and the microvascular network is necessary, the hierarchical system restored the structural stability and recovered the degraded strength, confirming its high potential under practical conditions.

## 1. INTRODUCTION

The authors' research group recently proposed an autonomous sensing-healing system applicable to large-scale composite structures (Fig. 1, [1]). First, sacrificial fibers (catalyst-impregnated polylactide (PLA) fibers, [2]) are woven into a dry fabric. After resin infusion and curing, the sacrificial fibers are removed by heating the panel to vaporize the PLA, which yields empty channels in the panel. Cross-sections of these empty channels are then exposed to the panel surface. The panel has a surface sacrificial layer, which does not bear a load, and the channels partially go

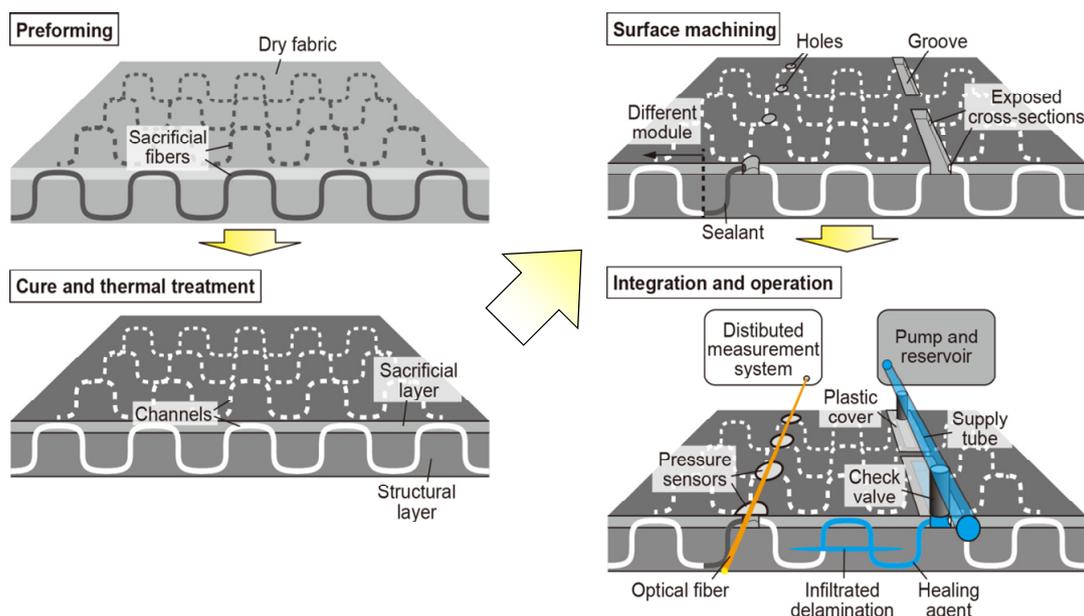


Figure 1: Overview of hierarchical system for autonomous sensing and healing.

through the sacrificial layer. By slightly machining the panel surface, one can expose the cross-sections of the necessary channels without damaging the structural layer. Channels are then connected to the main supply tube of a pressurized healing agent through check valves. Meanwhile, shallow holes are created on the other side of the channels, and fiber-optic-based pressure sensors are installed on them. When delamination occurs, the healing agent flows into the channels breached by the delamination and infiltrates the damage for healing. At the same time, the pressure sensors identify the damaged channels by detecting the internal pressure changes. Our previous paper validated the proposed system through detection and infiltration of damage [1]. This study presents the actual healing of a carbon/epoxy stiffened panel. This is, to the best of the authors' knowledge, the first attempt to demonstrate a sensing-healing system in a practical structural element.

## 2. MATERIALS

Figure 2 (left) depicts the schematic of the composite stiffened panel. The panel was manufactured using vacuum-assisted resin transfer molding (VaRTM) and composed of a T-shaped stiffener and a skin. Aluminum jigs were attached to both edges of the specimen to apply compressive loading. The materials used were non-crimp fabrics (SAERTEX GmbH & Co.) of aerospace-grade carbon fibers (Toray Industries, Inc., T800S) and an epoxy resin (XNR6813K/XNH6813K, Nagase ChemteX Co.). Stacking sequence of the skin and the stiffener was quasi-isotropic  $[-45/+45/0/90]_{2S}$ , and additional plies of plain-woven dry glass fabrics (M200×104H3, Unitika, Ltd.,  $[-45, 45]_3$ ) were laid on the surface of each stiffener flange as the sacrificial layer. Two chemically-treated PLA fibers (Unitika, Ltd., 200  $\mu\text{m}$  diameter, 80 mm length) were woven into the stiffener flange in the longitudinal direction. After the cure and heat treatment to vaporize the PLA, flow channels were formed in the interface between the stiffener and the skin. Both edges of the flow channels were positioned within the sacrificial layer and four shallow holes were formed on the surface using a milling machine to expose the cross-section of the embedded channels (Figs. 2 (left)). In the following test, only the channel close to the center of the stiffener was used. The smaller hole (2 mm diameter, 0.8 mm depth) was connected with the supply tube for the healing agent. Room-temperature curing, ultra-low-viscosity epoxy resin (E205, Konishi Co.,Ltd, 100  $\text{mPa}\cdot\text{s}$  at 20°C) was selected for the resin, after considering diameter of the embedded flow channel (200  $\mu\text{m}$ ), the mechanical property, and the practical healing condition. And the larger hole (8 mm diameter, 0.9 mm depth) was covered with a square acrylic substrate (20 mm side length, 1 mm thickness) and a fiber Bragg sensor was bonded on the plastic cover.

## 3. COMPRESSION AFTER IMPACT TEST

After the flow channel was filled with compressed air of 0.1 MPa gauge pressure, impact energy of 25 J was applied to the center of the flange width (Fig. 2 (left)). The strain dropped immediately after the disbond induced by the impact breached the flow channel, successfully detecting the damage. After the impact test, both surfaces of the specimen were visually checked. At the impact point (Fig. 2 (1a)), there was a small surface dent with depth of 0.3 mm and thus the damage introduced was barely visible impact damage (BVID). Furthermore, a long interface crack (80 mm length) was seen between the stiffener flange and the skin (Fig. 2 (2a)), implying that large disbond was introduced in the interface between the skin and the stiffener. Fig. 2

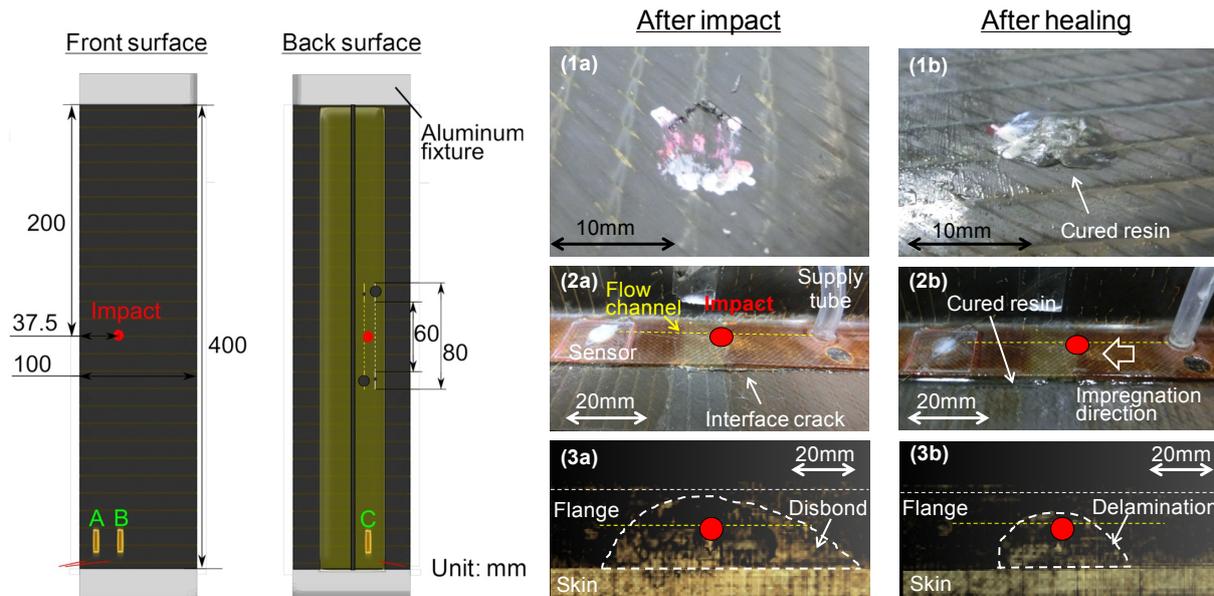


Figure 2: CAI specimen (left) and comparison of damage states (right).

(3a) presents a photograph of the internal damage observed by an ultrasonic inspection system. A semicircular disbond reaching the channel position was observed, indicating that flow channel was successfully breached by the disbond.

The damaged panel was then healed by injecting the healing agent. The injection was stopped when the gap (i.e., crack) between the flange and the skin was filled with the healing agent (visually checked). The healing agent was cured at room temperature for 24 h under atmospheric pressure. Figures 2 (1b) and (2b) present photographs of the specimen after healing. The gap between the flange and the skin was successfully closed with the resin (Fig. 2 (2b)). Furthermore, a cured resin was observed in the residual dent on the impacted surface (Fig. 2 (1b)), indicating that the resin injected from the back surface flowed in the through-thickness direction and finally reached the opposite surface. Figure 2 (3b) presents the result of the ultrasonic inspection. The disbond disappeared, and the delaminated area in the skin decreased. Even though perfect infiltration of the damage including the skin delamination was not achieved, the hierarchical system demonstrated its high performance to infuse large damage in practical structures.

Finally a compression test was performed using a material testing system (AG-50kN, Shimadzu Co.). The panel began to globally buckle at 19 kN and the buckling mode changed to a one half-wave mode at 23 kN. The load then increased while keeping the same buckling mode. However, the load suddenly dropped at 32.7 kN, and the panel failed at 34.41 kN. Figure 3 (left) presents photographs of the healed flange under compressive loading. At 32.7 kN, an interface crack occurred between the skin and the flange from the edge of the healed disbond (Fig. 2 (2b)), resulting in localization of the buckling deformation. The healed region lost the structural support from the stiffener and the final failure occurred. Preliminary tests confirmed that equivalent stiffened panels with and without damage had the strength of 26 kN and 43 kN, so the strength partially recovered by healing but the full recovery could not be achieved. This may be attributed to two reasons. One is that the healing agent utilized was weak and/or incompatible with the host resin. A more appropriate resin would be needed to fully recover the strength. Second reason is the resin impregnation direction. The healing agent flowed into the disbond from the breach

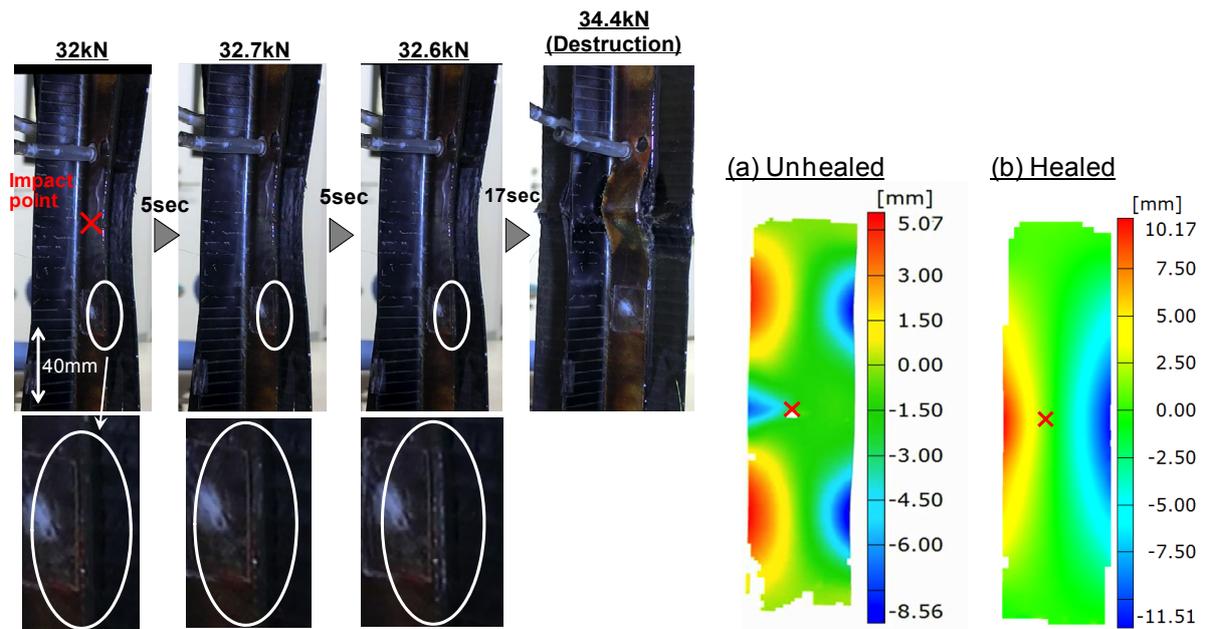


Figure 3: Photographs of healed flange (left) and comparison of deformation (right).

point of the channel nearest to the supply tube (Fig. 2 (2b)), thus the impregnation speed and pressure of the resin was significantly low at the pressure sensor side, where the interfacial crack occurred. Consequently, small non-impregnated area (i.e., origin of crack) might be generated even though ultrasonic inspection couldn't detect it (Fig. 2 (3b)). This implies the necessity to design more complex channel network to fully infuse complex damage in practical structures.

Nevertheless, the hierarchical system showed a high potential to sense and heal disbond in the practical structural element. The impact damage was detected immediately after its occurrence and the degraded compressive strength was recovered. Figure 3 (right) depicts the out-of-plane displacement of an equivalent specimen with damage, which was measured in a preliminary test. The unhealed panel locally deformed around the impact damage, and the damage gradually expanded with cracking sound until the final failure at 26kN. In contrast, the healed panel suppressed the local deformation around the damage and made no sound before the occurrence of the interface crack, indicating that the healing restored the structural stability of the damaged panel. In our future research, the healing performance will be further enhanced by optimizing the healing agent and the design of the flow channel network.

## ACKNOWLEDGEMENTS

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