SELF-HEALING CFRP COMPOSITES USING MULTIPLE SHORT-MICROVASCULAR-CHANNELS IN THROUGH-THICKNESS DIRECTION

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ABSTRACT

Self-healing composites using microvascular channel networks have been studied intensively. Microvascular networks in composite in-plane directions are normally utilized to deliver healing agents to damaged areas. However, this channel configuration is not optimal to form robust networks and to infuse large damage areas. This study proposes a self-healing system using multiple short-microvascular-channels in the through-thickness direction. First, the feasibility and advantage of this channel configuration are evaluated by 3D-imaging of the internal structure and damage formation around the channels. Next, double cantilever beam (DCB) tests are conducted to confirm its healing function. Finally, this system is applied to composite stiffened panels and the healing performance is evaluated using compression after indentation tests.

1 INTRODUCTION

Composite materials are widely used in aircraft structures due to their high specific strength and specific rigidity. However, internal complex damages can be introduced in composites and it is difficult to detect them with regular maintenance. Therefore, self-healing composites that repair damage immediately after its occurrence have been studied [1, 2]. Various methods have been proposed, one of which is a system that delivers healing agents to damaged areas using microvascular channel networks in composites in-plane directions. Sakurayama et al. introduced this system to composite stiffened panels and demonstrated its feasibility using compression after impact tests [3]. However, the whole healing function could be lost by blockage at just one point in the long micro-channel. Furthermore, the healing agent leaked from a single breached point of the channel and then flowed a long distance within the damage. So there was a possibility of non-impregnated parts such as damage edges.

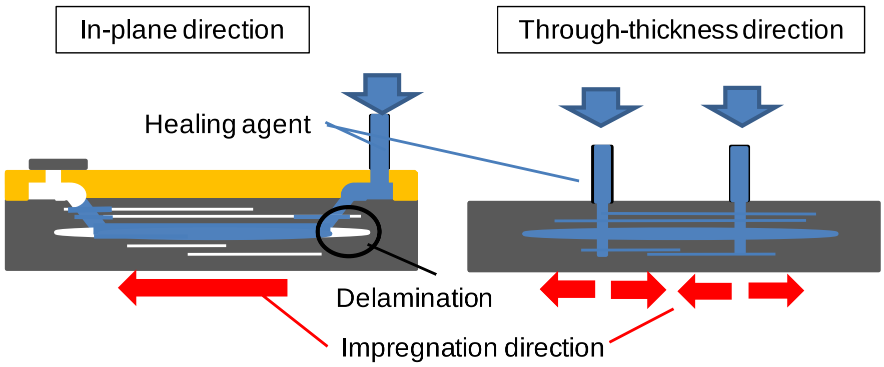


Figure 1: Comparison of channel configurations.

This research proposes a self-healing system using multiple short-microvascular-channels in the through-thickness direction. Figure 1 shows the comparison of these two channel configurations. The through-thickness channel network can directly inject the healing agent to the damage from the through-thickness direction. Furthermore the impregnation of healing agent is carried out from multiple points and multiple directions, so sufficient repair can be expected.

The aim of this study is to experimentally verify the effectiveness of the self-healing system using this channel configuration. First, the validity of a channel introduction method is evaluated from tensile strength and the three-dimensional X-ray CT image of specimens with channels. Next, the repair performance of the channels is evaluated by double cantilever beam (DCB) tests. Finally, this system is applied to composite stiffened panels and its healing performance is evaluated by compression after indentation tests.

2 TENSILE TEST

2.1 MATERIAL AND METHOD

Figure 2 depicts the schematic of the specimen. The laminate was prepared using carbon fiber reinforced plastic (CFRP) prepregs (T700S/2592, Toray Industries, Inc) and cured in an autoclave. The stacking sequence was $[0/90]_{2S}$. The channels are formed after cure by pulling out thin needles that have been inserted after lay-up in the through-thickness direction. The diameter of channels was controlled by changing the needle diameter. The specimens having a channel of three kind of diameters d (d = 0.1, 0.2, 0.5 mm) and no channels specimen (Virgin) were prepared. The GFRP tabs were attached to the specimen to apply tensile loading.

The tensile test was performed until failure using a material testing system (AG-100kNXplus, Shimadzu Co.) at a constant loading rate of 1 mm/min. Two strain gauges (KFG-10-120-C1-11L1M2R, Kyowa Electronic Instruments Co., Ltd.) were attached on the specimen surface to measure the strain development under the tensile loading. In addition, a random dot pattern was applied to the specimen surface to monitor the strain distribution in the tensile direction using digital image correlation (ARAMIS, GOM). Three tests were conducted for each specimen configuration.

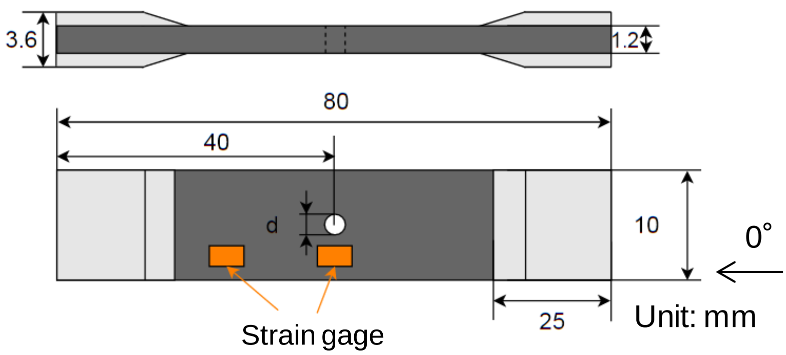


Figure 2: Tensile test specimens.

2.2 RESULTS

Figure 3 shows the results of failure load and failure strain (averages of 3 tests), and the error bars represent the maximum and minimum values. Compared to the Virgin specimen, the failure loads of the specimens with channel diameter of 0.5 mm, 0.2 mm and 0.1 mm were 83 %, 91% and 91 %, respectively. In the specimens with channel diameter d less than 0.2 mm, the place where the failure occurred was random. In contrast, the specimens with 0.5 mm channel broke at the channel position. Figure 4 presents the strain distribution in the tensile direction just before failure. In the specimen with 0.5 mm channel, stress concentration and a low stress part are observed around the channel. In contrast, no significant stress concentration was observed in the specimen with 0.2 mm channel, and the strain was uniformly distributed.

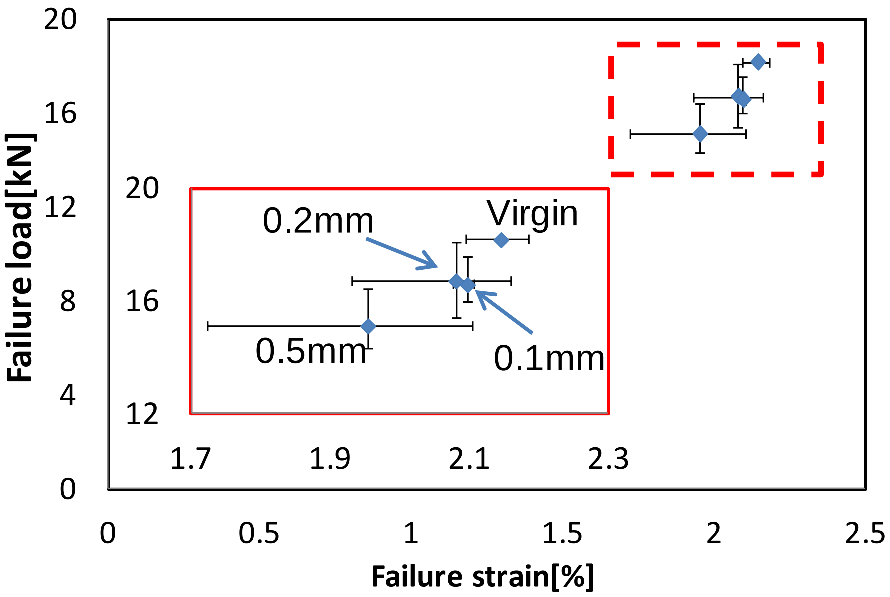


Figure 3: Failure load and failure strain depending on channel diameter. The error bars represent the maximum and minimum values.

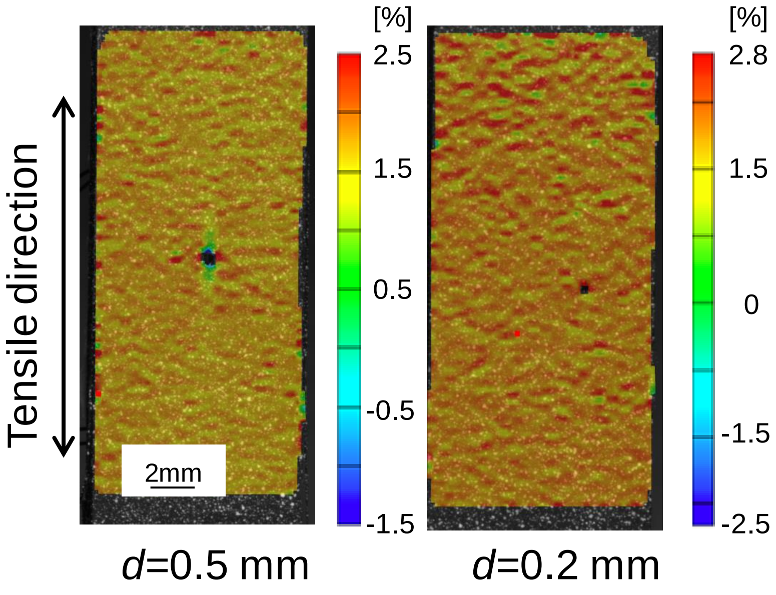
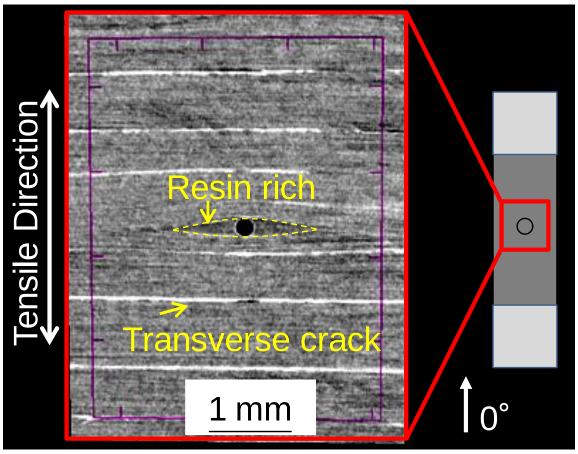


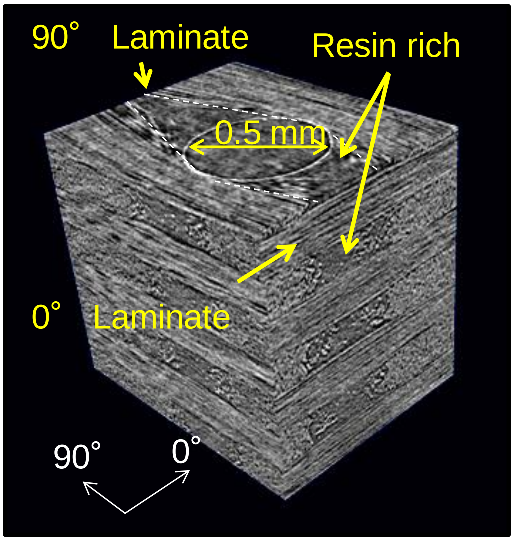
Figure 4: Strain distribution around the channel measured by DIC.

In addition, the specimen having 0.2 mm diameter channel was observed in an x-ray CT scanner (SKYSCAN 1272, Bruker) after applying 1.5 % tensile strain. The center layer (90 °) in the through-thickness direction of the specimen is presented in Figure 5 (a). Even though the channel disrupted the in-plane alignment of continuous fibers and the slight fiber waviness and resin-rich region were introduced, the transverse crack in the 90 ° layer did not occur around the channel because the adjacent 0 ° layer reinforced the resin rich region (Figure 5 (b)) and stress concentration was suppressed. In contrast, with conventional networks with in-plane channels, initial cracks occur around the channels, which leads to final failure [4]. In summary, in the specimens with channel diameter *d* less than 0.2

mm, it is obvious that the influence of the channel on the initial failure is negligible and the final strength is equivalent to that of the virgin specimen. These results successfully confirmed the feasibility and advantage to use channels in the through-thickness direction.



(a) Cross-section at the middle laminate (d = 0.2 mm)



(b) 3-D image of the channel (d = 0.5 mm)

Figure 5: X-ray CT scanner observation around the channel.

3 DCB TEST

3.1 MATERIAL AND METHOD

The DCB test was conducted by following ASTM D 5528. Figure 6 depicts the schematic of the specimen. The material were the same as in the Section 2. The stacking sequence was $[0]_{32}$ and, a polyimide film (12.5 μm thickness) was sandwiched at the through-thickness center to introduce an initial crack. The 0.2 mm diameter multiple channels with a depth of 4 mm were formed. Since these channels are very short and impregnation of a healing agent into the crack is completed in a short time, a cyanoacrylate-based adhesive with a short curing time can be used as a healing agent. In this experiment, Loctite 480 (Henkel) with good impact resistance and fracture toughness was selected. Although its viscosity was relatively high as 200 mPa·s, sufficient impregnation was expected because the channels were short.

The DCB test was carried out under displacement control of 2 mm/min. When the crack propagated, the specimen was removed from the test machine and healed by injecting the healing agent from the tubes connected to the channels at a pressure of 0.1 MPa for 5 minutes. The healing agent was injected from either one channel (the specimen is called hereafter "Healed-one", which simulates healing using an in-plane channel (Figure 1)) or all channels ("Healed-all"), and left at room temperature for 30 minutes to cure the injected adhesive. The DCB test was then conducted again and the mechanical performance of the healed specimen was evaluated.

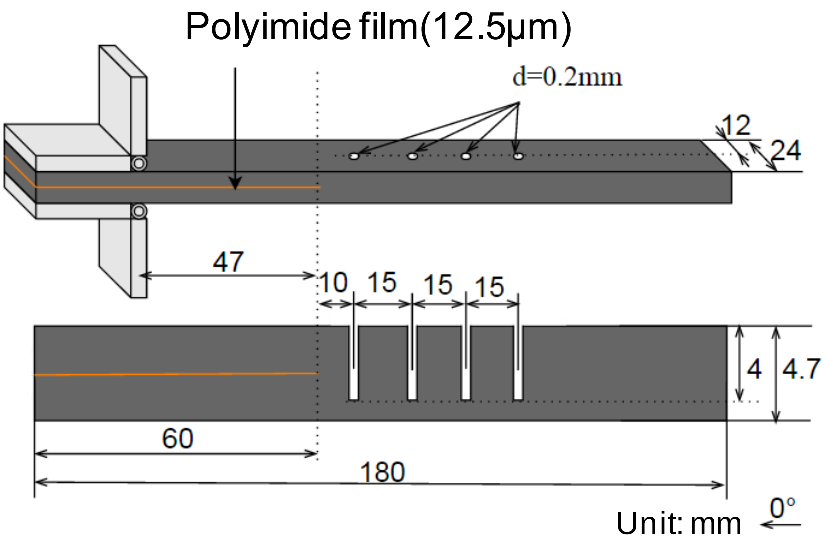


Figure: 6 Schematic of DCB specimen.

3.2 RESULTS

The load displacement curves before and after healing are compared in Figure 7. In both healing methods, the cracks propagated unstably but the maximum load was higher than the virgin specimen. In the specimens after healing, fiber bridging was not observed during crack propagation, and cracks propagated within the healing agent. Table 1 shows fracture toughness G_{IC} [kJ/m^2] at the initial crack position. In both healing methods, the fracture toughness increased by healing and it was confirmed that healing by through-thickness channel network performed well. The reason for the improvement of G_{IC} was attributed to excellent adhesion strength between the healing agent and the fracture surface of the CFRP specimens and higher fracture toughness of the healing agent than that of the matrix resin (epoxy) in the CFRP. In addition, G_{IC} was higher when the all channels was used for healing (Healed-all).

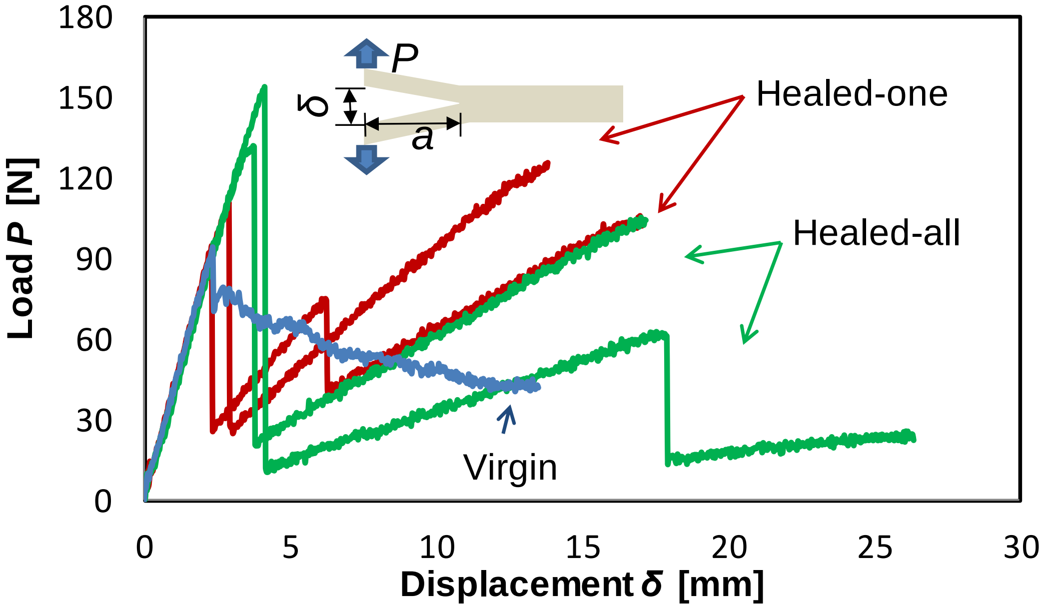


Figure: 7 Load-displacement curves obtained in DCB tests.

	Virgin	Healed
Healed-one	0.282	0.285
	0.252	0.435
Healed-all	0.255	0.857
	0.281	0.666

Table 1: Fracture toughness G_{IC}[kJ/m^2].

The fracture surfaces of the healed specimens were observed with a laser microscope (VK-X150, KEYENCE). At the positions where the unstable crack stopped and the load increased until subsequent crack propagation, the fractured surface was discolored black. Figure 8 shows the image and height distribution in the through-thickness direction around the initial crack tip observed in Healed-one and Healed-all specimens. A rough pattern was observed near the initial crack in the both fracture surfaces, and it was confirmed that local ductile fracture occurred before unstable crack propagation. Furthermore, from the height distribution this characteristic was widely observed in the fracture surface of the specimen healed using all channels (Healed-all, Figure 8 right). In order to confirm the mechanism of this difference, the cross-sections of untested specimens healed by the two methods were observed (Figure 9). The average thickness of the adhesive layer was thicker when healed from all channels (Healed-all). This was probably because the pressure of the healing agent was higher on the crack surface at the time of injection and larger amount of the healing agent was supplied. As a result, the energy absorption at the crack tip was larger and G_{IC} increased. So it can be said that the healing system using multiple channels is desirable.

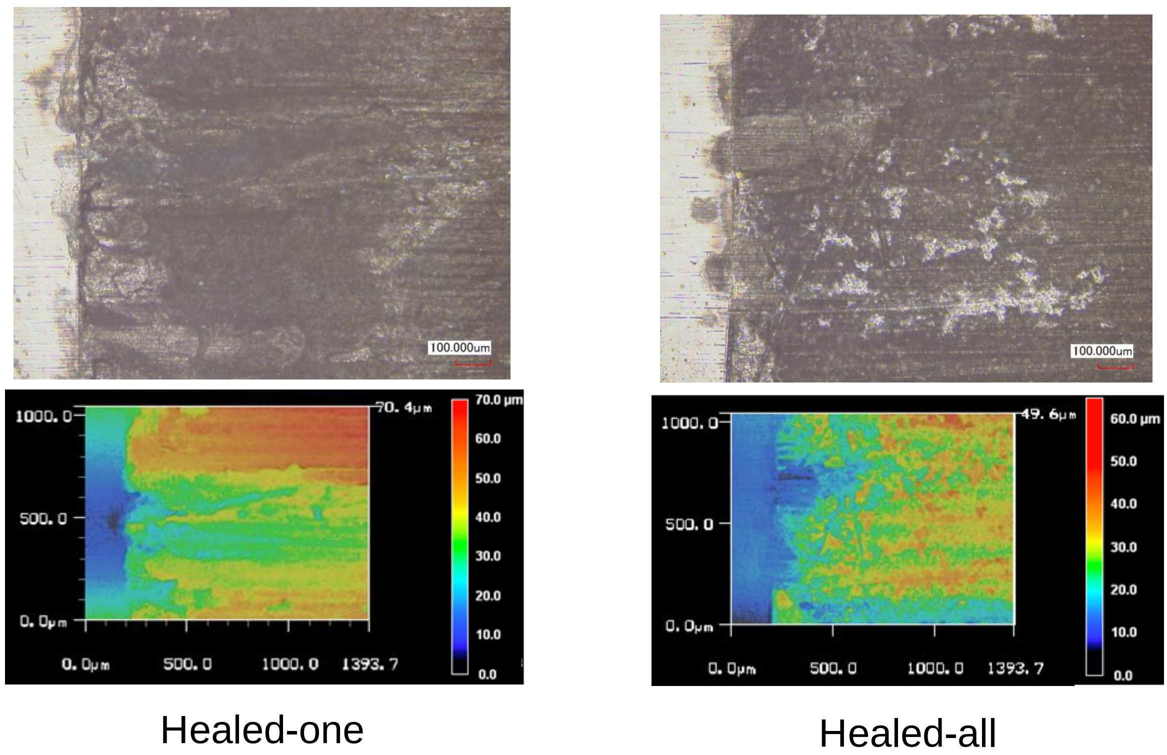


Figure 8 Fracture surface, and height distribution in the through-thickness direction.

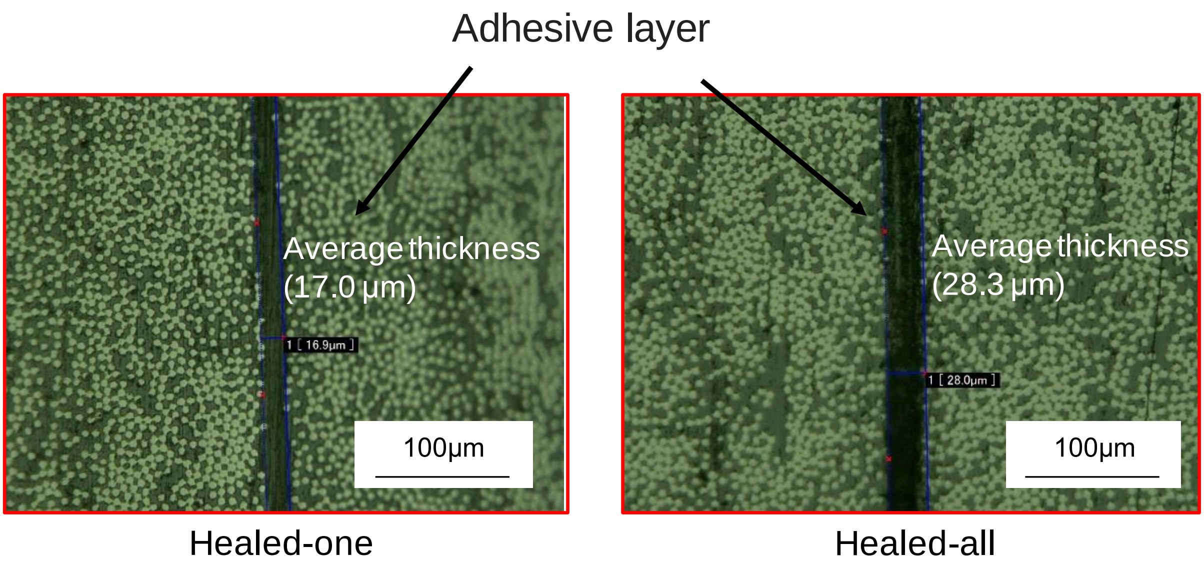


Figure 9 Cross-sectional observation of adhesive layer.

4 COMPRESSION AFTER INDENTATION TEST

4.1 MATERIAL AND METHOD

Figure 10 presents the schematic of the co-cured CFRP stiffened panels manufactured in an autoclave. The panel consisted of a single T-shaped stiffener and a skin. The prepreg sheets (T700S/2592, Toray Industries, Inc) were laid up to be $[-45/0/45/90]_{2S}$ for skin and $[-45/0/45/90]_S$ for stiffener. The 0.2 mm diameter multiple channels with a depth of 3 mm were formed in the same way as in the previous sections. Aluminum jigs were attached to both of the specimen edges to apply compressive loading.

First, the indentation displacement of 6.25 mm was applied to the stiffener flange position of two specimens using a hemispherical steel indenter (diameter 16 mm). Only one specimen was then healed by injecting the healing agent from the all channels until the adhesive overflowed from the disbond between the skin and the flange. Internal damage before and after healing was observed using an ultrasonic inspection equipment (Matrixeye, Toshiba Corp.) to confirm the impregnation state of the healing agent.

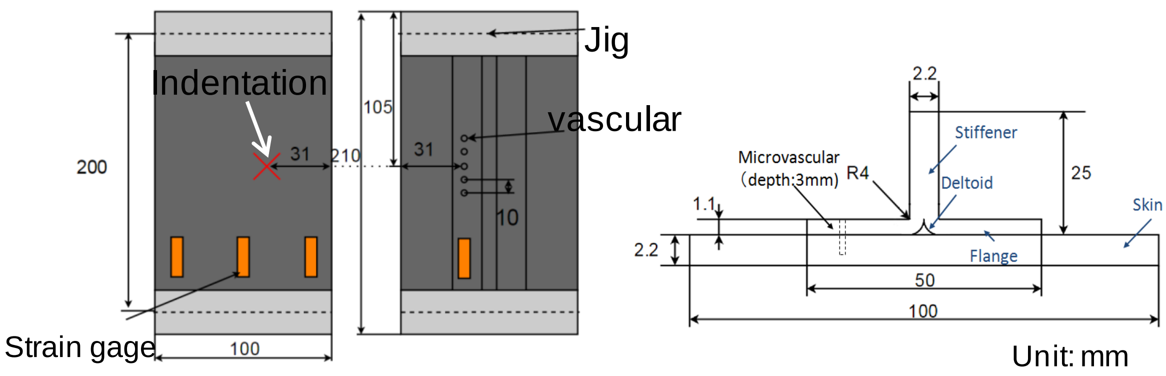
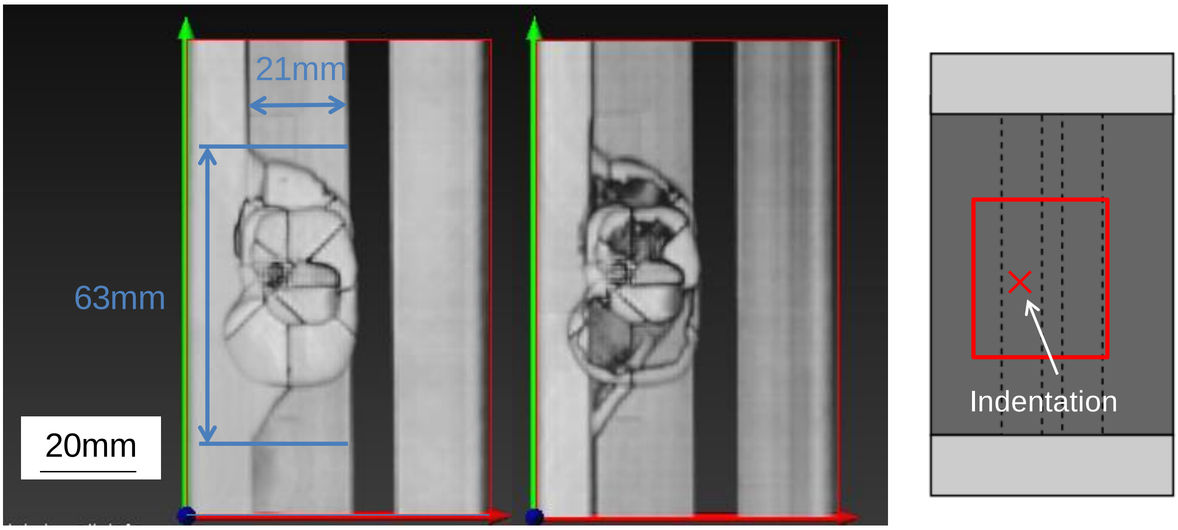


Figure 10 Compression specimen.

Next, compressive loading was applied to a non-damaged specimen (Virgin), the healed specimens (Healed) and the damaged specimens (Damaged) to evaluate their compressive strength. The test was carried out under displacement control of 0.5 mm/min. For axial alignment during compression, strain gauges (KFG-10-120-C1-11L1M2R, Kyowa Electronic Instruments Co., Ltd.) were attached to the skin and the stiffener. In addition strain distribution on the skin surface was monitored using digital image correlation (DIC, ARAMIS, GOM).

4.2 RESULTS

Figure 11 shows the ultrasonic observation before and after healing damage by indentation. Before healing, delamination in the skin and skin-stiffener disbond were observed. After healing, however, the delamination and disbond were almost healed even though the delamination edge and damages near the skin surface were remained. This was because the channels did not reach the damages in the vicinity of the skin surface, and the viscosity of the healing agent was slightly higher, so that it was not impregnated up to the edge of the delamination.



(a) Before healing (b) After healing

Figure 11 Ultrasonic observation of internal damage.

All the specimens first buckled and then failed while maintaining the buckling deformation. The load-displacement curves obtained from the healed specimen are shown in Figure 12. In that figure, the result of the strain gauge at each position of the specimen is indicated by the number, and the vertical lines indicate the failure loads in other specimens. The non-damaged specimens, the damaged specimens, and the healed specimens failed at 83.2 kN, 60.9 kN, and 74.2 kN, respectively. With reference to the non-damaged specimen, the strength decreased to 75 % after indentation but recovered to 90 % after healing. Figure 13 shows the strain distribution in the compression direction measured by DIC just before the failure of the damaged specimen and the healed specimen. It was confirmed that strain concentration around the indentation point was significantly suppressed after healing. Meanwhile, the strength was not completely recovered because the damage was not perfectly impregnated as seen in Fig. 11 (b). Indeed, only in the healed specimen there were cracking sounds probably due to crack propagation from this his un-impregnated area, and the failure occurred immediately afterward. Nevertheless, it was confirmed that the healing system is effective under realistic conditions and further strength recovery will be possible by using an optimized healing agent having lower viscosity.

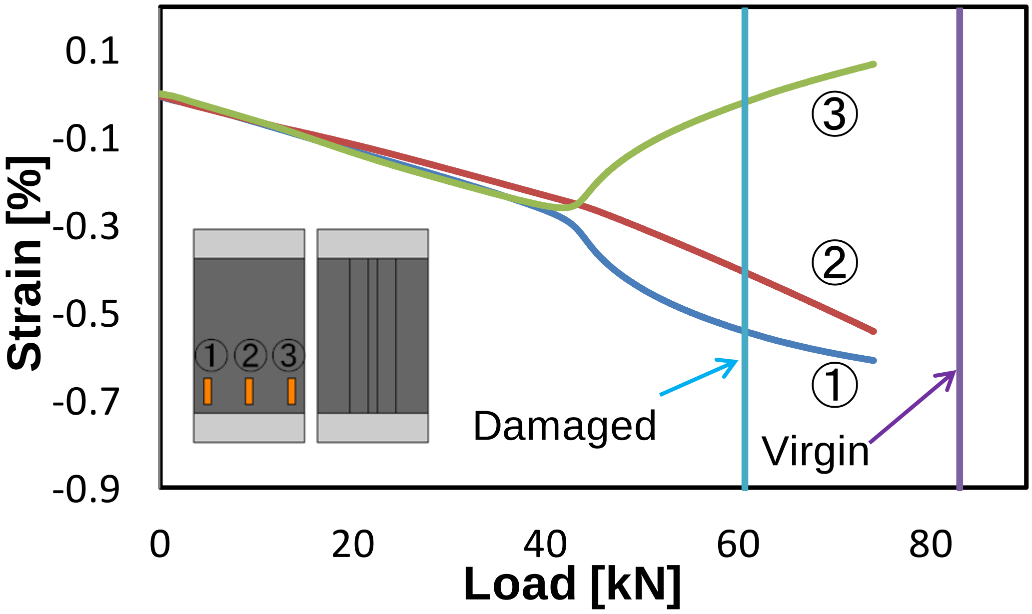


Figure 12 Strain-load curves obtained in compression (Healed specimen).

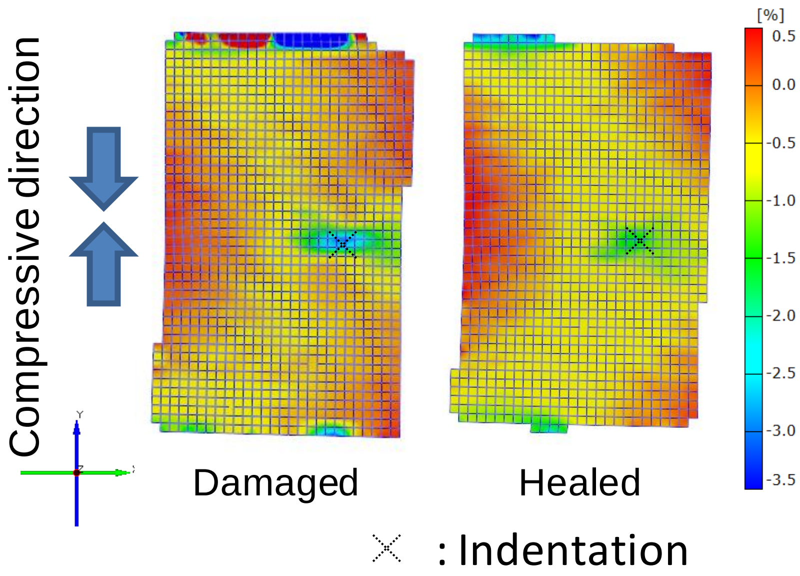


Figure 13 Compressive strain distribution just before failure obtained by DIC.

5 CONCLUSION

This study proposed a self-healing system using multiple short-microvascular-channels in the through-thickness direction. First, it was confirmed that the introduction of channels with diameter less than 0.2 mm was feasible and does not deteriorate the structural integrity significantly. Next, the impregnation of the healing agent and its healing function were demonstrated by the DCB tests. Finally, this healing system was applied to CFRP stiffened panels and the effectiveness of the system using the multiple channels in the through-thickness direction was successfully demonstrated.

ACKNOWLEDGEMENT

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